

RESEARCH ARTICLE

Combining seascape connectivity with cumulative impact assessment in support of ecosystem-based marine spatial planning

Per R. Jonsson^{1,2}  | Linus Hammar³ | Iréne Wåhlström⁴  | Jonas Pålsson³  |
Duncan Hume⁵ | Elin Almroth-Rosell⁴  | Martin Mattsson⁶

¹Department of Marine Sciences, Tjärnö Marine Laboratory, University of Gothenburg, Strömstad, Sweden; ²Environmental and Marine Biology, Åbo Akademi University, Turku, Finland; ³Swedish Agency for Marine and Water Management, Göteborg, Sweden; ⁴Swedish Meteorological and Hydrological Institute, Norrköping, Sweden; ⁵Geological Survey of Sweden, Uppsala, Sweden and ⁶Medins Havs och Vattenkonsulter AB, Mölnlycke, Sweden

Correspondence

Per R. Jonsson

Email: per.jonsson@marine.gu.se

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Abstract

1. Cumulative impact assessment (CIA) is a promising approach to guide marine spatial planning (MSP) and management. One limitation of CIA is the neglect of seascape connectivity, which may spread the impact of localized pressures to ambient areas, e.g. through lost dispersal and recruitment of organisms.
2. We here, for the first time, incorporate seascape connectivity into a traditional CIA model using a connectivity matrix, exemplified by dispersal of propagules estimated through biophysical modelling. Two *connectivity impacts* are identified: the *source impact* represents downstream areas losing recruits because of reduced larval dispersal from sites affected by the pressure, and the *sink impact* represents loss of recruits originating from upstream areas prevented from settlement in the site affected by the local pressure.
3. By including seascape connectivity in the Swedish MSP-guiding CIA tool Symphony we demonstrate how to practically account for remote effects of local environmental impact. Our example on blue mussel shows how reducing mussel fitness in a given area may have impacts on mussels far from the acting pressures. Overall, results indicate that connectivity impact for blue mussels plays a minor role in most areas, <10% of the ordinary cumulative impact. However, in some smaller areas, e.g. on offshore banks and the Danish Straits, seascape connectivity may increase ordinary cumulative impact with 20%–30%. In an example of scenario-based CIA analyses of MSP projections, we demonstrate how impacts of particular management actions, e.g. shipping rerouting and wind power developments, can be tracked far from the original area of influence.
4. Depending on the dispersal ability of ecosystem components, a local pressure may impact a considerable area through seascape connectivity, transgressing management units and national borders. Although the mean connectivity

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impact may be modest for a single ecosystem component, the consideration of seascape connectivity across multiple ecosystem components may significantly alter the mapping of cumulative impact and the assessment of different MSP scenarios.

5. *Synthesis and applications.* Our extension of Cumulative Impact Assessment offers a new method for mapping and practically integrating seascape connectivity with ecosystem-based MSP and other spatial instruments for policy making, such as marine protected areas.

KEYWORDS

biophysical model, blue mussel, cumulative impact assessment, dispersal, marine spatial planning, *Mytilus edulis*, seascape connectivity

1 | INTRODUCTION

Ocean biodiversity suffers dramatic losses from the combined effects of human activities and pressures, e.g. industrial fisheries, coastal land development, contaminants, eutrophication, shipping and the ongoing climate change (e.g. Halpern et al., 2019; Halpern, Walbridge, et al., 2008; Rocha et al., 2015). Effective policies and management actions across sectors are necessary to turn this deterioration of the marine environment and to allow sustainable use of marine resources (Duarte et al., 2020). At strategic level the environmental challenges must be targeted from a holistic perspective with an understanding of cumulative impacts, that are the simultaneous impacts of several concurrent pressures on several interconnected ecosystem components (Foley et al., 2010; Halpern, McLeod, et al., 2008). Abundance and intensity of such pressures vary across geographic space and have different effects on ecosystem components, which in turn interact over time and space. Cumulative environmental impacts are complex and ways of assessing them for design of effective management measures inevitably rely on balancing between simplification and justification.

Cumulative impact assessment (CIA) is a simple yet promising approach to guide marine management interventions by mapping cumulative impact (Halpern, Walbridge, et al., 2008). Cumulative impact is calculated as a relative index based on spatially explicit information about pressures from human activities, the distribution of ecosystem components (e.g. fish populations, mussel reefs and seagrass beds) and the approximate sensitivity of each ecosystem component to each human pressure (Andersen et al., 2020; Halpern, Walbridge, et al., 2008). Managers and planners may use CIA to identify areas of particularly high and low cumulative impact and to assess what pressures contribute most to the impact in any given area. This framework offers valuable guidance in the allocation of management resources including regulations, protected areas but also development of incentives. Changes of cumulative impact over time may further indicate where management actions are effective or inadequate (Halpern et al., 2019). CIA has proven particularly apt in support of spatially oriented policy instruments such as ecosystem-based marine spatial planning (MSP; Depellegrin et al., 2017; Fernandes et al., 2017). In Sweden,

scenario-based CIA has recently been applied to evaluate the expected environmental outcome of MSP as an integrated component of the planning process (Hammar et al., 2020).

