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Implementation of cumulative effect assessments in maritime spatial planning: insights from two North Sea case studies

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The implementation of an ecosystem-based Maritime Spatial Planning (MSP) requires a holistic understanding of the interactions between maritime activities and marine ecosystems. Cumulative Effects Assessments (CEA) are essential for providing planners with such knowledge. However, despite multiple national and international initiatives, their application in MSP still needs to be further developed. Significant challenges remain: methodological limitations such as the integration of the scale of pressures caused by each activity or the relative nature of the risk of cumulative effects calculated by most tools. In this context, we developed enhancements to the global framework for Cumulative Effects Assessments. To better integrate the scales at which different activities affects the environment, for each group of activities and category of pressures, we attributed a magnitude value approximating the proportion of the environment affected by the activity. We then integrated these magnitudes in an existing CEA tool to improve the binary relationship between activities and pressures. We also used these weighted relationships in combination with the sensitivities of ecosystem components to define an unsuitability value for activities: the unsuitability of an activity is higher wherever ecosystem components are highly sensitive to whichever pressures the activity emits at high magnitude. We completed a CEA applying these improvements in two North Sea case studies, respectively at local and sea-basin scales. Drawing on insights from these studies, we present conclusions regarding the application of CEA for MSP at local and sea-basin scales: weighting pressures by their magnitude refines the calculation without altering the overall distribution of results. The unsuitability of activities provides relevant information to organize activities sustainably. Finally, regarding scales, the use of a finer resolution, where possible, provides accuracy and reliability of results for the CEA that is most useful in the case of geographically restricted areas.

KEYWORDS
activity suitability, cumulative effects assessments, ecosystem-based approach, human activities, magnitude of pressures, maritime spatial planning

1 Introduction

In the last decades, the density and intensity of human activities across maritime space has increased globally. Alongside traditional and historical activities such as fishing and maritime transport, new industrial activities have emerged and experienced a significant growth in recent years, such as the production of energy through offshore wind farms.

In 2021, at the European level, the established sectors of the European Union (EU) Blue Economy directly employed nearly 3.59 million people and generated a turnover of around €623.6 billion and a Gross Value Added (GVA) of €171.1 billion (European Commission, 2024). Among the various sectors, two are particularly noteworthy. Marine living resources saw a 24% rise compared to 2020, with gross profits at €9.7 billion in 2021. Marine renewable energy, mainly offshore wind, also experienced significant growth, resulting in a 45% increase compared to 2020, with gross profits estimated at €2.4 billion and GVA at €3.3 billion in 2021 (European Commission, 2024). Within the EU27, Germany, France, Spain, Italy, and the Netherlands account for 70% of the entire EU Blue Economy's GVA.

Maritime and coastal activities are a pillar of the European economy and contribute significantly to providing the goods and services necessary for EU Member States (European Commission, 2024). Maritime activities, such as the production and extraction of living and non-living resources, maritime transport, offshore wind farms, maritime infrastructure construction, coastal tourism, etc., are very diverse and affect all economic sectors.

However, the importance and diversity of maritime activities represent major challenges for the management of maritime space and resources and for the conservation of marine ecosystems. These challenges include the growing demand for maritime space for emerging activities, conflicts of use in time and space, conflicting and incoherent plans and decisions taken by fragmented management of the numerous economic sectors involved (e.g., Collie et al., 2013). Moreover, along with the global ocean warming, the widespread anthropization of the marine environment is leading to extensive, expanding, and intensifying impacts on marine ecosystems, threatening marine biodiversity, ecological functions and ecosystems' services (Johnston et al., 2022; O'Hara et al., 2021; Piet et al., 2024).

Within the European Integrated Maritime Policy (European Commission, 2007), an integrated framework aimed at improving the coordination of policies affecting marine environments and maritime sectors, Maritime Spatial Planning (MSP) is a "cross-cutting policy tool enabling public authorities and stakeholders to apply a coordinated, integrated and transboundary approach" (Directive 2014/89/EU, 2014). MSP has received increasing attention as an ecosystem-based approach capable of enhancing socio-economic development while promoting environmental conservation (Abramic et al., 2024). MSP has been a very dynamic and growing field of research for the past two decades (e.g., Chalastani et al., 2021; Zuercher et al., 2022), with a number of MSP-related publications rising exponentially by more than 40% annually from 2003 to 2019 (Chalastani et al., 2021). In the European Union, the Directive establishing a framework for maritime spatial planning (Directive 2014/89/EU, 2014) implements the requirement for Member States to establish a national MSP. The EU MSP framework explicitly includes environmental objectives that must be consistent with the European environmental legislation, such as the Marine Strategy Framework Directive (MSFD; Directive 2008/56/EC, 2008).

Achieving such objectives is intrinsically linked to integrated MSP: beyond the implementation of Marine Protected Areas (MPAs), good environmental status across large sections of maritime space can be achieved through MSP by carefully organizing and regulating activities according to their effects on the environment. To this end, it is necessary to provide MSP practitioners with a comprehensive understanding of the effects of existing activities on the environment, which is why Member States' MSP must consider "relevant existing and future activities and uses and their impacts on the environment."

Within this context, the understanding and the assessment of the combined effects of human activities on marine ecosystems must be considered and represents a huge challenge in achieving the objectives of MSP (Borja et al., 2024; JPI Oceans, 2024).

Cumulative Effect Assessments (CEA) are holistic evaluations of the combined effects of human activities, associated pressures and natural processes on the marine environment and are a specific form of environmental impact assessment (Halpern et al., 2008; Judd et al., 2015; JPI Oceans, 2024).

In the context of MSP, CEA can be used by planners to obtain a detailed estimation of the combined effects of anthropogenic pressures in a given area. The use of CEA is therefore fundamental to the implementation of an ecosystem-based MSP. Several national and international studies apply CEA for MSP-related purposes, using tools like MYTILUS (Bonnevie et al., 2022) in the national Danish MSP, or SPIA (HELCOM Secretariat, 2018) in the holistic assessment of the Baltic Sea performed by the Baltic Marine Environment Protection Commission (Helcom). In addition, CEA allows MSP planners to monitor whether MSP environmental objectives are achieved, and to compare multiple planning scenarios following an Ecosystem-Based management approach (Bonnevie et al., 2022; Hammar et al., 2020).

Recent studies are dedicated to the development of methods, guidance and decision support tools based on CEA to support and inform planners in the implementation of MSP (Lonsdale et al., 2020; Hammar et al., 2020; JPI Oceans, 2024; Stelzenmüller et al., 2024; Borja et al., 2024; Piet et al., 2024). These national and transnational reports highlight the growing use of cumulative effects assessments and strategic environmental assessments in MSP, while also emphasizing the difficulty of aligning scientific recommendations with political decision-making (Brekelmans et al., 2024; Kuempel et al., 2025; Shih, 2025; Stelzenmüller et al., 2024).

However, despite numerous advances (Elliott et al., 2017; Halpern and Fujita, 2013; Judd et al., 2015; Lonsdale et al., 2020), implementing Cumulative Effect Assessments still poses several technical and scientific challenges (Halpern and Fujita, 2013; Judd et al., 2015).

Several existing CEA tools and methods are qualitative, semi-quantitative, or based on expert judgement (e.g., Quemmerais-Amice et al., 2020; Bonnevie et al., 2022; Halpern et al., 2008). As such, there is a need to develop quantitative, evidence-based tools for decision making in MSP (e.g., Chalastani et al., 2021; Zuercher et al., 2022).

Additionally, several parameters of CEA, for instance defining human activities or pressures at the appropriate level of detail or identifying the interactions of various pressures for each ecological component, amongst others, are still not completely understood in a comprehensive way that would enable their integration into CEA methods.

For instance, although physical and chemical processes can be predicted and are based on deterministic relationships, marine physical, chemical, and biological dynamics and the response of marine ecosystems to anthropogenic pressures are often nonlinear, particularly with regard to ecological tipping points and pressure response thresholds (Borja et al., 2024).

Overall, the integration of several of such processes into a CEA tool requires the incorporation of massive amounts of knowledge. The approximations used in several existing tools result in lower predictability of ecological processes, which limits the accuracy and robustness of analysis and their operational integration into management and decision-making processes (Borja et al., 2024).

In particular, the relationship between activities and pressures is often used to derive pressure intensity from activity data (e.g., Korpinen and Andersen, 2016), but has been known to introduce significant uncertainty into the assessment (e.g., Quemmerais-Amice et al., 2020; Korpinen and Andersen, 2016; Halpern and Fujita, 2013).

Here, we present the methods implemented within the Interreg North Sea project Norsaic with the aim of adapting and improving an existing Cumulative Effects Assessment tool (the RCE Carpediem tool) and testing their practical application on benthic habitats within the context of MSP in the North Sea.

The RCE Carpediem tool is based on the approach proposed by Halpern et al. (2008) and incorporates a method for estimating the variability and robustness of the analysis based on different assumptions for calculating the risk of cumulative effects (Quemmerais-Amice et al., 2020). It was developed during the Carpediem project (Quemmerais-Amice et al., 2020) and previously used to perform CEA on benthic habitats within the French maritime spaces (internal waters, territorial sea, and exclusive economic zone). It is fairly adaptable, applies a risk-based approach and can derive pressure intensities from human activity data, which is why it was chosen for this study.

Within the Norsaic project, the RCE Carpediem tool has been improved (Figure 1) and adapted to meet specific needs, particularly to address some still valid concerns raised by Halpern and Fujita (2013), and provide additional capabilities useful for the integration of CEA in the MSP process.

The main improvements developed here concern the following points:

- To better consider the relative contributions of activities to the risk of cumulative effects, the contribution of each activity to a given pressure was weighted by the magnitude at which the activity emits the pressure. In this case, the magnitudes approximate the proportion of the environment affected by the activity.
- A module was developed to identify mismatches between activities and ecosystem components, by comparing all the pressures generated by each activity to ecosystem components' sensitivities.

Furthermore, a comparison between the results of CEA on benthic habitats in two case studies was provided, exploring two spatial scales, two grid cell resolutions, and local vs. international, sea basin-wide assessments. The results presented here are then discussed along with their limitations, in order to demonstrate the ability of the upgraded version of the Carpediem tool to identify sources of cumulative effects and provide useful new information for MSP planners while acknowledging the remaining uncertainties associated with the results of the assessment.

2 Materials and equipment

During this study, a new version of the RCE Carpediem tool, first published in 2020 by the French Biodiversity Office (Quemmerais-Amice et al., 2020) was developed in order to integrate our improvements to the model used to calculate the risk of cumulative effects.

The RCE Carpediem tool is a cumulative effects assessment tool written in the R programming language (R Core Team, 2021), which uses relative intensities of human activities to estimate the intensity of the pressures they generate, if the actual intensity of the pressures is not provided by the user. RCE Carpediem tool then calculates a "Risk of Cumulative Effect" (RCE) based on the surface area and the sensitivities of the benthic habitats to various pressures, and provides results in a grid covering the study area.

The RCE Carpediem tool offers various possibilities for users to adjust the parameters of the analysis: for each assessment, the user can use their own lists of activities and pressures, and input their own activity-pressure relationship matrices, as well as their own environmental data with sensitivities to selected pressures. Activities can also be separated by phase (e.g., exploration and maintenance phases in offshore wind farms). As input data, the RCE Carpediem tool accepts both intensities of human activities in any relevant unit (e.g., bottom trawling, in vessel-hours), and pressures measured directly (e.g., underwater noise). When setting up the assessment parameters, users can choose to aggregate multiple pressures (e.g., Surface abrasion and Deep abrasion can be aggregated into Abrasion), or to use multiple data layers as one single activity (e.g., using two datasets, respectively, on Danish seine and Scottish seine, to describe the activity listed as seine fishing).

The RCE Carpediem tool uses a grid over the study area. During the assessment, the RCE Carpediem tool calculates for each grid cell the total sensitivity to each pressure as a product of the sensitivity of benthic habitats to pressures, times the fraction of each cell covered by the habitats. In this step, a matrix of benthic habitat sensitivity links the habitats and the pressures. In parallel, activity data are first log-normalized between zero and one, based on the range of each activity intensity across the study area. Whenever data of the pressure intensity is not directly available, pressure intensity is derived from the intensities of activities causing

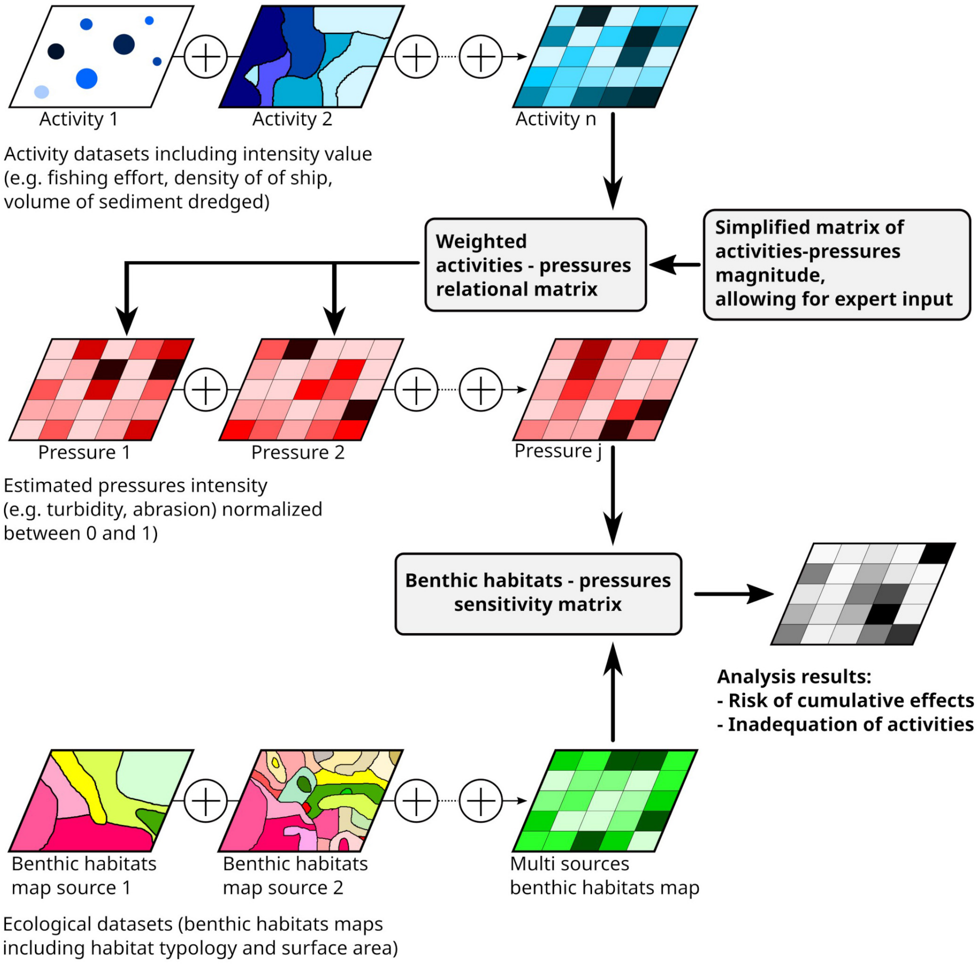

FIGURE 1
Description of the main phases of the analysis in the CarpeDiem tool. Adapted from Quemmerais-Amice et al., 2020 (published under the Creative Commons Attribution licence "CC-BY" in Frontiers in Marine Science).

it, using an activity-pressure relationship matrix as a link. Using these two intermediate results, the RCE Carpediem tool produces a gridded map of the index of risk of cumulative effects, as well as indicators of concentrations of pressures or activities per cell (i.e., number of different pressures per cell, number of different activities per cell, etc.) and an index of Risk of Exposure equal to the product of the surface of habitats times the intensity of pressures. Additionally, Carpediem is capable of performing Monte-Carlo simulations to represent the potential variations of seven parameters, which simulate the potential variability in the results that could be introduced by parameters for which uncertainties remain. Such parameters include gaps in scientific knowledge and subsequent lack of evidence-based models, such as the potential interactions (synergistic, additive, and antagonistic) between multiple pressures; potential misestimation of ecosystem components' sensitivities to pressures, activity intensities, or the relationships between activities and pressures; and variability introduced by the spatial spreading of pressures around their point source.