The CIA method carries several critical simplifications implying some substantial limitations (Halpern & Fujita, 2013; Hodgson & Halpern, 2019; Stock & Micheli, 2016). One such limitation of CIA relates to the neglect of seascape connectivity. Pressures acting at one location only exert impacts at the same location, disregarding the possibility that different locations are ecologically connected due to dispersal and migration of organisms. For instance, even a human intervention that occurs in a very limited area, causing local loss of a fish spawning ground or a mussel reef, may have a far-reaching impact on recruitment also in other areas because of connectivity through dispersal of eggs and larvae. This limitation to the CIA methodology is particularly relevant for spatial planning of hazardous activities and the design of Marine Protected Areas (MPAs), where remote human pressures may have significant impact within areas aimed for protection and restoration (Jonsson, Moksnes et al., 2020). The connection between areas with distinct human activities and their remote impacts may also be important in stakeholder conflicts, as well as within international management of cross-border effects (Ehler & Douvère, 2009).

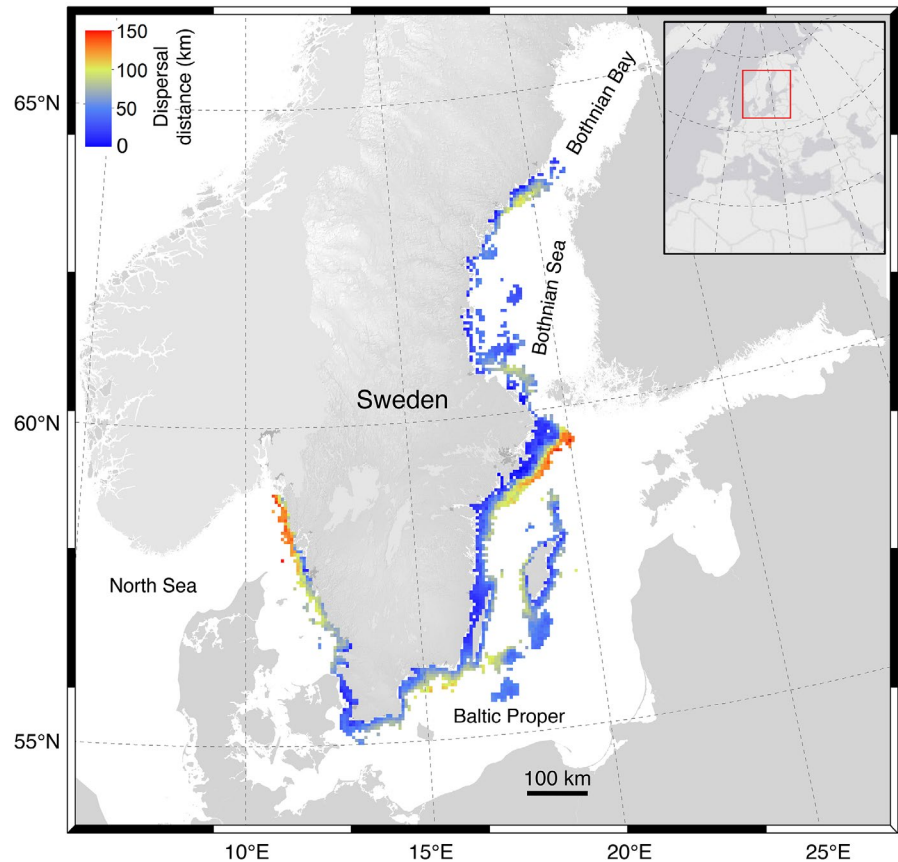
In this paper we demonstrate, for the first time, a method to combine CIA with seascape connectivity. Using examples from Sweden, we explore the significance of accounting for connectivity when mapping cumulative impacts in MSP.

2 | MATERIALS AND METHODS

2.1 | Cumulative impact assessment in Swedish marine spatial planning

Marine spatial planning serves to allocate marine space amongst multiple sectors and outline geographically detailed governmental strategies to the benefit of blue economy and environmental protection (Ehler & Douvère, 2009; EU, 2014). Swedish national ecosystem-based MSP is a guiding (non-binding) instrument. The national MSP area covers Swedish territorial water and Exclusive

FIGURE 1 The Baltic Sea. The colour-coded grid shows modelled site-specific dispersal distance of blue mussel larvae. Modelled dispersal distance is shown for all areas with a depth of <30 m



Economic Zone (EEZ), but does not include the coastal waters (within 1 nautical mile from the coastal baseline), which are under the authority of the local municipalities. Stretching from northern Bothnian Bay, through the Baltic Sea and west to the North Sea (Figure 1), the area includes sensitive and heavily polluted water bodies and several sounds with important water exchange between the different basins.

Swedish national MSP is coordinated by the Swedish Agency for Marine and Water Management (SwAM) under the Ministry of the Environment. Following Directive Framework for Maritime Spatial Planning 2014/89/EU (EU, 2014) the first Swedish marine plans will be implemented by 2021, after 7 years of formal preparation and stakeholder dialogue. As part of the ambition to undertake a truly ecosystem-based MSP, a scenario-based CIA tool, Symphony, was developed. This tool allows marine planners to estimate cumulative environmental impact across space and compute approximations of how different planning options would alter the level and geographical distribution of environmental impact. The Symphony CIA tool has been used by Swedish marine planners since 2016 (Hammar et al., 2020).

Symphony, founded on the traditional CIA methodology (Halpern, Walbridge, et al., 2008), includes maps of 37 pressures from human activities and 33 ecosystem components representing the marine environment in the region. These maps of intensity and ecological value, for pressures and ecosystem components respectively, are normalized (0–100) and predominantly based on continuous data but in some cases categorical or binary data. Metadata and assumptions for calculating cumulative impact and

incorporating MSP scenarios are provided elsewhere (Hammar et al., 2020). The Symphony CIA tool is static and does not consider the spatial-temporal relationships exerted by marine connectivity, despite the pronounced water exchange in the region and the vital role played by dispersed biological propagules (Jonsson, Moksnes et al., 2020). Symphony and CIA methodology in general produce relative estimates of environmental impact which are difficult to validate by quantitative measures. Andersen et al. (2015) however provide a coarse level validation of the method, based on comparison of environmental status.

2.2 | Principles for combining seascape connectivity with Cumulative Impact Assessment

CIA builds on the combination of multiple data layers, representing n pressure intensities (P_i) and distribution of m ecosystem components (E_j), and sensitivity scores (S_{ij}) that specify what magnitude of effect each pressure may have on each individual ecosystem component. Cumulative impact score (I_{sum}) is calculated for each geographical unit according to Equation 1 (Halpern, Walbridge, et al., 2008).

$$I_{sum} = \sum_i^n \sum_j^m P_i \times E_j \times S_{ij}. \quad (1)$$

The connectivity of an impact from an area exposed to a pressure to the surrounding seascape may be caused by several mechanisms

through the exchange of drifting propagules that may be reasonably well estimated by biophysical modelling.

2.3 | Biophysical modelling of seascape connectivity

As a demonstration of seascape connectivity to be incorporated in the CIA model, we here modelled the larval dispersal of blue mussels (*Mytilus edulis/trossulus*). Dispersal of the microscopic, free-swimming mussel larvae are strongly influenced by ocean currents (McQuaid & Phillips, 2000) although larvae may exert some control through preferred drift depth and pelagic larval duration (PLD). Dispersal trajectories were simulated with the Lagrangian particle-tracking model TRACMASS (De Vries & Döös, 2001) driven off-line with flow fields from an ocean circulation model. The stored ocean transport data were produced with the NEMO-Nordic model, which is a regional configuration of the NEMO ocean engine covering the Baltic Sea and the eastern North Sea (Hordoir et al., 2019). The model has a horizontal spatial resolution of 3.7 km, and 84 vertical levels. At the boundaries, tidal harmonics define the sea surface height (SSH) and velocities, and Levitus climatology defines temperature and salinity (Levitus & Boyer, 1994). The model has a free surface, and the atmospheric forcing is based on the re-analysis dataset ERA40. Climatological data from a number of different databases for the Baltic Sea and the North Sea provided freshwater runoff. Validation of the NEMO-Nordic model has shown that the model is able to correctly represent the SSH, both tidally induced and wind driven (Hordoir et al., 2019).

Particles simulating drifting larvae were released from all model grid cells overlapping with mussel occurrence in the Symphony data layer. The dispersal simulations assumed that mussels spawned between May and July, that they drifted between surface and 26 m depth (25% 0–2 m, 50% 10–12 m, 25% 24–26 m) and with a PLD between 20 to 30 days (50% each; Jonsson, Moksnes et al., 2020). From each grid cell, representing the mussel habitat, 49 virtual larvae were released (a 7 × 7 array) each spawning month and for the assumed drift depths and PLD. This was repeated for 8 years (1995–2002), which cover a wide range of the North Atlantic Oscillation index (Hurrell & Deser, 2009), which is known to correlate well with the variability in circulation pattern in this geographic area. In total the trajectories of 100 million larvae were simulated. Potential connectivity (Watson et al., 2010) between model grid cells, satisfying the habitat restriction was calculated as the proportion of trajectories starting in grid cell x and ending in grid cell y and then summarized in a connectivity matrix (CM). Figure 1 shows the mean dispersal distance of mussel larvae, calculated from the connectivity matrix, indicating areas where consideration of seascape connectivity may be particularly important. There are so far no explicit studies in the Baltic Sea if and how the supply of mussel larvae is linked to the distribution of adult populations. Indeed, also on a global scale there are few studies exploring this relationship for marine invertebrates. One of few examples is a study on blue mussels from the Canadian east coast of larval–adult relationship on scales between

12 to 30 km indicating source–sink effects mediated through larval dispersal in the coastal circulation (Smith et al., 2009).