The RCE Carpediem tool was chosen for this work due to its existing features at the time. As an open-source program under the free GNU-GPL license, the RCE Carpediem tool was also easy to transform to suit the purposes of this analysis, and could be published afterwards. Finally, as the objective was to obtain a spatial representation of cumulative effects, Carpediem was deemed suitable for this study.

For each assessment, various datasets describing human activities and ecosystem components were selected and included in the analysis. Data formatting and processing in preparation for the analysis was performed using the QGIS geographic information system (QGIS Development Team, 2024) and the R language (R Core Team, 2021). Code developments and execution was managed in the RStudio IDE (Posit PBC, 2025). In accordance with the RCE Carpediem tool software requirements, input data was stored and output data was exported in PostgreSQL databases (The PostgreSQL Global Development Group, 2018) with the PostGIS extension (PostGIS Project Contributors, 2018), managed with the pgAdmin 4 database manager (pgAdmin Development Team, 2024). For efficiency, openness and interoperability reasons, the original .xlsx configuration file was replaced with a .ods equivalent which was managed with LibreOffice 25.2.6.2 (The Document Foundation, 2025).

3 Methods

3.1 Context

In accordance with the methodological principles developed within the Carpediem project (Quemmerais-Amice et al., 2020), this study adopts an approach based on the assessment of the risk of cumulative effects (RCE). This concept is understood here as a "potential risk of cumulative effects," rather than as evidence of confirmed effects. The use of this notion of potential is justified by the uncertainties inherent in modeling cumulative effects, as well as by the limitations of field monitoring and ecological status indicators in enabling their precise quantification. The assessment was conducted based on the principles of the DAPSI(W)R(M) model (Elliott et al., 2017; Patrício et al., 2016). In this study, an "effect" is defined as "a negative consequence on an ecosystem component of changes caused to the environment by a pressure" (Quemmerais-Amice et al., 2020; La Rivière et al., 2016), while a "pressure" is defined as "a change to the original state of the environment caused by human activities." An "activity" is defined as "any human use of maritime space which may cause one or several pressures."

"Magnitude" in this study is defined as "the scale at which an activity or pressure is capable of affecting the environment." In the case of activities, it represents the scale at which the activity is capable of generating a given pressure; an activity can generate several pressures at different magnitudes. As for pressures, it represents the scale at which the pressure is capable of causing an effect.

3.2 Methodology overview

In this study, a new method of calculating the risk of cumulative effects was developed, building upon previous methods in order to better represent the relative contributions of activities to multiple pressures affecting the environment, as well as the relative magnitude of pressures, while keeping the "risk of effect" methodological framework that was developed previously (Quemmerais-Amice et al., 2020).

Digital developments for this study were essentially building on the already existing RCE Carpediem tool (Quemmerais-Amice et al., 2020), written in the R language, versions 3.5.1 and above (R Core Team, 2021). The initial version of the RCE Carpediem tool, uses two relationship matrices between activities, pressures and receiving ecological components. Firstly, an activity-pressure relationship matrix, which allows listing all the pressures theoretically generated by each activity, with a binary relationship (0 or 1) between activities and pressures. Secondly, a sensitivity matrix of ecological components to pressures, which allows listing the theoretical ecological sensitivities of each ecological component to each anthropogenic pressure. In the new version, a third matrix is added, which lists the magnitude of each activity for each pressure, that is to say the contribution of each activity (its weight) to each pressure.

The new version of the RCE Carpediem tool is also written in the R language (version 4.3.3). However, significant changes were implemented:

(i) The setup parameters are now contained in an Open Document Spreadsheet (ODS) format (with the .ods extension) instead of Office Open XML (XLSX, with the .xlsx extension) for increased accessibility, as ODS is a free and open format.
(ii) The sensitivity matrix is now contained in a separate ODS spreadsheet, instead of being in the database table containing the ecological components. This method facilitates potential maintenance of the matrix.
(iii) Many geographic data formats are now accepted as input to the model: ESRI Shapefile (.shp) and Geopackage (.gpkg) in addition to the native PostgreSQL-PostGIS tables.

Additionally, a number of "Quality of Life" and optimization updates were made to the tool, including enhanced code maintainability through clear variable naming, implementation of a cleaner data flow using the "tidyverse" package pipe operators, reduction of intermediate variables to streamline code readability, and more performant operations to increase efficiency.

3.3 Evolution of the calculation of the risk of cumulative effects

Originally, the RCE Carpediem tool applied the DAPSIR cycle in a simple way: activities cause Pressures, Pressures cause Effects on ecological components depending on their sensitivities to each Pressure. However, due to its treatment of multiple activities, it overrepresented the contributions of certain activities to the estimated intensities of pressures.

As such, this study aimed to improve the assessment of the relative contributions of various activities to the various pressures and to the final RCE index. The revised calculation of the RCE index includes additional steps, and the new workflow contains six stages: (i) normalizing activities, (ii) weighting of activities-pressures relationships by the corresponding magnitudes, (iii) using the activities and weighted relationships to compute the intensity of human pressures, (iv) readjusting the normalized pressures based on the magnitudes of the human activities causing them, (v) computing the total sensitivity of each grid cell to each pressure, and (vi) calculating the risk of cumulative effects.

(i) Normalization of activities

The Carpediem tool natively applies a log-normalization formula at various steps: to the unweighted intensities of activities, then to the computed pressures, and also to the total sensitivity of grid cells to each pressure. The log-normalization formula is as follows:

$$x_{norm} = \frac{log\{x+1\} - log\,(x_{\min}+1)}{log\{x_{\max}+1\} - log\{x_{\min}+1\}}$$

In which x_{max} and x_{min} are the extrema of x across the study area. The inclusion of this formula in the tool serves multiple purposes: setting a common range from 0 to 1 enables the comparison of variables described in different units, and the use of log-scale reduces the impact of outlying high values by compressing the scale.

Normalization is an important step to be able to compare different variables (Halpern and Fujita, 2013; Esquerre et al., 2025; Quemmerais-Amice et al., 2020; Halpern et al., 2008). Therefore, this formula was not modified in this study. However, while its use is indispensable, it also allows for the comparison of activities, or pressures, of extremely different orders of magnitude. For instance, when computing the intensity of the abrasion pressure due to two activities, the normalized maximum values for scuba diving and bottom trawl fishing contribute equally to the result. This results from the inherent assumption that activities have an equal contribution to the total pressure intensity, which was already pointed out as a potential area of concern in the process of CEAs in 2013 (Halpern and Fujita, 2013). The present work attempts to address the distortion resulting from treating activities of vastly different spatial scales as equivalent in the calculation.

At any rate, the first stage of the calculation of the RCE is to apply this log-normalization formula to each human activity intensity included in the assessment.

(ii) Weighting of activities-pressures relationships by the corresponding magnitudes

In order to readjust the proportionality of activities in the computation of each individual pressure, we transformed the initial matrix describing the activities-pressures relationship. Where the prior activity-pressure matrix only contained binary Yes/No relationships (corresponding to whether the activity caused the pressure or not), we created a matrix that associates a value of magnitude to each activity-pressure relationship, using the definition of "magnitude" detailed above in *Context*.

To assign magnitudes to each activity-pressure relationship, using the original binary Yes/No matrix as reference, activities were grouped together, depending on the broad category of activity (e.g., fishing with pelagic active gear, fishing with bottom active gear, existing recolonized structures, etc.) into categories, in which all activities caused similar pressures, based on the original Carpediem activities-pressures binary matrix. Some activities could not be integrated into any group and were left as their own categories. Similarly, pressures that are susceptible to be applied in the same manner and with the same magnitude, should an activity cause both, were grouped into thematic categories: bottom pressures, pressures affecting the chemical and physical properties of seawater, pressures directly affecting individuals, etc. Once again, some pressures were not comparable to any other, and were left as their own respective categories.

We then assigned a magnitude on a 0–3 scale to each couple Activity group–Pressure group. Magnitudes were determined following different criteria for each group of pressures. For instance, sea bottom physical pressures were assigned magnitudes based on the area potentially affected by one unit of activity intensity (e.g., 1 square kilometer of harbor dredging, or 1 h of bottom trawl fishing), while modifications of seawater physical and chemical properties were assigned magnitudes based on the volume potentially affected by one unit of activity intensity. In any case, the assignation of magnitude was entirely independent of habitat sensitivities.

The magnitude values were then reported onto individual relationships from the activity-pressure binary matrix, using the following formula:

$$\theta_{A,P} = \theta_{Binary} \times 10^{Magnitude}$$

In which the final relationship $\theta_{A,P}$ between an activity and a pressure (including the magnitude of emission) is defined as the product of a binary variable θ_{Binary} (indicating whether the activity causes the pressure, where 0 indicates that the activity does not cause the pressure, and 1 indicates that it does) and 10 raised to the power of the corresponding magnitude ($10^{Magnitude}$) where *Magnitude* corresponds to the value assigned to the relationship between the relevant categories of activities and pressures.

(iii) Computation of the intensity of human pressures

This step of the calculation was modified to include the magnitude at which an activity generates a pressure.

In this stage, the intensity of a single pressure in a cell is computed as the sum of the products of the final relationships $\theta_{A,P}$ between each activity and the pressure, and the intensities of each activity in the cell, as shown in the following formula:

$$Intensity_P = \sum_A \theta_{A,P} \times Intensity_A$$

The RCE Carpediem tool then applies a log-normalization to the pressure intensity across the study area, using the formula presented in stage (i).

(iv) Potential magnitudes of calculated (and measured) pressures

As explained in stage (iii), after summing the intensities of activities, the RCE Carpediem tool applies a log-normalization to pressure intensities. This normalization is essential to compare pressure intensities in a coherent way: since users can include pressure intensities measured directly in the analysis, this allows to compare such pressures to those estimated by proxy from activity intensity. Furthermore, log-normalization harmonizes pressure intensities derived from sums of activity intensities, evens out the variance of the values and reduces over-representation of outliers.

However, if a pressure is only caused by a handful of activities at low magnitude, then the pressure itself must affect the environment at a low magnitude. But since this normalization rescales each pressure between 0 and 1, after log-normalization of pressures, each pressure would then have a range of 0–1, negating the correction of magnitude from the previous steps: a pressure caused by a single activity of high magnitude, and a second pressure caused by a single activity of low magnitude, would have the exact same range, regardless of the largely different scales at which they are capable of affecting the environment.

To solve this distortion of the relative scales of pressures, we corrected the log-normalized pressures in the next step of the assessment. As the chosen approach of cumulative effects was the frame of a risk assessment, we weighted each pressure using the highest value of $\theta_{A,P}$ (weighted relationships between activities and the pressure) amongst all the activities that can generate the pressure, as an approximation of the magnitude of the pressure. In the framework of a risk assessment, this was chosen as a precautionary approach.

(v) Computation of the total sensitivity of grid cells to each pressure

This step was not modified compared to the initial version of the RCE Carpediem tool. For each pressure, the calculation uses the following formula:

$$CellSensitivity_P = \sum_H Sensi_{H,P} \times Surface_{H/Cell}$$

With H designating the different habitats found across the cell, $Surface_{H/Cell}$ the ratio of a habitat's surface by the total cell surface, and $Sensi_{H,P}$ the habitat's sensitivity to the pressure P, obtained from the matrix of habitat sensitivities to pressures.

For each pressure, the total sensitivity is then log-normalized using the same formula presented above.

(vi) Calculation of the risk of cumulative effects

The calculation of the risk of cumulative effects itself is not modified:

$$RCE_{Cell} = \sum_P TotalCellSensi_{P,lognorm} \times P_{Cell,lognorm\,Weighted}$$

In which the risk of cumulative effects in a cell is the sum, across all pressures, of the log-normalized total cell sensitivity to each pressure multiplied by the corresponding log-normalized and weighted pressure intensity.

The resulting grid of values of risk is then normalized linearly: each value is divided by the maximum value of risk across the study area.

Other features of the RCE Carpediem tool, such as the calculation of a general Confidence Index based on the Confidence Indexes included in data, and the Monte-Carlo simulations linked to Uncertainty Analysis, were not modified and will not be considered in this study.

3.4 Development of a module of activity unsuitability

In order to represent the potential effects of activities on the environment, a module of activity unsuitability was also developed and integrated to the RCE Carpediem tool. Using the results of stage (v) in which Carpediem calculates the total sensitivity of a cell to each pressure, the module uses the magnitudes of pressures generated by each activity to determine the unsuitability of each activity in the grid cell: considering a single pressure to which the cell is highly sensitive, activities which generate this pressure with high magnitude, will be more unsuitable in this cell, than activities which only generate it with low magnitude. This principle is then applied to each pressure, weighted by the corresponding total sensitivity of the cell.

For each human activity listed in Table 1, the unsuitability value is calculated based on the total sensitivity of each cell to all the pressures in the assessment and the relationship between the activity and each of these pressures (i.e., weighted by the magnitude at which the activity may cause the pressure), using the following formula:

$$Unsuitability_{A,Cell} = \sum_P TotalSensi_{P,Cell} \times \theta_{P,A}$$

With $TotalSensi_{P,Cell}$ the total sensitivity of the cell to each pressure P, and $\theta_{P,A}$ the final relationships between activity A and each pressure P (including the magnitude of emission). This unsuitability indicator is higher when an activity is likely to cause one or multiple pressures to which the habitats in the grid cell are particularly sensitive.

However, at this stage this unsuitability is not related to the actual (or planned) distribution and intensity of human activities. For this, we calculated an activity risk indicator for each activity included in the assessment. In each cell where an activity is present, the activity risk indicator is calculated with the following formula:

$$Activity\ Risk\ Indicator_{A,Cell} = Intensity_{A,Cell} \times Unsuitability_{A,Cell}$$

In which, for an activity A, in a given grid cell, the activity intensity is multiplied by the activity unsuitability value.

The activity risk indicator highlights cells in which the activity is highly unsuitable and yet very intense. Cells in which either the activity intensity, or its unsuitability value, is somewhat low, will have a lower activity risk indicator, and cells in which both intensity and unsuitability are low will have the lowest values.

3.5 Case studies descriptions

In order to investigate the differences in the application of Cumulative Effects Assessments to benthic habitats between local scale and sea basin scale, two case studies were chosen for this study: a local scale case study in the Bay of Seine, and a sea basin scale case study in the Greater North Sea, restricted to the maritime spaces of European Union Member States (maritime space of France, Belgium, The Netherlands, Germany, Denmark and Sweden, Figure 2).

The two study sites were chosen for multiple reasons: the Bay of Seine is in a closed sea area, yet has a high density of diverse activities, much like the European Union Greater North Sea is a part of a closed sea basin with a comparably high density of similar activities. Additionally, the Bay of Seine itself is found within the Greater North Sea, which allows for the comparison of the effects of scale on the results of a Cumulative Effects Assessment. Finally, the datasets available for human activities and benthic habitats in both study areas are comparable.

TABLE 1 Details of activity datasets for each case study.

Activity	Intensity parameter	
	Bay of Seine	EU Greater North Sea
Fishing—Bottom trawl	Fishing hours	Fishing hours[a]
Fishing—Beam trawl	Fishing hours	Fishing hours[a]
Fishing—Pelagic trawl	Fishing hours	**Pelagic trawls and seines:** fishing hours[a]
Fishing—Purse seines	Fishing hours	
Fishing—Danish and Scottish seines	Fishing hours	Fishing hours[a]
Fishing—Dredges	Fishing hours	Fishing hours[a]
Fishing—Lift nets	**Static nets:** catch, in tons	**Static gears:** fishing hours[a]
Fishing—Set bottom nets		
Fishing—Drift nets		
Fishing—Bottom longlines	*Activity absent in area*[b]	
Fishing vessels	**Surface navigation:** density of ships	**Surface navigation:** density of ships[c]
Tankers and cargos		
Passengers		
Leisure craft and scuba		
Speedboat		
Other vessels		
Marine or lagoon cage fish farming	*Activity absent in area*[a]	Number of sites per cell[d]
Land-based fish farming	*Activity absent in area*[a]	Number of sites per cell[e]
Shellfish aquaculture on nets	*Activity absent in area*[a]	Number of sites per cell[f]
Oyster aquaculture on rack-and-bag	Surface area of site	Number of sites per cell[g]
Land-based submersible aquaculture ponds	*Activity absent in area*[a]	Number of sites per cell[h]
Macro-algae aquaculture on nets	*Activity absent in area*[a]	Number of sites per cell[i]
Dumping of dredged materials	Weight in tons	Weight in tons[j]
Harbor and fairway dredging	Surface area of site	Surface area of site[k]
Underwater cables—Permanent presence	Length	Length[l]
Fixed-base offshore wind turbine—Construction	Surface area of site	Surface area of site[m]
Fixed-base offshore wind turbine—Operation	Surface area of site	Surface area of site[m]
Fixed-base offshore wind turbine—Acoustic surveys	Surface area of site	Surface area of site[m]

Datasets merging multiple activities for a case study are in merged table cells and named in bold before the intensity parameter. The datasets in the case study Bay of Seine are described in the Table 4 in Quemmerais-Amice et al. (2020). The datasets in the case study EU Greater North Sea are described on the metadata.

[a] Fishing: https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/d57fbdea-489e-4e11-9ff1-f0f706cfe783.

[b] Confirmed absence of the activity: official national dataset for the activity does not display any presence in the Bay of Seine study area.

[c] Navigation: https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/0f2f3ff1-30ef-49e1-96e7-8ca78d58a07c.

[d] Aquaculture—Marine or lagoon cage fish farming: https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/03c35b79-808f-4168-9d30-2de44a55a6f4.

[e] Aquaculture—Land-based fish farming: https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/03c35b79-808f-4168-9d30-2de44a55a6f4.

[f] Aquaculture—Shellfish aquaculture on nets: https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/55886bab-2932-4d6d-bfe3-06626b0172ab.

[g] Aquaculture—Oyster aquaculture on rack-and-bag: https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/55886bab-2932-4d6d-bfe3-06626b0172ab.

[h] Aquaculture—Land-based submersible aquaculture ponds: https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/03c35b79-808f-4168-9d30-2de44a55a6f4.

[i] Aquaculture—Macro-algae aquaculture on nets: https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/7b849214-e6ae-4199-a3f0-d4539f1f1289.

[j] Dumping of dredged materials: https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/8625adee-fa92-4304-881a-6bcd4c5c9f0a.

[k] Harbor and fairway dredging: https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/d3e86612-35a7-4c0f-a995-245062fd2792.

[l] Underwater cables—Permanent presence: https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/41b339f8-b29c-4550-b787-3d68f08fdbcc. and https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/39ebe289-410b-4a5d-88a4-51bfcde538de.

[m] Fixed-base offshore wind turbines (note: Acoustic surveys are assumed to be carried out in areas where offshore wind farms are planned): https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/8201070b-4b0b-4d54-8910-abcea5dce57.

3.5.1 Case study 1: the Bay of Seine local scale case study

The case study in the Bay of Seine is located offshore of the Seine river estuary, in the French side of the English Channel. Several human activities are located in this area (e.g., Ministère de la Transition écologique et solidaire, 2019; Dauvin et al., 2020): harbor activities including transportation of passengers and goods, especially from Le Havre as well as two inland harbors connected to the sea through the Seine river (Paris

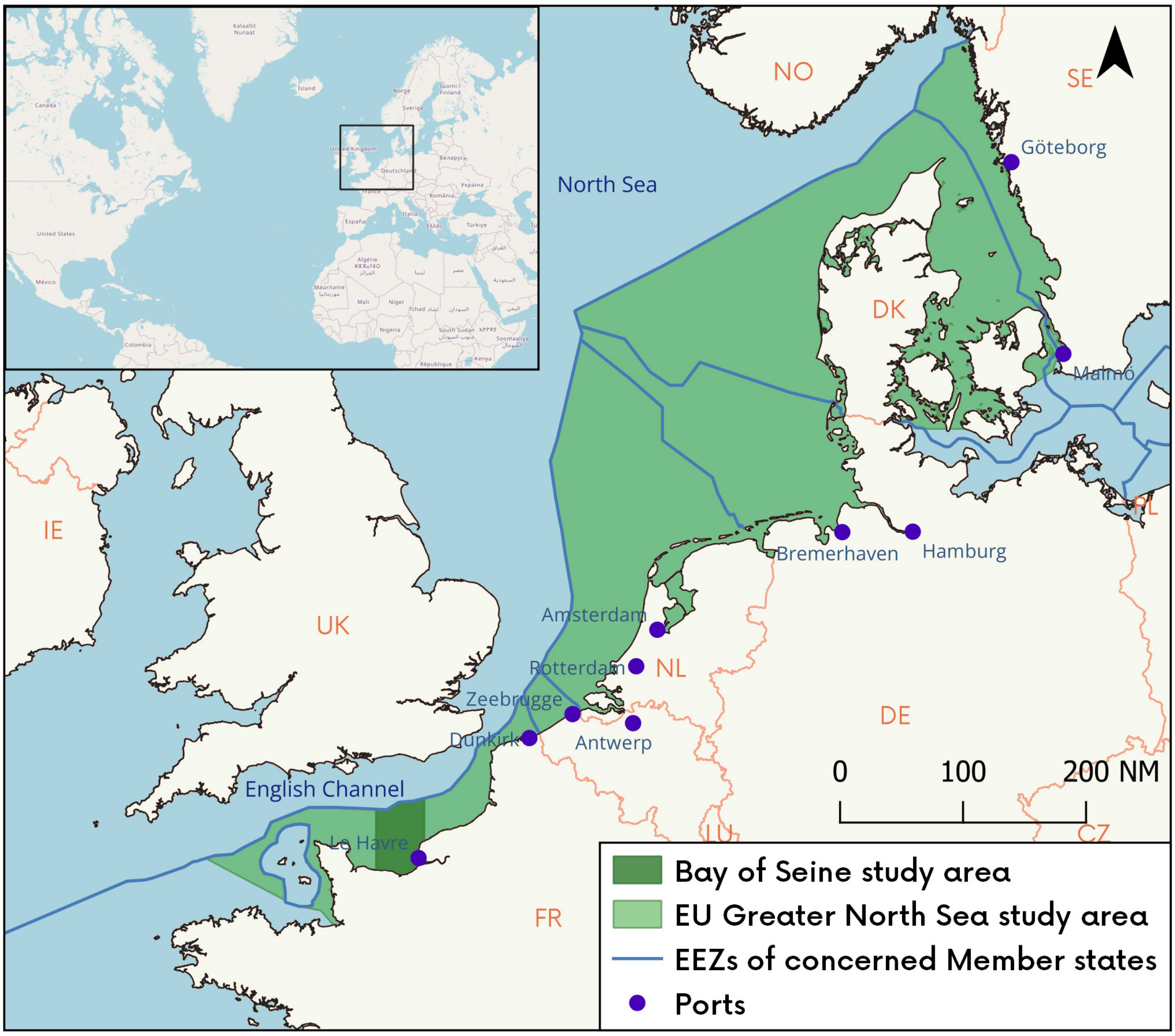

FIGURE 2
Greater North Sea with the study areas for the Bay of Seine and EU Greater North Sea case studies.

and Rouen); but also fishing activity. Offshore wind energy is densely present in the area as well, with one active offshore wind farm (OWF), one OWF currently under construction, and one area designated for exploration for future OWF development. The Bay of Seine has a sufficient diversity of habitats of varying ecological sensitivities to various pressures, to illustrate the principles of RCE.

Data sources used for this study include: national datasets gathered by various French State services and institutions and processed during the Carpediem project (Quemmerais-Amice et al., 2020), as well as additional datasets produced with the same methods for human activities which were not part of the Carpediem project (e.g., professional fishing with static gear). These datasets are available in a square grid cell resolution of 1 min of degree in latitude and longitude.

3.5.2 Case study 2: the Greater North Sea basin scale case study

The sea basin scale study area is the Greater North Sea, restricted to the maritime spaces (Exclusive Economic Zone, territorial sea) of European Union (EU) Member States. It comprises the entire maritime spaces of Belgium, the Netherlands, the parts of the Danish, German and Swedish maritime spaces covering the North Sea, the Danish Straits, the Kattegat and the Skagerrak as defined by the International Hydrographic Organization, and the "Eastern Channel—North Sea" subdivision of the French maritime space. The Greater North Sea in general is a shallow and partially enclosed marine area, while the Skagerrak is a wide strait leading from the North Sea into the Kattegat, a narrow, reefy sea area with many islands.

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The study area contains a very high density of multiple activities such as fishing, offshore wind farms, underwater cables, aquaculture, maritime traffic linked to the transportation of goods and passengers, etc., and contains various harbors of international importance, like Rotterdam, Le Havre, Antwerp, Hamburg, Bremerhaven, etc. Projections and scenarios are planning for an increase of human uses and activities, particularly in marine renewable energies (Quirk et al., 2021).

The study area was restricted to the maritime spaces of EU Member States due to the availability of harmonized data through portals such as the European Marine Observation and Data Network (EMODnet), which made it possible to collect the necessary data to complete the assessment. For this reason, the data sources used for this study include harmonized activity datasets and a model of benthic habitats, all of which is available on EMODnet.

3.6 Data selection and preparation

Through the workflow of the RCE Carpediem tool, a majority of pressure intensities are derived from the relative intensities of the human activities causing them. To perform this step, detailed data describing the intensity of each human activity integrated into the analysis were selected and prepared.

The list of selected datasets is provided in Table 1. The data used in the study comprise national validated datasets produced by French State services (local scale), and European datasets harmonized from national sources through a validated protocol (sea basin scale). However, there are differences in the data production processes: several EU datasets available on portals such as EMODnet and used for the sea basin scale case study were prepared by harmonizing national datasets similar to the French national datasets used for the local scale case study. These national datasets were often produced with different protocols depending on the country.

Regardless of the overall quality of the data, the datasets retained in the analysis only depict an incomplete rendition of the various human activities present in the area. Activities for which no dataset was available were removed from the analysis (Table 2), including activities which are known to happen in the study area but are not quantifiable. Similarly, activities for which no relationship with pressures was known were removed. Finally, in order to allow a relevant comparison of different scales, only activities for which datasets were available at national and sea basin scales were retained in the analysis: activities for which data was only available for one of the study cases, as well as activities for which the data production processes were too different between study cases, were removed for comparability reasons. For instance, coastal artificialization was removed for this reason. Similarly, existing datasets of directly measured pressures which were not produced with comparable methods, or whose spatial resolution was much wider than the mesh size (e.g., gridded data with meshes wider than $1' \times 1'$ in the Bay of Seine case study), were not considered in the study; rather, the corresponding pressures were derived from activity data.

Finally, due to differences in data collection schedules, activity and pressure datasets used in the analysis do not cover the same calendar year. To ensure comparability of results, multi-annual averages were used to represent repeated activities with annual variability (e.g., fishing, fairway dredging) rather than selecting a single year. Permanently present structures (e.g., cables) were included without modification.

TABLE 2 Examples of activities removed from the study.