2.4 | Implementing seascape connectivity into the CIA framework

The Symphony CIA tool (Hammar et al., 2020) was used to calculate the combined impact of all human pressures on blue mussels (*M. edulis/trossulus*) alone (Equation 2). Blue mussels were selected to illustrate how to implement connectivity into CIA because their distribution in the area is well documented, their sensitivity to a range of pressures is reasonably well understood, and their seascape connectivity is largely driven by planktonic larval dispersal. The geographical distribution of mussels across the analysed area was derived from the existing data layer for mussel reefs used in Symphony. This data layer of national coverage was previously produced with a Species Distribution Model where occurrence data (5,061 training sites, 573 test sites) were fitted (AUC > 0.8) to environmental layers of salinity, bathymetry, hard bottom, wave exposure and seabed slope using a General Additive Model (Guisan et al., 2017). Probability of mussel bed occurrence was classified into absence (pixel value = 0), >10% predicted cover (pixel value = 30) and observed mussel reef (pixel value = 100; Hammar et al., 2020).

Following the general procedure demonstrated in Section 2.2, the cumulative impact on blue mussel ($I_{Mytilus}$) in each grid cell was calculated and multiplied with mussel source probability ($p_{sourceMytilus}$) and sink probability ($p_{sinkMytilus}$) based on the connectivity matrix (CM), thus generating values for mussel source impact ($I_{sourceMytilus}$) and sink impact ($I_{sinkMytilus}$) respectively, across the grid (Figure 2). The full mussel connectivity impact ($C_{Mytilus}$) was calculated by summarizing the values for source- and sink-related impact for all pressures in each grid cell.

First, the Symphony 250 × 250 m geographic grid for blue mussels was adjusted to fit the grid of the biophysical model used to estimate the connectivity matrix, which has a different projection and larger cell size (Figure 2). To handle the larger cell size in the connectivity matrix, mean values of the mussel cumulative impact were calculated over each connectivity matrix cell.

Source- and sink-related impacts were calculated from the following formulas (Equations 3 and 4), where CM contains source and sink probabilities ($p_{sourceMytilus}$) and ($p_{sinkMytilus}$) respectively:

$$I_{source Mytilus} = \sum_i^n CM_{source} \times I_{Mytilus} \times \frac{Cell\ area\ Symphony}{Cell\ area\ CM}, \quad (3)$$

$$I_{sink Mytilus} = \sum_i^n CM_{sink} \times I_{Mytilus} \times \frac{Cell\ area\ Symphony}{Cell\ area\ CM}. \quad (4)$$

We finally converted source and sink impacts back to the Symphony grid. Figure 3 illustrates these results for a single MSP area. All computations were performed in Python, C++ and CUDA (Nvidia Corp).

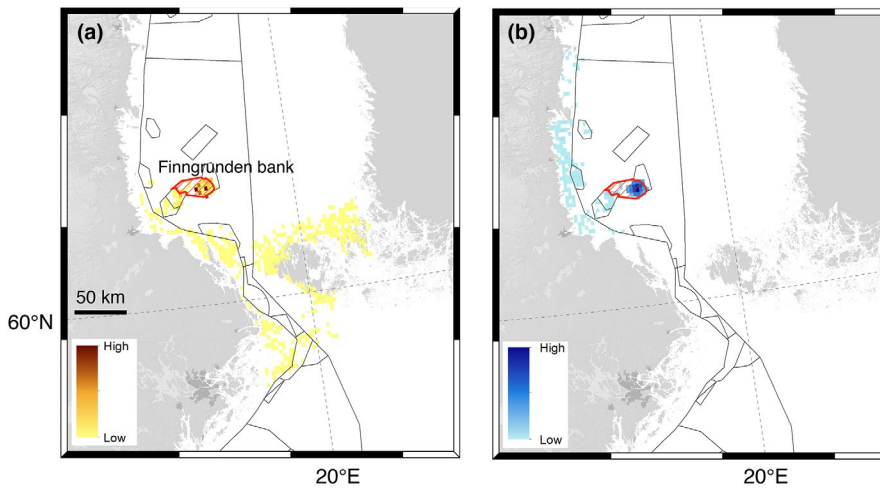


FIGURE 3 Source-related impact (a) and sink-related impact (b) for blue mussels within the confined area (red zone) of Finngrunden offshore bank in southern Bothnian Bay. Zonation indicates areas of Swedish marine spatial planning (MSP) guidance. Colour-coded scale in relative units of low to high impact

Assuming that the supply of larvae is limiting, the source-related impact is interpreted as an impact on ecosystem component j in an MSP area, caused by seascape connectivity and pressures, on recruits that happens during departure from another specific area. The sink-related impact is interpreted as an impact on ecosystem component j in an MSP area where arriving recruits are affected by pressures in ambient areas (Figure 2).