Activity	Reason for removal
Floating offshore wind farm	Absent in both study areas
Urban and industrial uses	No pressure diffusion model for pressures caused by land-based activities
Agriculture in coastal catchments	No pressure diffusion model for pressures caused by land-based activities
Defense activities	Magnitudes were not determined
Coastal artificialization	French national data available, but no harmonized international data; Low relevance given cell resolution
Construction of infrastructures for marine aquaculture	No available dataset at either scale
Sand and gravel extraction	Magnitudes were not determined
Spearfishing	No available dataset at either scale
Water extraction	No relationship known with any pressure
Waterfowl hunting in coastal wetlands	No relationship known with any pressure
Scuba diving	No harmonized international data

Datasets on ecosystem components (benthic habitats) were chosen according to specific criteria: benthic habitats must be described using the European Nature Information System classification (EUNIS), going up to the fourth hierarchical level of habitat detail whenever possible, and the dataset must cover the entirety of the study area. The EUNIS classification was chosen for harmonization between the local scale and the international case studies. Due to the lack of existing matrix of habitat sensitivities to pressures for the more recent revisions of the EUNIS classification, the EUNIS 2012 classification (European Environment Agency, 2012) was retained. At the local scale, the benthic habitats composite map produced during the Carpediem project was used (Quemmerais-Amice et al., 2020). At the sea basin scale, the dataset produced with the EUSeaMap broad-scale predictive model (Vasquez et al., 2023), published on EMODnet Seabed Habitats, was used.

Datasets were then prepared according to the recommendations of the Carpediem project methodological article (Quemmerais-Amice et al., 2020) and Carpediem specifications and guidelines (Barrere et al., 2022; Lodier and Quemmerais-Amice, 2024): the data was transcribed into the analysis mesh depending on their geometries. In a given cell, the intensity of an activity described by a point-geometry dataset was the sum of the intensities associated with all the points inside the cell. The intensity of an activity described by a line-geometry dataset was the sum of the fraction of each line intersecting the cell, multiplied by its own associated intensity. Similarly, the intensity of an activity described by a polygon-geometry dataset was the sum of the fraction of each polygon intersecting the cell, multiplied by its own associated intensity. When no intensity field was attributed to the data (e.g., all features have the same intensity), 1 was used instead.

Benthic habitats data was recomputed into the grid in longer format, in which a grid cell is duplicated for each habitat it contains, with the duplicate containing one habitat EUNIS code and the percentage of cell surface covered by this specific benthic habitat. Benthic habitats' sensitivities to pressures were automatically added during the analysis based on the benthic habitat EUNIS code.

Two different grids were used for the assessment. At the local scale, we used the same grid cell resolution of the data previously processed by the French Biodiversity Office (a grid cell resolution of 1 min of degree). At the sea-basin scale, we used a similar grid, with larger cells measuring $3'$ in longitude and latitude. The grids align perfectly: each $3' \times 3'$ cell from the latter contains exactly nine $1' \times 1'$ cells from the former, with no partial overlaps.

4 Results

In this section, we present the results of the assessments carried out with the RCE Carpediem tool in the Bay of Seine and EU Greater North Sea case studies. Through the results of the Bay of Seine case study, we compare the outcomes of an assessment in the Bay of Seine (local scale) performed with the original version of the RCE Carpediem tool (the "binary pressures method") and those obtained using the updated approach described in this article (the "weighted pressures method"). We also use the results of both case studies to highlight the differences between the risk of cumulative effects calculated in the Bay of Seine in each case study. Finally, we present the results of an assessment carried out for each case study with the unsuitability module.

4.1 Bay of Seine—comparison of two methods

Figure 3 shows the results of a Cumulative Effects Assessment with the standard binary pressures method (presented in Quemmerais-Amice et al., 2020) and the weighted pressures method developed in this article (respectively, Figures 3A, B). In both maps, the calculated risk of effects across the study area is displayed using a 10-class gradient defined by the deciles of the risk distribution. The class boundaries are roughly equivalent between the two methods, for example, $D1_{\text{binary}} = 0.164$ and $D1_{\text{weighted}} = 0.187$, and $D9$ is around 0.32 for both, and the average difference is around 0.03 (Table 3). This illustrates a similar spread of the calculated values: the weighted pressures method refines the calculation without altering the global distribution of the results.

Regarding the spatial distribution of the risk of cumulative effects, the southern part of the Bay of Seine, closest to the river estuary, where numerous human activities are found in high intensities (e.g., bottom trawling, maritime traffic from Le Havre, etc.), concentrates large areas with higher risks of cumulative effects on benthic habitats. It consistently remains a hotspot of risk of cumulative effects across both methods. Conversely, with both methods the northern part of the study area generally shows low levels of risk.

The central bay area, in which a medium-to-high risk of cumulative effects is identified with both methods, as well as small spots in the northern part of the study area, exhibit higher values of risk of cumulative effects with the binary pressures method compared to the weighted pressures method (e.g., RCE is 0.37 with the binary pressures method and 0.22 with the weighted pressures method). Another major difference is that while the binary pressures method highlights two (permanently present) cables in the northern part of the study area as a major source of risk of cumulative effects, the weighted pressures method does not; this illustrates the improved balance of activities and the pressures they cause in the weighted pressures method, since underwater cables would only cause pressures affecting a few square meters around them. Conversely, the weighted pressures method highlights a zone of higher risk of cumulative effects in the east of the study area, around the offshore wind farm in operational phase, which appears as low risk with the binary pressures method.

4.2 EU Greater North Sea—sea basin scale

As shown in the Section 4.1, the weighted pressures method demonstrate better relevance in CEA analyses, particularly when applied on datasets with more uncertainties in the intensity of activities. Compared to the data at local scale (national datasets), the data at sea basin scale (harmonized datasets made from several datasets compiled with multiple methods) is less robust. As such, in the EU Greater North Sea, at the sea basin scale, only the weighted pressures method was applied.

There are several areas with missing values of risk of cumulative effects in the EU Greater North Sea (Figure 4), for example, along the coasts of the Netherlands, Germany and Denmark. These missing values can largely be linked to habitats for which the sensitivities to most pressures are not known, or habitats which EUNIS levels are too low (e.g., EUNIS level 2) to attribute relevant sensitivities.

In the rest of the study area, in which habitat sensitivities are better known, large areas with high risk of cumulative effects can be found off the northern coasts of Normandy and the Bay of Somme; several patches in the Danish Straits; offshore in the middle of the North Sea, just to the east of the Doggerbank sand bank; and in the Skagerrak. Many nearshore areas within 2–3 NM of the shore also exhibit high levels of risk of cumulative effects. In contrast, offshore areas near Denmark and off the Western coasts of the Netherlands showed lower risks of cumulative effects. Additionally, the spatial distribution of the risk of cumulative effects is different from the spatial distribution of the total intensities of activities (Figure 5), which confirms that activity intensity alone is not sufficient to explain a high risk of cumulative effects, and higher concentrations of activities do not necessarily result in a higher calculated risk of cumulative effects, which shows that the tool effectively calculates risk rather than merely mapping

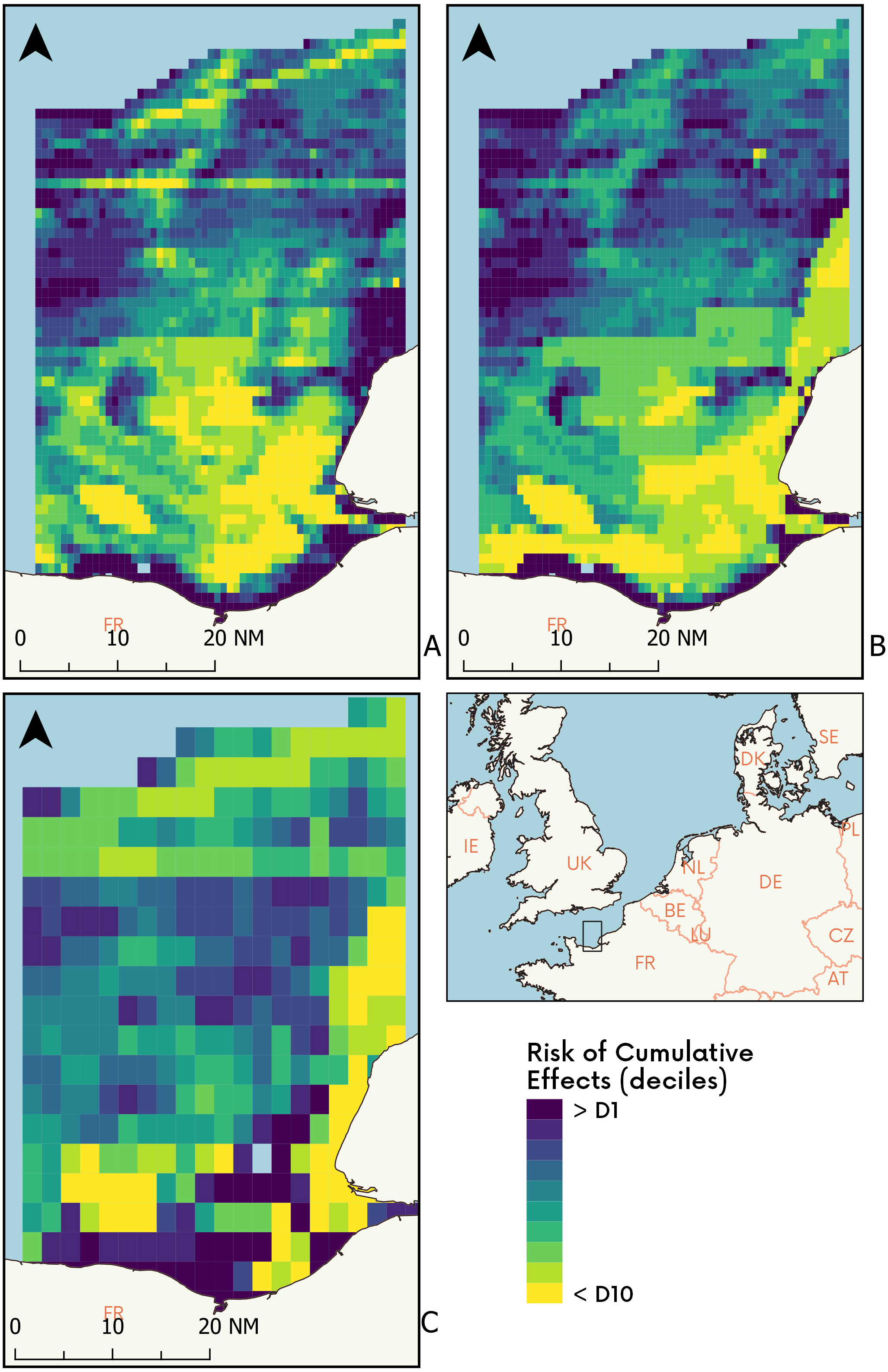

FIGURE 3
Comparison of various assessments of the risk of cumulative effects in the Bay of Seine: **(A)** local scale case study, binary pressures method; **(B)** local scale case study, weighted pressures method; **(C)** extract from the sea basin scale case study results, weighted pressures method.

TABLE 3 Class thresholds (deciles) for representation of the risk of cumulative effects in the Bay of Seine with the two methods.

Deciles	Weighted pressures method	Binary pressures method	Difference
$D1$	0.1874	0.164	0.0234
$D2$	0.1956	0.196	0.0004
$D3$	0.2005	0.215	0.0145
$D4$	0.2065	0.231	0.0245
$D5$	0.2109	0.248	0.0371
D6	0.2181	0.264	0.0459
D7	0.2273	0.284	0.0567
D8	0.2432	0.305	0.0618
D9	0.3149	0.327	0.0121

where activities are most intense. However, at this scale, it is more difficult and time-consuming to trace back each value of risk to its causes.

The statistical distribution of cumulative impact values (Figure 6) shows that values in some regions are relatively homogeneous, such as in the North Sea. In contrast, the Skagerrak region contains more extreme cumulative impact values, illustrating a more spatially concentrated organization of activities. These distributions also highlight the higher number of grid cells with high cumulative impact scores in the Danish Straits.The distribution of results in this case study is different: the ninth decile is much lower than in the other case study ($D9 = 0.004$) and less than 1% of the risk values are greater than 0.01, which is caused by the log-normalization of the results with an extremely high maximum, compared to the majority of the results.

4.3 Comparing the Bay of Seine in both scales

The risk of cumulative effects was extracted in the Bay of Seine from the EU Greater North Sea assessment results (weighted pressures method), for direct comparison with the results of both methods in the first case study (Figure 3c).

The significantly lower resolution (1 sea basin scale cell contains 9 local scale cells) makes it difficult to compare results properly: the lower resolution of the EU Greater North Sea case study is less suitable for a study area of this size.

The spatial distribution of the risk of cumulative effects in the Bay of Seine extract from the sea basin scale results displays a high risk of cumulative effects in the south of the bay and a medium-high risk of cumulative effects in the central bay, similarly to the results in the local scale case study. However, the extracted results show more noise and artifacts of estimated low risk of cumulative effects in the middle of the high-risk area, which may be related to the low resolution of the habitat map used in the sea basin case study.

Similarly to the local scale results from the weighted pressures method, the extracted results highlight the eastern part of the study area, around the offshore wind farm, as an area of high risk of cumulative effects. On the contrary, in the northern part of the study area, the sea basin scale results display lines of higher risk of cumulative effects which follow the underwater cables, like the results obtained in the local scale study with the binary pressures method.

In general, the results from the sea basin scale are similar to the results from both methods at the local scale, but less precise.

4.4 Activity unsuitability

The results of the activity unsuitability assessments are presented for maritime traffic and pelagic trawling in the Bay of Seine, and pelagic trawling in the EU Greater North Sea.

Unsuitability values for each activity were sorted into logarithmically spaced classes, defined by consecutive powers of ten and their geometric means: 1–3.16, 3.16–10, 10–31.6, etc. As the classes of pressure magnitude are powers of ten, a logarithmic scale appropriately represents the unsuitability values. Further subdivisions using the geometric means allows to better distinguish the influence of habitat sensitivities on activity unsuitability. For instance, an activity causing a pressure at a magnitude of 1,000 on a cell containing one single habitat with a sensitivity of five to that pressure results in an unsuitability of 5,000. In another cell containing one single habitat with a sensitivity of one to that pressure, the unsuitability of the activity will be 1,000, one class below.

In the Bay of Seine, the unsuitability values of both activities are uniform across a large patch of maritime space offshore (Figure 7), which can be related to the low habitat variability in this zone (Figure 8). Areas closer to the coast with different habitats and a higher habitat variability (Figure 8) show more variation in activity unsuitability. The areas of high pelagic trawling unsuitability have the same outline as the areas in which habitats are sensitive to the pressures emitted by pelagic trawling with a high magnitude (two or three, with $\theta_{A,P} = 100$ or 1,000) which are shown in Figure 9.

The comparison of results by activity shows that certain activities, such as pelagic trawling, are much more unsuitable in general than others, such as maritime traffic, for benthic habitats in the Bay of Seine. However, both pelagic trawling and maritime traffic are unsuitable to a certain extent in the part of the bay closest to the Seine estuary, with unsuitability values above 1,000. Notably, the unsuitability values of both activities are comparable in a large part of this zone. Compared to the dominant unsuitability values across the entire study area, though, pelagic trawling is slightly less unsuitable in the estuary of Seine (Figure 7A) than in most of the study area, while maritime traffic is considerably more unsuitable in the same zone (Figures 7B, 10). These representations illustrate the spatial localization of conflicts that must be integrated into MSP revisions in order to effectively implement the Ecosystem-Based Approach in planning.

In the EU Greater North Sea, the unsuitability values of pelagic trawling are divided in large zones of high unsuitability and low unsuitability (Figure 11). In general, pelagic trawling unsuitability is higher in offshore areas in the North Sea proper, as well as in the Danish Straits, Kattegat and Skagerrak, than in the Channel. The large areas of similar unsuitability values in the EU Greater

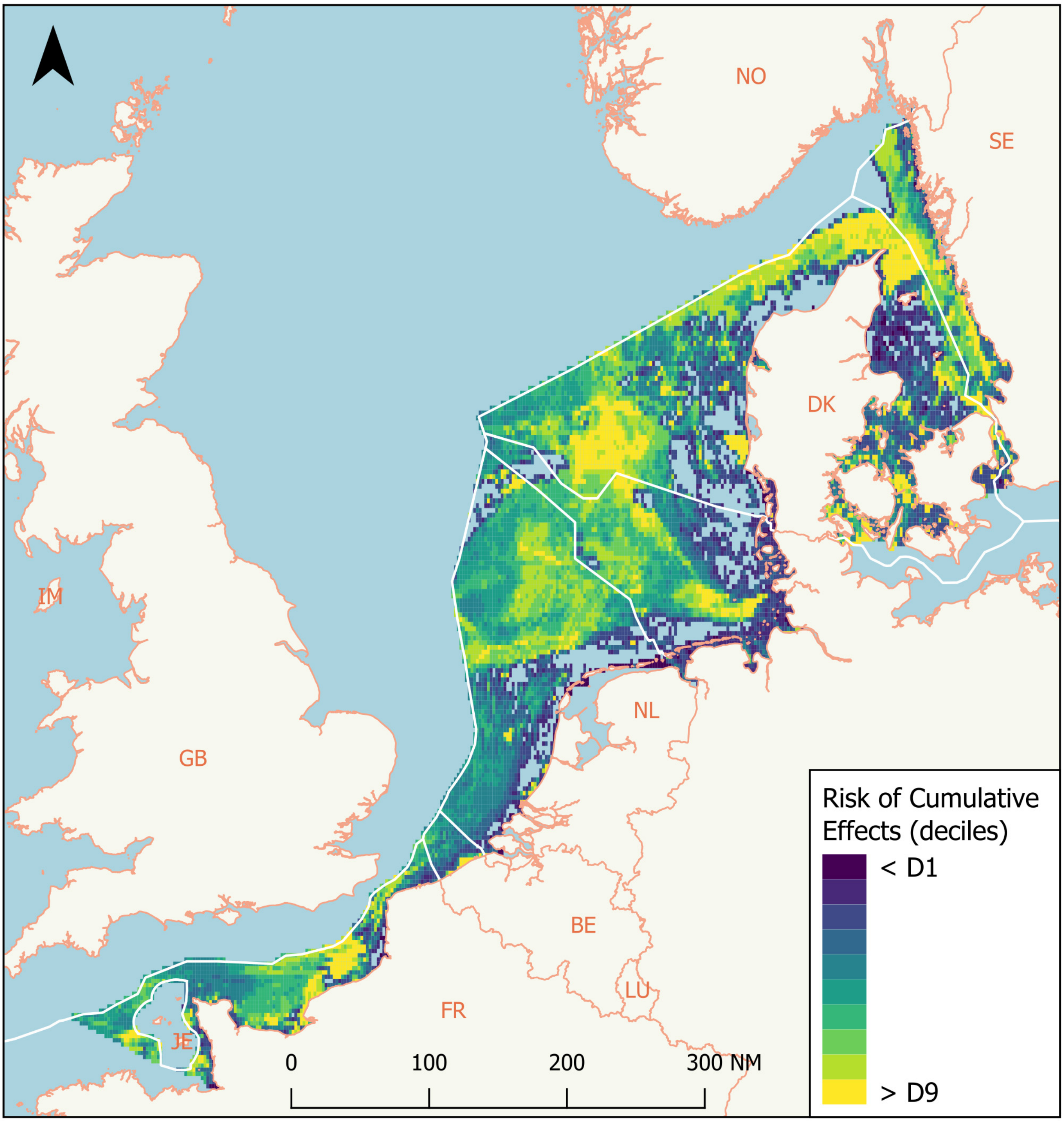

FIGURE 4
Risk of cumulative effects (in deciles) in the Greater North Sea (restricted to the maritime spaces of European Union Member States).

North Sea can be linked to various adjacent combinations of different habitats (Figure 12) which exhibit similar sensitivities to the pressures emitted by pelagic trawling.

An activity risk indicator combining activity intensity with activity unsuitability at cell level was calculated for maritime traffic in the Bay of Seine (Figure 13A), and for pelagic trawling across the EU Greater North Sea (Figure 14). As the available activity dataset for the EU Greater North Sea (Table 1) aggregated pelagic trawling and seine fishing, in line with the principles of a risk-based framework, the activity intensity was treated as if representing exclusively pelagic trawling.

Higher activity risk indicator values align with high activity intensity (Figure 13) in cells of high maritime traffic unsuitability (Figure 7) in the Bay of Seine, near the Seine estuary. Similarly, high activity risk indicator to the west of Denmark and Germany, in the Skagerrak or in the middle of the Channel coincide with higher activity intensity (Figure 14) in the large zones of higher activity unsuitability (Figure 11), though activity risk indicator values for pelagic trawling in the EU Greater North Sea are generally lower than values for maritime traffic in the Bay of Seine (Figures 13, 14). In general, the activity risk indicator identifies correctly areas in which an activity is

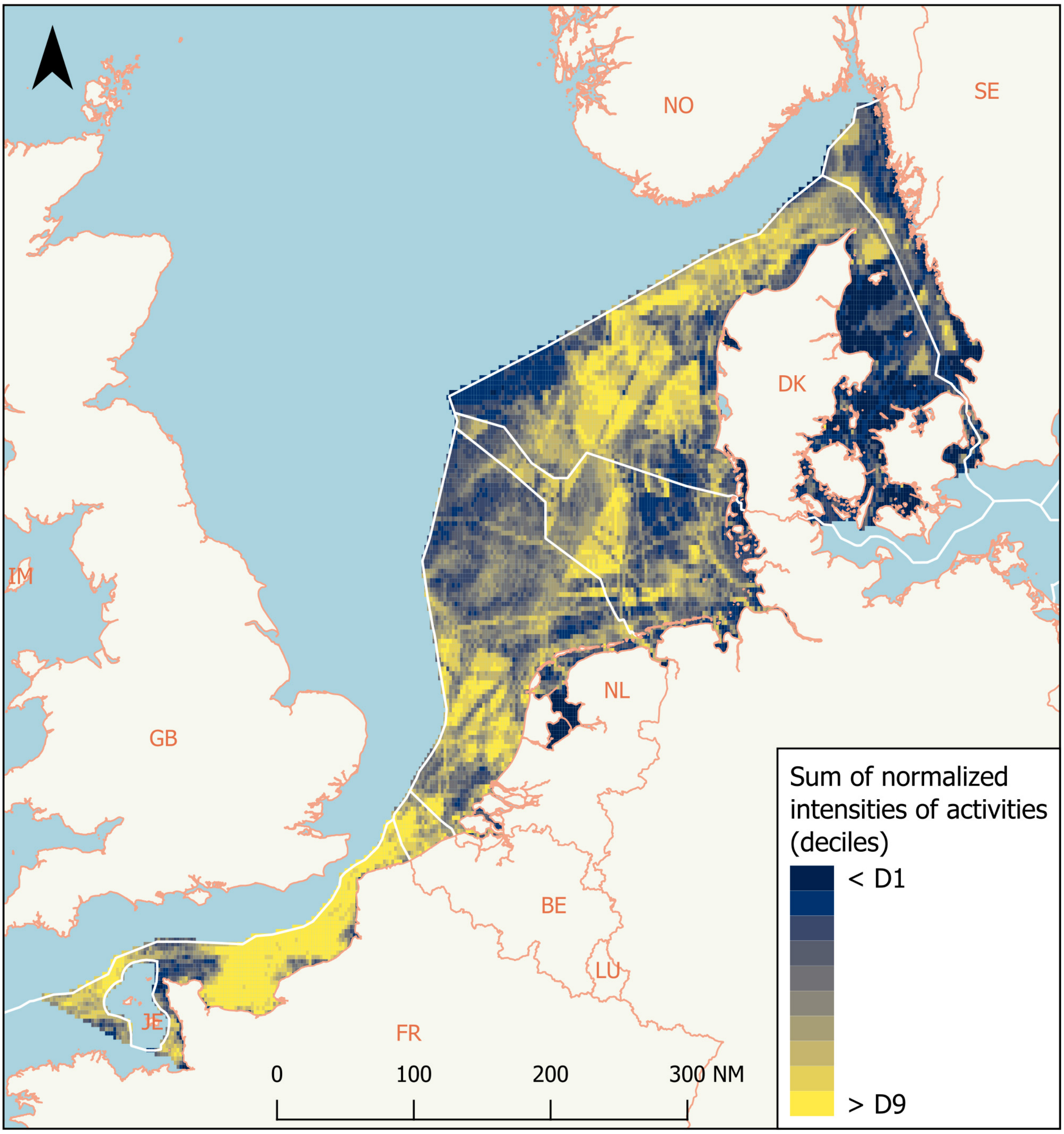

FIGURE 5
Sum of the normalized intensities of activities across the EU Greater North Sea.

unsuitable, yet is still currently carried out, causing a risk of cumulative effects.

5 Discussion

This study aims to explore the potential use of cumulative effects assessments within Maritime Spatial Planning. As part of this effort, an existing method of calculation of the risk of cumulative effects (e.g., Andersen et al., 2015; Bergström et al., 2019; Depellegrin et al., 2017; Quemmerais-Amice et al., 2020) was improved through the inclusion of the magnitudes of pressure generation by activities, and a module of activity unsuitability in an area was created. By addressing several persistent gaps (Quemmerais-Amice et al., 2020; Korpinen and Andersen, 2016; Halpern and Fujita, 2013) in the calculation of the risk of cumulative effects, such as the lack of weighting of the contributions of different activities to the intensities of pressures, these developments contribute to strengthening the methodological robustness of cumulative effects assessments, improving the reliability of cumulative effect assessments in an MSP context.

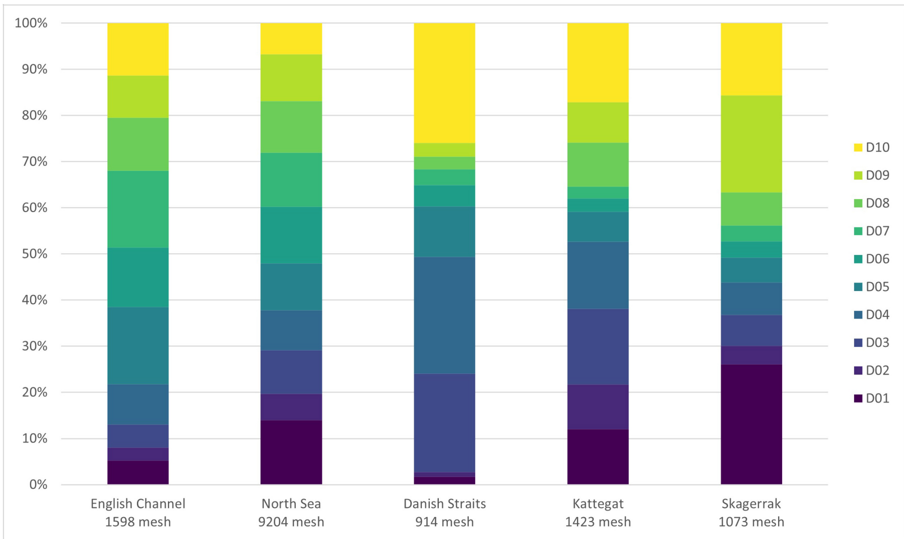

FIGURE 6
Percentage of mesh in each decile of cumulative impact, per marine region.

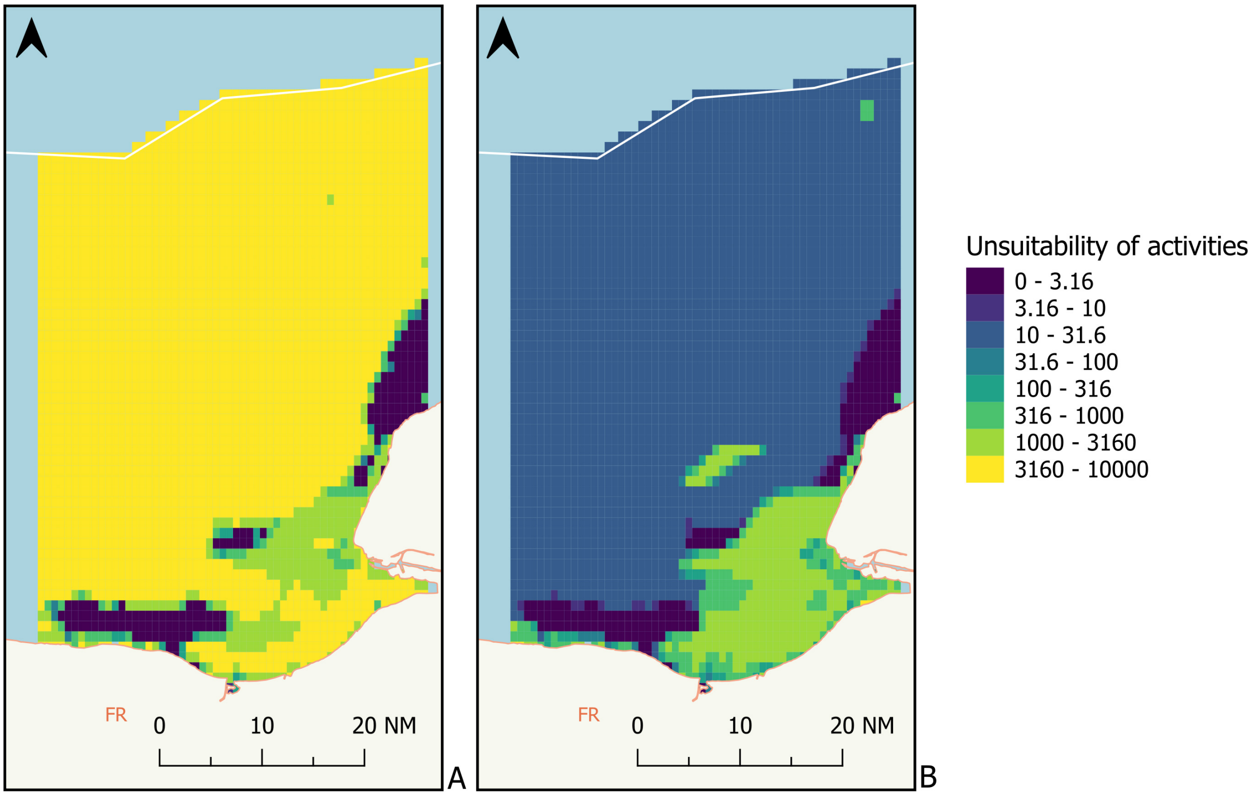

FIGURE 7
Calculated unsuitability values of activities in the Bay of Seine. **(A)** Pelagic trawling; **(B)** Maritime traffic (i.e., surface navigation).