2.5 | Modelling MSP-related change to mussel connectivity impact

Marine spatial planning may change the current state of cumulative environmental impact by guiding the future use of marine space to the benefit of activities and/or interests such as conservation at the expense of certain human activities. Such MSP-induced changes can arise from environmental as well as economical concerns. These changes with inherent uncertainty can be simulated by the Symphony CIA tool using scenario-based modelling. Simulations involve adding, increasing and reducing pressure maps and adjusting sensitivity scores in accordance with MSP guidance (Hammar et al., 2020). For example, where MSP indicates rerouting of ship traffic the pressures from shipping, such as underwater noise, oil spill and propeller-induced turbidity, are removed or reduced from one area and added or increased in the area of the new route. Such changes have effect on all ecosystem components sensitive to the altered pressures. Where changes have effect on only specific ecosystem components this is simulated by alternation of sensitivity scores, such as reducing the sensitivity of benthic habitats to bottom trawling where MSP recommends fishing gear regulations that minimize abrasion but still catch fish (Hammar et al., 2020).

In order to demonstrate how seascape connectivity can be addressed during such scenario-based modelling, MSP-related change to mussel connectivity impact ($C_{Mytilus}$, Equations 3 and 4) was calculated using the Symphony CIA tool with MSP scenario assumptions set as for the 2019 plan iteration (Hammar et al., 2020).

3 | RESULTS

3.1 | Connectivity impact on Baltic Sea blue mussels

Incorporating blue mussel seascape connectivity into the CIA model demonstrates that any environmental impact on mussels in a given area may have consequences for mussels in other areas, far from the impact events. Figure 3 shows the seascape connectivity aspects of environmental impact, as calculated by the Symphony CIA tool, on blue mussels at the MSP zone Finngrunden offshore bank. Most of the connectivity impact remains within the bank, but mussel banks along the Swedish south-eastern coast and the archipelago are negatively affected through source-related impact ($I_{sourceMytilus}$). This result is caused by the reduced opportunity of impacted mussels on the Finngrunden bank to provide recruits to neighbouring banks. In addition, mainly mussels on banks along the Swedish north-eastern coast suffer reduced fitness due to sink-related impact ($I_{sinkMytilus}$), caused by declining recruitment opportunity in the Finngrunden area. Noteworthy, this connectivity impact transcends borders as it reaches from Swedish far into Finnish waters. Nevertheless, the local connectivity impact within the Finngunden bank is higher by several orders of magnitude compared to surrounding areas, which is a result of relatively low mussel connectivity to ambient habitat areas. Also note that many larvae from the Finngrunden area may disperse into unsuitable areas and fail to recruit.

Figure 4 demonstrates the full connectivity impact ($C_{Mytilus}$) calculated for source- and sink-related impact (Equations 3 and 4), and all pressure layers for blue mussels within the Baltic Sea area of Swedish national MSP, in relation to the ordinary (direct) cumulative impact ($I_{Mytilus}$). The results indicate that connectivity impact plays a minor role in most areas, <10% of the ordinary cumulative impact. The overall connectivity impact for blue mussels in the Swedish Baltic Sea national MSP area is 2% of the ordinary cumulative impact on blue mussels. When considering the full model with all 35 ecosystem components, the mean connectivity impact for blue mussels only contributes 0.02%

FIGURE 4 Full connectivity impact ($C_{Mytilus}$) for blue mussels throughout the Swedish Baltic Sea national marine spatial planning (MSP) area, calculated as the ratio (%) between source and sink seascape connectivity (C_s) and the ordinary cumulative impact (I_o) on blue mussels without considering connectivity. Zonation indicates areas of Swedish MSP guidance