5.1 Methodological improvements

The weighted pressures method introduced in this article significantly improves (Halpern and Fujita, 2013; Piet et al., 2021) the calculation of the risk of cumulative effects compared to binary models (Andersen et al., 2015; Quemmerais-Amice et al., 2020).

The values of RCE obtained in the Bay of Seine with the weighted pressures and the binary pressures methods generally have a roughly equivalent distribution, as shown by the deciles of both series, which on average have a difference of around 0.03 (Table 3). Additionally, the same areas of high and low risk also tend to emerge in both methods (Figure 3), which indicates that

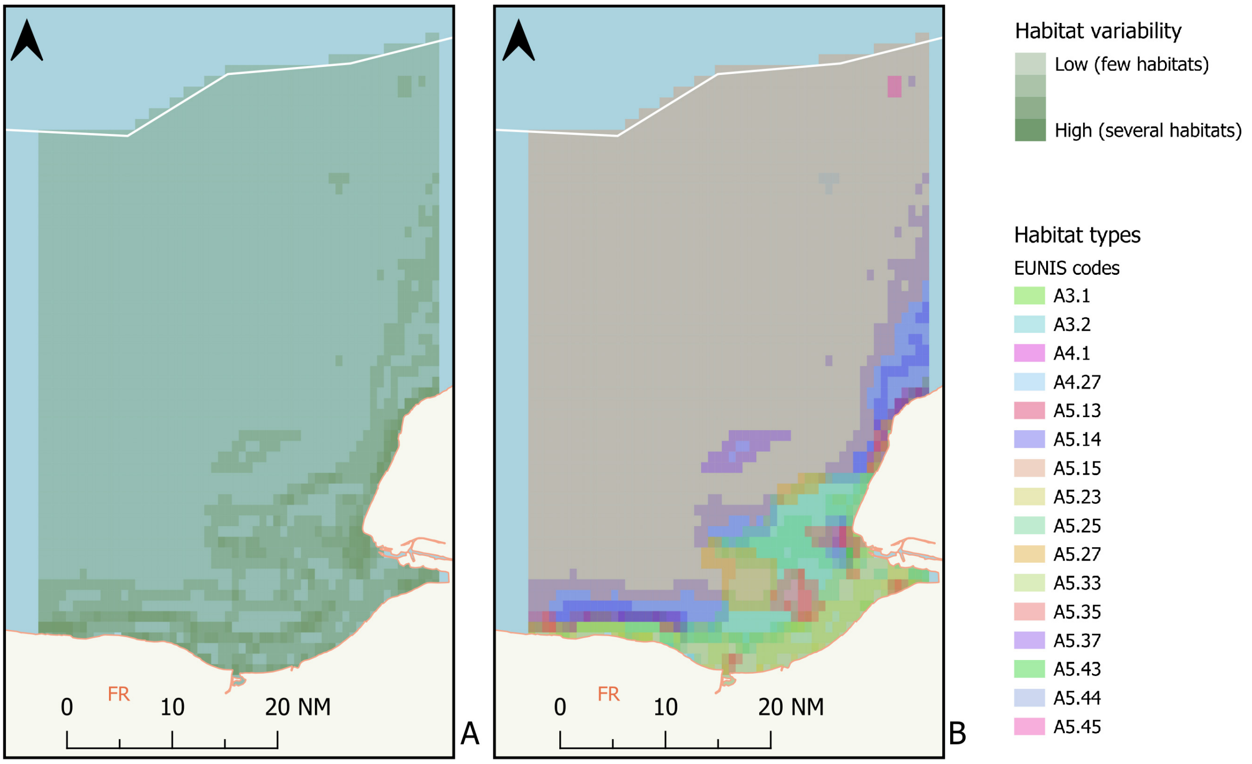

FIGURE 8
(A) Habitat variability defined as the number of different habitats in a cell and represented through cell transparency, with lower variability appearing more transparent. **(B)** Habitat types per cell in the Bay of Seine study area overlaid with a 40% opacity.

the results of the weighted pressures method are mostly comparable to the results of the binary method. Since the high and low risk areas correspond to high intensities of various activities known to generate pressures at high magnitudes, to which many habitats are highly sensitive, it can be concluded that the weighted method generally produces reliable results.

In contrast with the broad similarities of the results, as shown by the comparison of results obtained with both methods, the weighted pressures method readjusts the contributions of activities to pressures (Figure 3) and especially reduces the contributions of activities which only emit pressures to a low magnitude (e.g., affecting a small area), such as the presence of underwater cables. Furthermore, the weighted pressures method better identifies areas of high risk of cumulative effects in which only one activity is carried out. An example could be the case of offshore wind farms, in which a higher risk of cumulative effects is found with the weighted pressures method than with the binary pressures method. Using the binary pressures method, offshore wind farms' pressures have as much weight as other activities' pressures. Therefore, when comparing an area in which only the offshore wind farm generates a given pressure, to an area in which multiple other activities generate that same pressure, then the estimated pressure would likely be higher in the latter. Since it is common for other activities (e.g., fisheries, maritime traffic) to be forbidden or restricted in offshore wind farms, then only the offshore wind farms themselves are likely to generate this pressure within their boundaries, to the exclusion of other activities. Thus, with the binary pressures method, the contribution of the offshore wind farm to the overall intensity of this pressure across the study area may be underestimated, especially after the log-normalization of the pressure intensity. In contrast, with the weighted pressures method, the contribution of each activity to the overall intensity of this pressure also depends on the magnitude at which each activity generates the pressure, which removes this bias. From an MSP perspective, this method provides planners with better, more reliable results, which can then be used in the MSP process (Bonnevie et al., 2022; Esquerre et al., 2025; HELCOM Secretariat, 2018).

These methodological improvements also face limits; namely, the matrix used to distribute the magnitude values to the relationships between activities and pressures works by grouping together activities, and pressures, respectively. Ideally, each activity-pressure relationship would be examined individually. Additionally, while the reasoning behind the magnitude attribution by category was based on physical descriptors, it would be best to base the magnitude associated with each individual activity-pressure relationship on measurable data rather than expert opinion (Jones et al., 2018; Stelzenmüller et al., 2018; Piet et al., 2021).

5.2 Scale comparison

Spatial scale has a high importance in CEAs (Willsteed et al., 2023; Depellegrin et al., 2017; Halpern et al., 2008; Holon, 2015). In this study, the risk of cumulative effects is assessed at two different scales: single-country local scale in the Bay of Seine

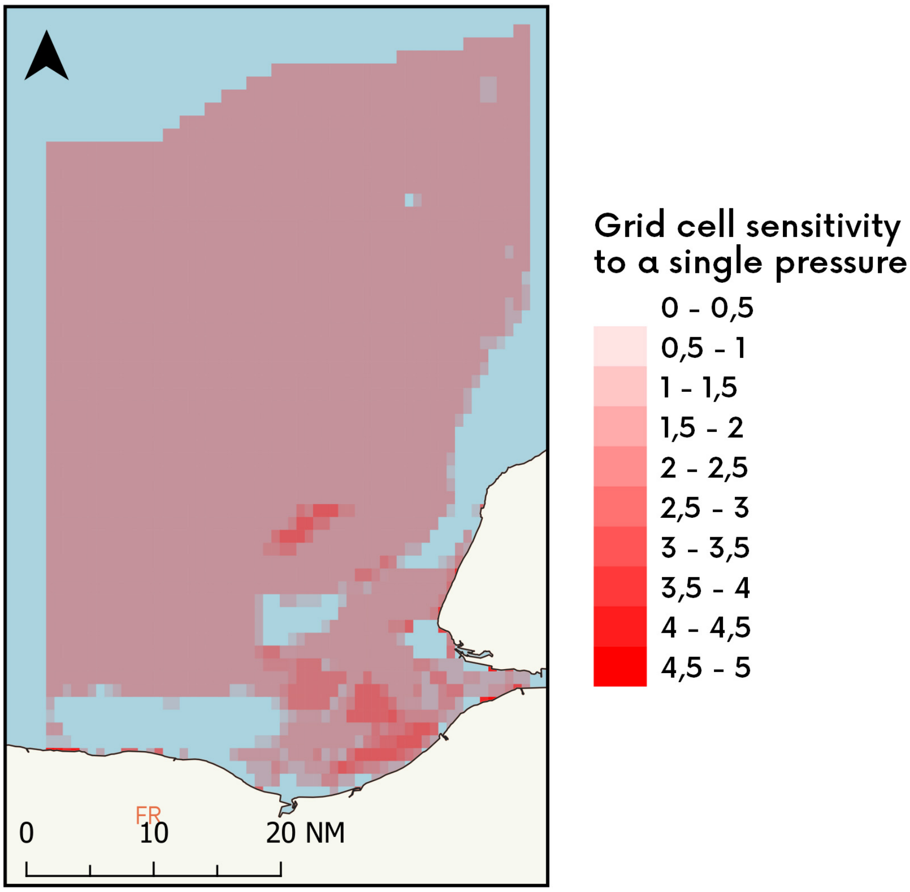

FIGURE 9
Overlay of total sensitivities of grid cells to pressures emitted by pelagic trawling with magnitudes of 2 or 3 (θA, $P = 100$ or 1,000). For each pressure, sensitivity is represented through cell transparency, with less sensitive cells appearing more transparent, and all individual pressure layers are overlaid to show the combined cell sensitivities.

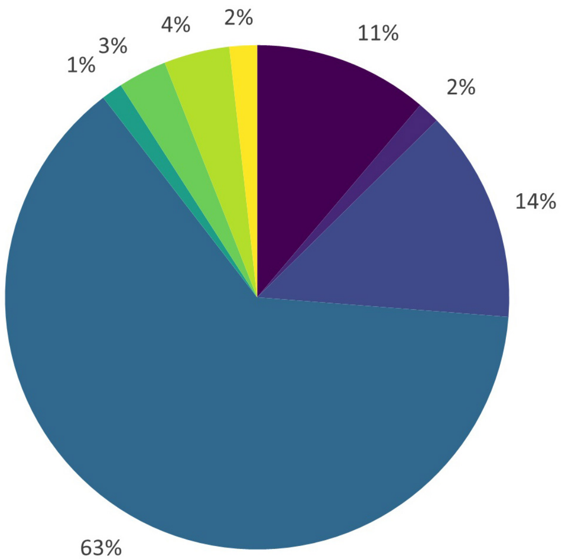

FIGURE 10
Percentage of mesh of unsuitability of activities for maritime traffic in the Bay of Seine case study.

(Figure 3), and international sea basin scale in the European Union Greater North Sea (maritime spaces of France, Belgium, The Netherlands, Germany, Denmark and Sweden, restricted to the North Sea, Skagerrak, Kattegat, English Channel and Danish Straits, Figure 4). The effects of scale on the assessment results are discussed here. At both scales, the results were globally coherent with the distribution of activities (Figures 4, 5), especially regarding the high concentration of activities known to generate various pressures at high magnitudes in the Danish Straits, Skagerrak and Kattegat, but also to the north of the Netherlands and off the coasts of Normandy.

5.2.1 Results at different scales in the Bay of Seine

While both assessments highlight similar broad areas of high and low risk, the distribution of the risk of cumulative effects in the Bay of Seine still shows differences between the local scale and the sea basin scale assessments (Figure 3).

Some of the differences in RCE values can be explained by the normalization of activities (and pressures) across a much larger area

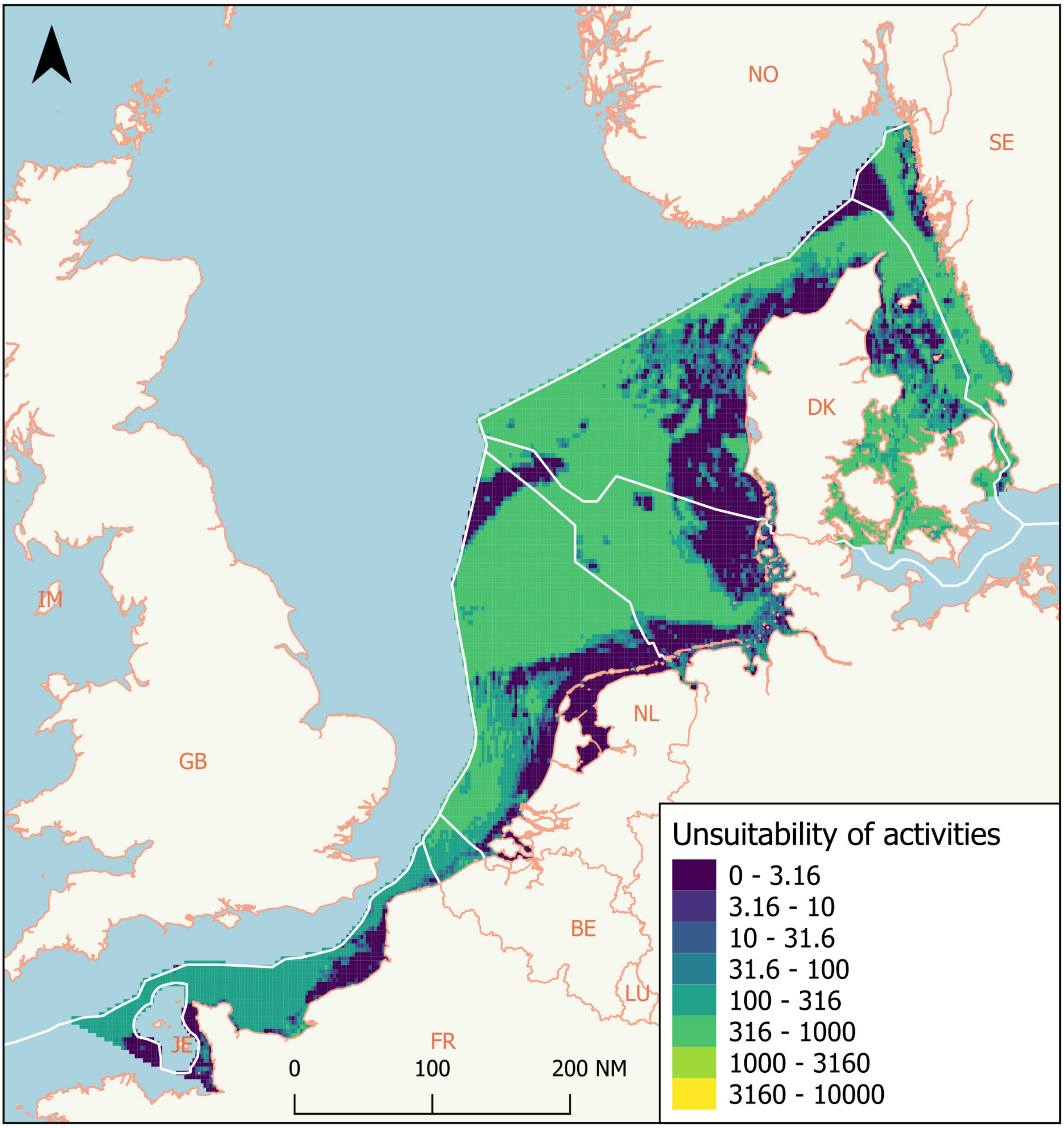

FIGURE 11
Calculated unsuitability value of pelagic trawling in the EU Greater North Sea.

in the sea basin scale assessment: in the sea basin scale assessment, the activities datasets extend beyond the Bay of Seine (Figure 5). For a given activity, if the range of intensities in the whole study area is wider than the range of intensities in the Bay of Seine, then the normalization step will not attribute the same normalized values to the activity in the sea basin scale assessment as it would in the local scale assessment. Depending on the distributions of activities' intensities, this can change the distribution of calculated pressures across the Bay of Seine.

Furthermore, due to differences in grid cell resolution, a single sea-basin-scale cell encompasses nine local-scale cells. Consequently, if a habitat is present in only one of these local-scale cells, the overlying sea-basin-scale cell records its presence across its entire area. Therefore, the calculation of the risk of cumulative effects compares this habitat against activities occurring anywhere within the nine local-scale cells it contains, even if those activities do not occur within the local scale cell containing the habitat. Conversely, the calculation integrates habitat surface coverage in the form of a percentage of the total cell area. In that same example, the contribution of the habitat within the sea-basin-scale cell (originating from just one of the nine local-scale cells it encompasses) is diluted by a factor of nine. Imagining any pressure

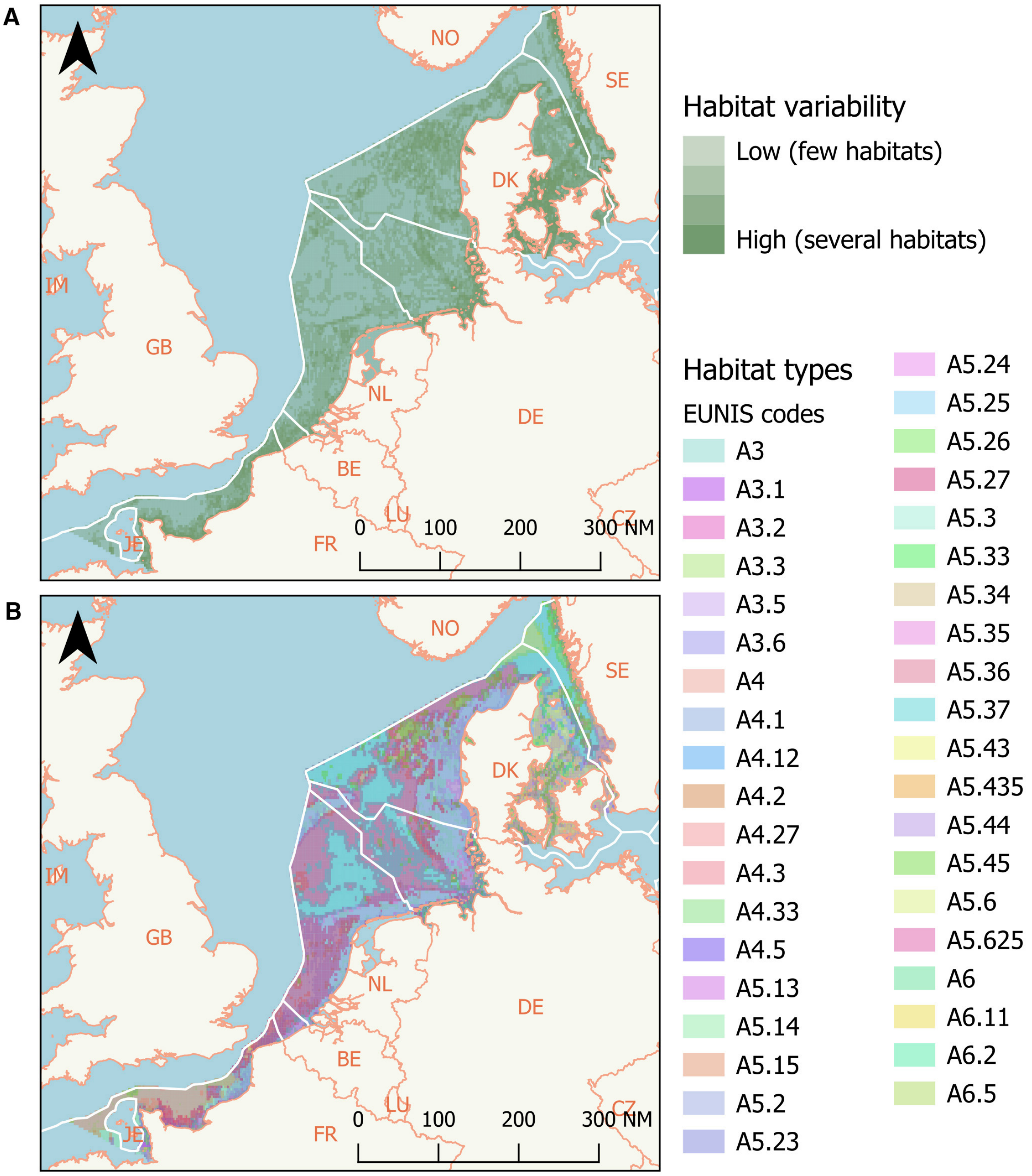

FIGURE 12
(A) Habitat variability defined as the number of different habitats in a cell and represented through cell transparency, with lower variability appearing more transparent. **(B)** Habitat types per cell in the EU Greater North Sea study area overlaid with a 40% opacity.

the habitat is sensitive to, occurring at a high intensity only in the same cell, the same dilution would also apply.

Finally, some of the differences can also be explained by the differences in the activity datasets (see below).

5.2.2 Data availability

Data availability is one of the most frequent limitations of CEAs (Foley et al., 2017; Depellegrin et al., 2017; Clarke Murray et al., 2015). The scale of the assessment affects which data is available (Depellegrin et al., 2017). Suitable data was available and accessible for the sea basin scale assessment on the European Marine Observation and Data Network (EMODnet), while the local scale assessment used publicly available national data: there were differences in data origin and accuracy between the two assessments.

A few activities, such as coastal artificialization (Table 2), had to be removed from the study as there weren't available datasets describing these activities at the sea basin scale. Some activities, particularly fisheries, are represented in the two assessments by datasets using different units. Additionally, certain activities (e.g.,

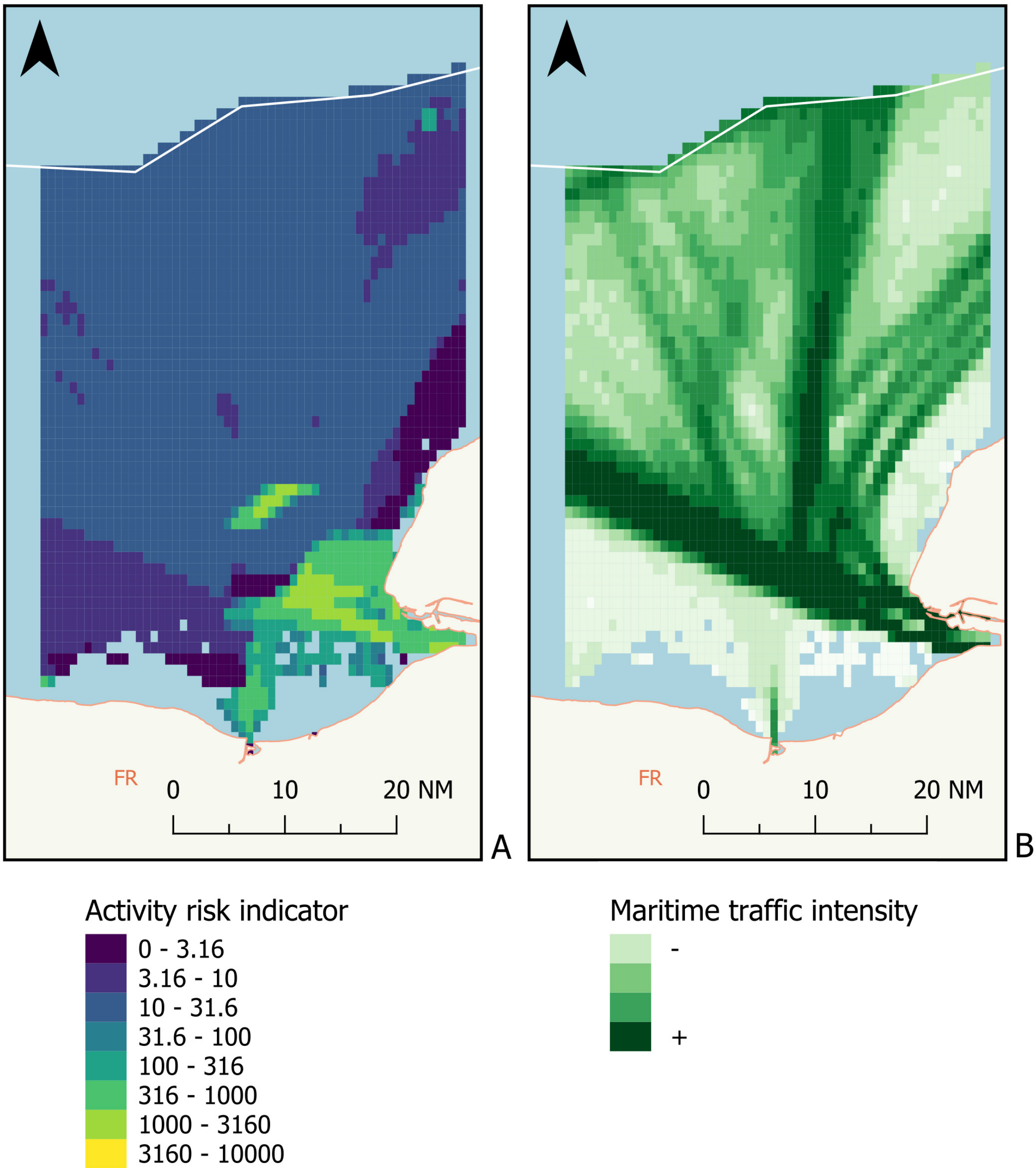

FIGURE 13
(A) Activity risk indicator calculated in the Bay of Seine for maritime traffic; **(B)** normalized intensity of maritime traffic in the Bay of Seine.

fishing gears) in the EMODnet datasets are not distinguished as precisely as in the national datasets. For instance, one EMODnet dataset contains the intensity of pelagic trawls and seines indiscriminately, while the corresponding national datasets separate the intensities of pelagic trawls and pelagic seines (Table 1). To represent the national fishing effort, we crossed the raw VMS position dataset from fishing vessels (provided by the French ministry in charge of fishing) with declarative data gathered by Ifremer, a national French institution. Due to statistical confidentiality and commercial data protection, these datasets are not public.