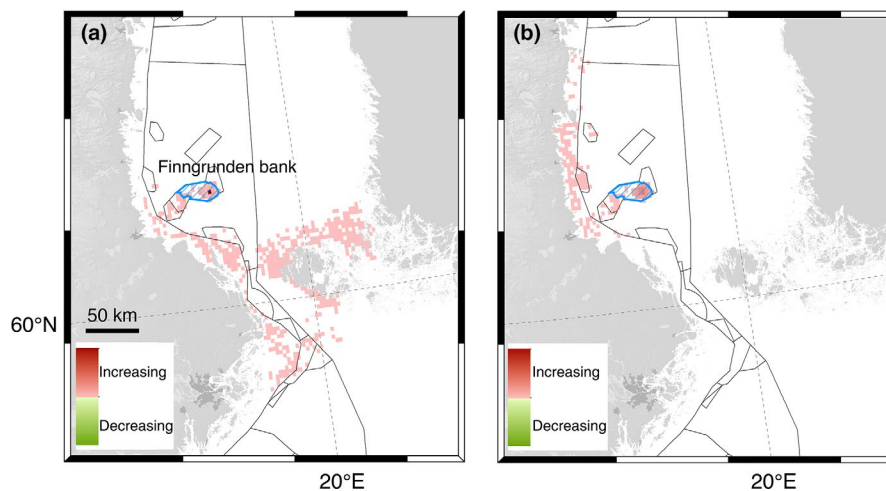
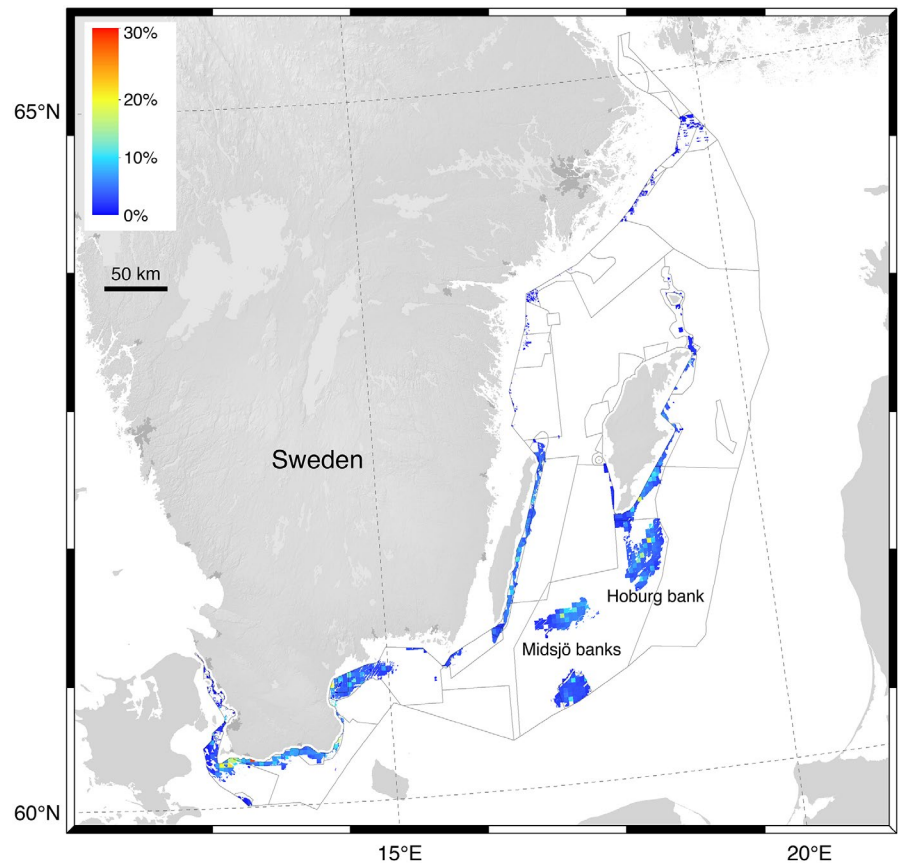


FIGURE 5 Area-specific changes to connectivity impact on blue mussels in consequence of marine spatial planning (MSP). Panels show modelled change to source impact (a) and sink impact (b) caused by impact on mussels within the Finngrunden offshore bank (blue polygon) in southern Bothnian Bay. The MSP designates the Finngrunden area to an MPA, while offshore wind power is prioritized in neighbouring areas (zones to west and east of blue zone). In this scenario, rerouting of ship traffic (with underwater noise, oil spill and propeller-induced turbidity) around planned wind power parks is expected to change the distribution of pressures generating some increase of environmental impact to mussels in the MPA. Zonation polygons indicate areas of Swedish MSP guidance. Colour-coded scale shows relative change in impact due to MSP scenarios

to the total CIA, reflecting that blue mussels are not among the most disturbed species in the region. However, in some areas along the southern coast of Sweden and on the Midsjö and Hoburg offshore banks south of the island of Gotland, seascape connectivity seems to play an important role, with blue mussel connectivity impact corresponding to 10%–30% of the ordinary cumulative impact.

3.2 | MSP-related change to mussel connectivity impact

The specific impact of management measures on connectivity can be assessed by incorporating seascape connectivity to scenario-based CIA analyses. Figures 5 and 6 show the anticipated effect of Swedish

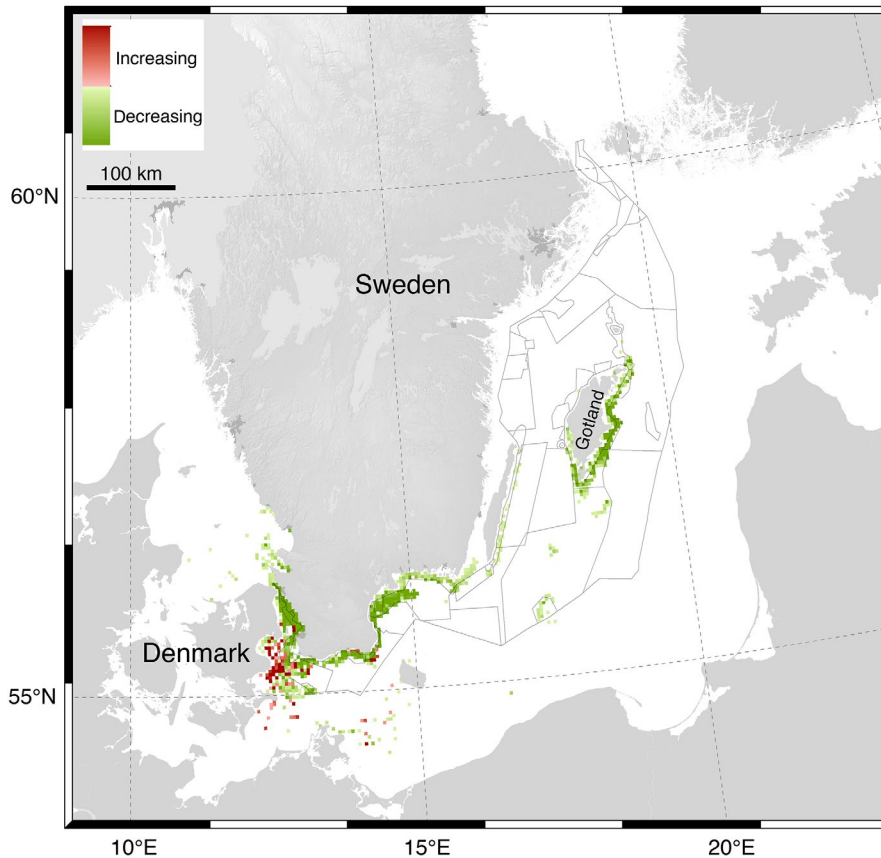


FIGURE 6 Marine spatial planning (MSP)-related changes to blue mussel connectivity impact across the Baltic Sea. Red colour indicates a slight net increase of connectivity impact while green colour indicates net decrease in connectivity impact

national MSP on blue mussel connectivity impact compared to a null-alternative with projected development without MSP (Hammar et al., 2020). The analysis demonstrates the potential of this approach for integrating seascape connectivity in evaluation of particular management actions. In this particular case (Figure 5) the MSP promotes new wind power developments at the slope of an offshore bank, including a slight alteration of ship traffic routes which in turn affects blue mussels in the area. By including source- and sink-related impacts, the (small) negative effect of this MSP guidance can be tracked far from the original area of influence. Figure 5 exemplifies how negative effects are expected in the designated MPA Finngrundens bank, caused by connectivity impacts from distant pressures.

In the Baltic Sea, Swedish MSP may influence blue mussel connectivity impact as illustrated in Figure 6, with most changes in southernmost Sweden and around the island of Gotland. In these areas, the net effect of MSP mainly implies a reduced connectivity impact for blue mussels (comparatively lower $C_{Mytilus}$ for scenario with implemented MSP). However, the MSP scenario seemingly has negative effects on blue mussels in neighbouring Danish waters, indicating that changes in use of marine space according to Swedish MSP will raise the connectivity impact on Danish mussel habitats (comparatively higher $C_{Mytilus}$ with MSP in place).

4 | DISCUSSION

Cumulative impact assessment is currently viewed as a useful approach to map environmental impact of multiple pressures, offering

support for spatially oriented ecosystem-based MSP (Depellegrin et al., 2017; Fernandes et al., 2017; Hammar et al., 2020; Korpinen et al., 2012). The Swedish MSP with the CIA tool Symphony has been criticised for not including connectivity aspects into the planning framework. This work explores a novel way to address this limitation, applicable to all CIA models. By including connectivity, e.g. the dispersal of larvae from mussel banks, a pressure that reduces (or promotes) fitness locally will have an extended impact over an area determined by the extent of larval dispersal and the mussel habitat distribution. Two different components of connectivity impact are identified. The source impact is represented by connected areas losing recruits because of reduced larval production in the site affected by the pressure. The sink impact occurs when connected upstream banks suffer reduced fitness caused by their loss of recruits in the site affected by the local pressure. Depending on the type of pressure the source and sink impacts may be unequally severe. If a local pressure reduces the population of adult mussels, e.g. through harvesting, but does not affect the habitat suitability, the source impact may be substantial but with little effect on sink impact. In contrast, if a local pressure deteriorates the habitat suitability, e.g. through contaminants, anoxia or dredge spoils, both source and sink impacts are potentially important.

Depending on the dispersal ability of target ecosystem components, e.g. of key species, a local pressure may impact a considerable area through seascape connectivity, transgressing management units and even national borders (Figure 5). This added redistribution of impact will differ greatly among ecosystem components depending

on their seascape connectivity. Examples where connectivity may cause particularly large-scale impact from local pressures include species with long-distance dispersal through seeds (e.g. seagrasses) and invertebrate larvae, localized spawning grounds and nursery areas for fish and breeding areas for marine mammals and seabirds.