This is in part due to the complexity of harmonizing datasets from multiple countries using different standards, which is one of the methods of production of the EMODnet datasets used in this study. For the same reasons, some of the harmonized datasets (especially regarding aquaculture) needed an additional step of data preparation and cleaning; besides, data quality may vary depending on the sources used in the creation of the harmonized datasets, but it isn't possible to determine how much. On the other hand, the availability of complete habitat models and harmonized activity datasets at large scale made the sea basin case study feasible by providing coherent data across the entire study area. Manually

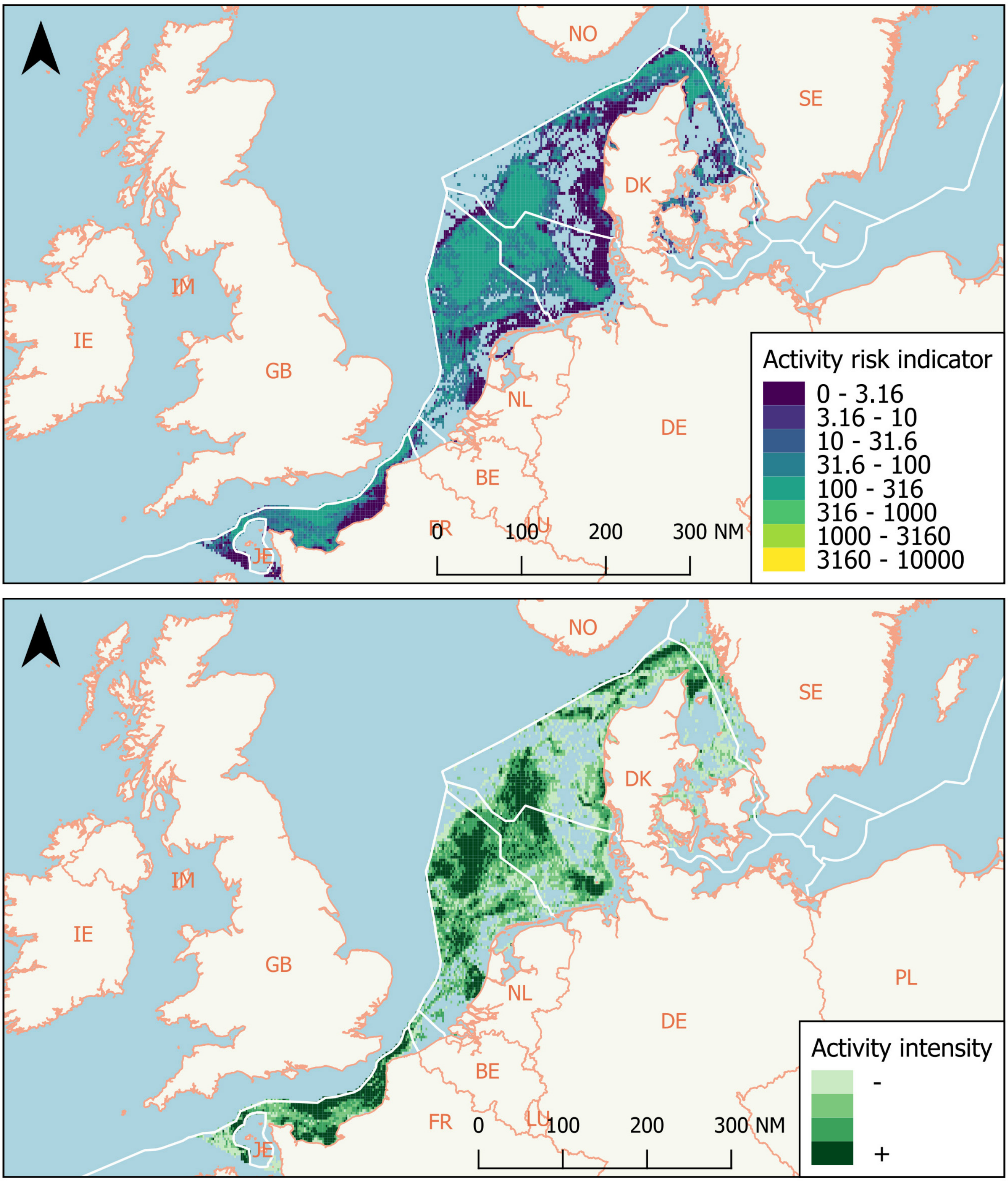

FIGURE 14
(A) Activity risk indicator calculated in the EU Greater North Sea for pelagic trawling; **(B)** normalized intensity of pelagic trawling in the Bay of Seine.

gathering and harmonizing the necessary data from each country would be much more difficult.

5.2.3 Application to MSP

In conclusion, in the context of MSP, due to the differences between the assessments at the two scales (log-normalization, data availability, RCE values distributions), the question to be answered by the assessment appears to be the main driver behind the choice of an appropriate scale (Esquerre et al., 2025); for instance, an effort to limit cumulative effects in a national MSP appears to benefit more from a local scale assessment than it would from a full sea basin scale assessment, while international coordination in MSP needs a large-scale assessment of the risk of cumulative effects (HELCOM Secretariat, 2018). The choice of scale will then have consequences on data availability and data origin. However, regardless of the scale, the risk of cumulative effects calculated by the improved tool should be reliable and similar areas should be highlighted as high-risk and low-risk.

5.3 Unsuitability and activity risk indicator

Decision support tools are universally recognized as highly useful to the MSP process (Depellegrin et al., 2021, 2017; Pinarbaşi et al., 2017). An unsuitability module was added to the RCE Carpediem tool, providing multiple functionalities and potential uses to the RCE Carpediem tool, which other tools often lack (Pinarbaşi et al., 2017).

The module calculates the unsuitability of an activity based on the total sensitivity of each grid cell to all of the pressures the activity emits, and the magnitudes at which these pressures are emitted. The calculated unsuitability does not depend on the intensity of the activity as it is currently carried out in the area. The module also calculates an activity risk indicator based on the activity unsuitability, compared to whether the activity is actually carried out in the area. While there are differences, for example, which variables are normalized or not, the activity risk indicator is analogous to a risk of cumulative effects (e.g., Quemmerais-Amice et al., 2020) calculated across the study area for a single activity.

For a given activity A, for each pressure P it emits, each $\theta_{A,P}$ (the relationship between activity A and each pressure P weighted through the magnitude of emission) is homogeneous (e.g., 1,000 for pressure P_1, 100 for pressure P_2, etc.) across the entire study area. Considering the unsuitability formula:

$$Unsuitability_{A,Cell} = \sum_{P} TotalSensi_{P,Cell} \times \theta_{A,\,P}$$

This means that the distribution of unsuitability values for this activity depends essentially on the total cell sensitivities to each pressure. This is exemplified by how the distribution of unsuitability values for pelagic trawling in the Bay of Seine is driven by the distribution of cell sensitivities to the main pressures emitted by pelagic trawling (Figure 9).

At both local and sea-basin scales, the developed module can identify zones in which a given activity is more or less unsuitable. The outlines of the zones are coherent with the distributions of activities and habitats (Figures 7, 11). However, scale still influences the observed patterns: in the Bay of Seine, at local scale, the largest identified zones primarily coincide with areas in which a single habitat type defines the activity unsuitability. In contrast, in the EU Greater North Sea, at the sea-basin scale, large areas of homogeneous unsuitability for a given activity result from different combinations of habitats coincidentally having overall similar sensitivities to the pressures exerted by the activity. Therefore, while the large zones identified at small scales would show similar unsuitability values for every activity, the zones identified at sea-basin scale for two different activities may not be the same.

Notably, habitats in the local scale study area show less variability than in the sea basin scale study area (Figures 8, 12), which explains some of the uniformity. Local scale zones with higher habitat variability may show areas of high and low unsuitability depending on the pressures emitted by the activity, and the sensitivities of the habitats to these pressures.

Additionally, local scale uses a higher resolution grid: smaller cells may contain fewer habitat types. Consequently, considering an activity emitting a certain pressure, a given cell containing a habitat highly sensitive to that pressure will display a high unsuitability for this activity, whereas neighboring cells with less sensitive habitats, whereas neighboring cells containing different habitats of lower sensitivity will display a low unsuitability for the activity. In a small cell, the fraction of surface covered by the sensitive habitat will also be higher than in a larger cell. Because of these reasons, small resolution grids are more likely to display high variability from one cell to another.

The MSP Directive sets sustainable development requirements for national MSPs. Countries must establish an MSP which facilitates the sustainable development of human activities while considering economic, social and environmental aspects, and use an ecosystem-based approach. Moreover, the MSP Directive specifically mentions the need to consider the impacts of relevant activities and uses on the environment (Directive 2014/89/EU, 2014). In the context of national MSP, activity unsuitability is particularly useful to complete these requirements, as it can help planners determine the objectives and purposes of defined areas in a State's maritime space, and plan activities to achieve these objectives. The results obtained at both scales can be used to compare the unsuitability of various activities in given areas in order to decide on priority activities in each area. Moreover, the unsuitability of activities can be compared to restrict or forbid the most unsuitable activities in certain areas in order to achieve ecological planning objectives (e.g., achieving Good Ecological Status). High resolution, local-scale assessments can also identify precisely spots in a subdivision of maritime space in which an activity is particularly unsuitable. As such, activity unsuitability builds upon, and complements, existing tools providing planners with environmental assessments (Bonnevie et al., 2022; Depellegrin et al., 2021; HELCOM Secretariat, 2018). Additionally, as ecosystem components aren't defined by the boundaries of countries, activity unsuitability values at a sea basin scale provide an international reference for potential human effects on the environment. This reference can then facilitate international cooperation in order to organize activities to fulfill the needs of all the countries bordering a sea basin and develop human activities in a sustainable way while maintaining a healthy marine environment. As such, activity unsuitability can facilitate trans-boundary cooperation between Member States, as well as the coherence and coordination of maritime spatial plans across a sea basin, as required by the MSP Directive (Directive 2014/89/EU, 2014), especially in order to achieve the MSP Directive sustainable development requirements at the scale of the entire sea basin.

However, data accuracy and completeness, especially regarding the habitats and their sensitivities to pressures, are crucial to accurately determine activity unsuitability. Therefore, the application of unsuitability analysis to MSP must be carried out with sufficiently detailed data, especially at larger scales (Depellegrin et al., 2017; Esquerre et al., 2025), and the potential weaknesses of the results need to be communicated to planners with full clarity in order to properly inform the decision-making process (Esquerre et al., 2025). For instance, the unsuitability of pelagic trawling is influenced by the sensitivities of the habitats found across the study area. There are habitats for which very few sensitivities are known, which decreases the value of unsuitability in the cell. For instance, at the north of the study area, in the Skagerrak, a patch of habitat "A6.5" (its EUNIS 2012 code), and in the middle of the study area and to the west of Denmark, two patches of habitat "A5.2"; for both of these habitats, few sensitivities are known (in part due to the low level of detail in their classification). Based on such results, MSP planners could allow activities in zones where the calculated unsuitability is low due to lack of data, but could be higher with finer habitat identification. This could cause an undetected mismatch between the planned activities and the actual habitats, which is why clear communication of results and how to interpret them is crucial.

In this study, an activity risk indicator was also developed and added to the RCE Carpediem tool. Across the study area, it combines the unsuitability values of an activity with the activity's existing (or planned) intensity. The results of activity risk indicators obtained in this study are coherent with the maps of habitats and their sensitivities to certain pressures, the corresponding activity unsuitability values, and the activity intensities (Figures 13B, 14B). For instance, in the Bay of Seine, areas of high activity risk indicator for maritime traffic correspond to the overlap of high maritime traffic unsuitability and high maritime traffic intensity.

In the context of MSP, the activity risk indicator can be used in order to identify sectors in which a potentially unsuitable activity is carried out intensely, emitting pressures which increase the risk of cumulative effects on the marine environment. The activity can then be restricted, or measures can be taken to mitigate the emitted pressures.

However, similar to the activity unsuitability, it is essential to use accurate and detailed input data to obtain fully usable results. In the sea basin scale case study, the activity risk indicator for pelagic trawling was calculated with intensity data combining pelagic trawling and sennes. Compliant with the principles of a risk-based approach, the dataset was treated as if 100% of the intensity in the data was attributable to the investigated activity, pelagic trawling in this case. Therefore, it is possible to obtain high activity risk indicator values for pelagic trawling in areas without any pelagic trawling occurring. As such, while the results provide a first approach to determine potential areas in which certain activities can largely increase the risk of cumulative effects, they must also be communicated to planners with instructions on how to interpret them, as is the case for Cumulative Effects Assessments in general (Esquerre et al., 2025).

5.4 Remaining limitations

This study proposes new developments in the calculation method of the risk of cumulative effects. These advances increase the reliability of Cumulative Effects Assessments and improve their potential use in the maritime spatial planning process. However, many challenges remain in the implementation of CEA in MSP.

In spite of methodological improvements to reliability and robustness producing results that more closely reflect real-world conditions, the tool presented in this study still requires the log-normalization of activities' intensities and emitted pressures to harmonize input data. Although this supports the reliable and replicable integration of multiple input data sources, it also imposes a gradient of relative intensities starting at 0, which can underrepresent the fact that even low-intensity activities exert measurable pressures in real systems.

Similarly, sensitivity values derived from expert judgment currently provide the most practical means of characterizing the interactions between numerous pressures with numerous ecosystem components, but while experts broadly agree on sensitivity values of ecosystem components to numerous pressures, expert judgment still introduces variability from the chosen methodology (Kallio et al., 2025). Evidence-based quantitative sensitivities would offer a more objective and robust foundation for analysis (e.g., Jones et al., 2018).

Indirect pressures through the food web (i.e., pressures indirectly affecting an ecosystem component, by causing a direct effect on parts of the food web it is attached to) are scarcely integrated into Cumulative Effects Assessments. Studies exist which connect the results of a Cumulative Effects Assessment with a food web model in the marine environment such as Ecopath with Ecosim, but typically merely combine the CEA outputs and the food web model to derive results on specific topics, such as human impacts on ecosystem services (e.g., Piet et al., 2024).

The temporal dimension of pressures and effects is still poorly considered in most Cumulative Effects Assessments: while for instance the seasonality of pressures is now better understood, the effects of time are still not completely included in most CEA (Willsteed et al., 2023). The duration of pressures and their effects on the environment in particular need to be better integrated, and compared with the resilience and recovery of the environment after a pressure ends (Morejón et al., 2025).

Finally, studies show that some human activities may have positive effects on certain ecosystem components, such as offshore wind farms providing artificial reefs, attracting fish, and creating a refuge effect by restricting or removing other human activities like commercial fishing (e.g., Bergström et al., 2013; Galparsoro et al., 2022). However, the RCE Carpediem tool in its current version is focused on the risk of negative cumulative effects, and is not yet capable of integrating the potential positive effects of certain activities into its assessment of the risk of cumulative effects.

In conclusion, while there exist several studies, including this one, which overcome some of the issues remaining in Cumulative Effects Assessments, no study has yet managed to gather all the advances proposed in a single comprehensive tool (Hodgson and Halpern, 2019). Cumulative Effects Assessments would benefit greatly from further developments that combine the advances made so far, and further tackle the remaining challenges in this field.

Data availability statement

Certain restricted national datasets owned by State services (e.g. fisheries data), which cannot be published or distributed without owner approval, are not publicly available and can only be accessed upon request, pending the approval of the owner. Requests to access the datasets should be directed to the corresponding author, Antonin Gimard. Updated Carpediem scripts can be found at https://github.com/FredQuemmerais/carpediem/.

Author contributions

AE: Conceptualization, Data curation, Methodology, Writing – original draft, Investigation, Writing – review & editing, Visualization, Formal analysis, Software. FQ-A: Writing – review & editing, Writing – original draft, Data curation, Conceptualization, Methodology, Validation, Visualization. AG: Project administration, Methodology, Data curation, Conceptualization, Writing – review & editing. GVH: Data curation, Writing – review & editing. AQ: Project administration, Writing – review & editing, Conceptualization. OL: Conceptualization, Writing – review & editing, Project administration.

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Conflict of interest

The author(s) declared that this work was conducted without any commercial or financial relationships that could constitute or be construed as a potential conflict of interest.

Generative AI statement

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