It should be noted that we have only tested this approach to one specific taxon, whose connectivity is related to current-driven larval dispersal. The connectivity impact from multiple ecosystem components may be combined into cumulative connectivity impact ($C_{\text{sum}, j, \dots, n}$) and added to or compared with the ordinary cumulative impact (I_{sum}). Where ocean currents strongly influence connectivity, several ecosystem components (e.g. key-stone species) may show similar connectivity patterns and thus together amplify the connectivity impact in some areas (De Witt et al., 2020). When adding up the cumulative impact across ecosystem components the inclusion of seascape connectivity may significantly alter the spatial distribution of CIA and also of the relative impact of different MSP scenarios. Moreover, blue mussels in the Baltic Sea do not represent the most sensitive organism. Migratory commercial fish species (Neuenfeldt et al., 2007), seabird populations (Skov et al., 2011) and harbour porpoises (Verfuß et al., 2007) may be relevant examples of more sensitive ecosystem components in the Swedish context.

Our example is limited by the simplicity of used CIA model. Symphony and many other CIA models lack a temporal dimension and thus rely on the assumption that geographically overlapping pressures and ecosystem components also concur in time. In reality, however, mussel reproduction which is abundant during spring will not be affected by a pressure exerted during diverse periods of the year. This shortcoming can be solved by more detailed and tailored CIA model runs where data are delimited to certain temporal windows. This and other shortcomings advocate that broad-scale CIA such as Symphony are used mainly for strategic assessments to be followed by detailed studies where necessary (Hammar et al., 2020).

Furthermore, seascape connectivity is not known for all ecosystem components. As in this study, biophysical modelling is increasingly used to estimate connectivity of a range of species with sufficient coverage in space and time (Cowen & Sponaugle, 2009). Several recent studies suggest that biophysical models may adequately represent connectivity when compared to independent methods mainly based on genetic markers (Jahnke et al., 2018; De Witt et al., 2020). However, biophysical models may only represent connectivity for species where dispersal is significantly influenced by the oceanographic circulation excluding, e.g. migratory fish. Note, that the interface between CIA tools like Symphony and connectivity as described here is the connectivity matrix, which may be constructed from other methods than biophysical models. In principle the connectivity matrix may be estimated from GIS-based landscape analyses of habitat distribution and corridors (Sundblad et al., 2011), fish tagging (Moland et al., 2011) bird ringing (Ambrosini et al., 2009) or genetic assignment (Manel et al., 2005). However, it may be challenging to reach sufficient spatial coverage, and extensive interpolation may be necessary.

Failing to include seascape connectivity in CIA will underestimate the full impact in apparently undisturbed areas caused by distant pressures (Manel et al., 2019). Where connectivity impacts reach far, management plans need to extend outside of the boundaries of MPAs (Jonsson, Moksnes et al., 2020). For the same reason, connectivity is important in MSP. The most appropriate allocation of marine space for harmful human activities may not be the same once seascape connectivity is accounted for. Such considerations are essential in ecosystem-based MSP (Manel et al., 2019) but very difficult to implement without quantitative data and modelling.

Inclusion of seascape connectivity in CIA models inevitably adds complexity to the model and reduces the ease of understanding of the method by users. Whether to include connectivity and other complex functions should always be a thought-through trade-off between simplicity and justification with respect to level of importance. Uncertainty increases when different models are combined, as in this case, and it is important to note that CIA has only been quantitatively validated at a low level of geographical detail (Andersen et al., 2015).

CIA are becoming common decision support tools within marine management, with applications at national scale such as MSP (Depellegrin et al., 2017), at regional scale (HELCOM, 2018), and possibly soon for strategic environmental assessments within Areas Beyond National Jurisdiction (Maina et al., 2020) where large-scale connectivity plays an essential role. Seascape connectivity (sometimes labelled green/blue infrastructure) is central to large-scale and area-based marine management. Therefore, the option to include connectivity in CIA enables improvements of practical relevance for marine management. For the reasons mentioned above, it is nevertheless recommended that CIA users and developers act cautiously and choosy, and focus on incorporating the most essential and well-understood connectivity patterns.

In summary, we demonstrate that it is possible to include seascape connectivity into assessments of cumulative environmental impact, where both source and sink impacts can be added to traditional estimates of CIA. Our preliminary assessment shows that connectivity can significantly change spatial impact patterns, which calls for added caution in the interpretation of impacts for MSP scenarios. We therefore recommend the inclusion of essential seascape connectivity to advanced CIA models being used for strategic decision making.

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AUTHORS' CONTRIBUTIONS

All authors contributed to conceptual development, with L.H., P.R.J. and M.M. devising the models; P.R.J., L.H. and M.M. wrote the manuscript, with input and revision from I.W., J.P., D.H. and E.A.-R., and final approval for publication from all authors.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository <https://doi.org/10.5061/dryad.ghx3ffbmq> (Jonsson, Linus et al., 2020).

ORCID

Per R. Jonsson  <https://orcid.org/0000-0002-1793-5473>

Irène Wählström  <https://orcid.org/0000-0001-8735-268X>

Jonas Pålsson  <https://orcid.org/0000-0002-3134-4602>

Elin Almroth-Rosell  <https://orcid.org/0000-0003-4052-045X>

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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