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Assisting Coastal and Marine Governance: Enhancing Decision Support Through Digital Tools for Cumulative Impact Assessment

Jonne Kotta [1], Jean-Marc Douguet [2], Elis Vollmer [1], Mihhail Fetissov [1], Elisa Furlan [3], Gea Grassi [3], Federica Zennaro [3,4], Hector Charles Pagan [1], and Helen Orav-Kotta [1]

[1] University of Tartu, Estonia
[2] Université Paris-Saclay, France
[3] Euro-Mediterranean Center on Climate Change (CMCC Foundation), Italia
[4] Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice, Italy

Correspondence: Jonne Kotta (jonne.kotta@sea.ee)

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Abstract

Coastal regions are increasingly pressured by diverse human activities, leading to cumulative effects that undermine ecosystem integrity and functioning, including disruptions to biodiversity, habitat degradation, and alterations of ecological processes. Understanding and addressing these complex interactions is a prerequisite for effective environmental management. This study demonstrates how the web-based PlanWise4Blue tool analyzes the cumulative effects of human activities on coastal ecosystems using a data-driven approach, enabling stakeholders to compare different management scenarios and identify options to mitigate ecological impacts or enhance marine health. By bridging the complexity of natural systems and decision-making, the tool strengthens e-governance, promoting more effective environmental management.

Keywords

coastal ecosystems; coastal management; ecosystem integrity; e-governance; environmental decision-making; environmental impact assessment; marine ecosystem health

1. Introduction

Coastal ecosystems face escalating pressures from a variety of human activities, which often produce overlapping stressor footprints and lead to cumulative effects (Halpern & Fujita, 2013; Thrush et al., 2021). Cumulative effects refer to the combined effects of multiple human activities, natural processes, and environmental stressors on ecosystems or communities over time and space. These effects can result from the interaction of different factors that may be individually minor but collectively significant, potentially leading to profound ecological or societal changes (Halpern et al., 2008). These interactions include nonlinear dynamics, legacy effects, and ecosystem responses that are often spatially and temporally disconnected from the original stressors (Ellis et al., 2017). Consequently, these cumulative effects can erode ecosystem resilience, push systems toward tipping points, and result in irreversible ecological damage (Low et al., 2023; Norkko et al., 2002).

Effective management of cumulative effects is vital to mitigate the threats from complex interactions between human activities and natural systems (Hewitt et al., 2016). Understanding these interactions, including spatial and temporal variability, and sharing this knowledge with policymakers, managers, and communities are key to fostering resilience and adaptive governance for sustainable ecosystem health (Gladstone-Gallagher et al., 2019; Singh et al., 2017). Nonetheless, this task is challenging due to the complexities arising from the interactions between human activities, the pressures they generate, and the ways these cumulative pressures affect ecosystems.

Current cumulative effect assessments are largely expert-driven, focusing on stressor and activity footprints, yet they often overlook the complexity of dynamic ecosystem responses that emerge through indirect effects, legacy impacts, and context-specific interactions (Halpern et al., 2015; Thrush et al., 2021). Advancing these assessments requires the integration of data-driven frameworks that emphasize ecosystem response footprints, which account for nonlinear effects, resilience, and recovery dynamics (Hewitt et al., 2022). Such approaches should incorporate spatial and temporal variability, including legacy effects that persist beyond stressor cessation and the effects of multiple overlapping stressors (Ellis et al., 2017). The cumulative effect tool should prioritize methods that link response footprints with predictive models and management actions to foster integrated strategies (Low et al., 2023; Norkko et al., 2002; Thrush et al., 2013).

Traditional frameworks, often based solely on expert opinion, are insufficient for capturing the complexity of cumulative effects. However, the increasing intensity and diversity of human activities open opportunities to integrate ecological modelling into cumulative effect assessments. Data-driven methodologies provide structured approaches to analyzing and managing interactions within natural systems with greater accuracy and confidence.

The PlanWise4Blue tool, hosted under the Blue Bio Sites portal (https://gis.sea.ee/bluebiosites), is a decision support system developed to bridge the gap between scientific research and policymaking. It is designed for data-driven cumulative impact analysis, integrating scientific knowledge of geophysical environments, spatial distributions of natural assets, and the projected effects of various human activity scenarios. The tool predicts environmental outcomes in complex ecosystems, supporting sustainable marine development and effective conservation strategies for European seas amidst rapid human-induced environmental change. The platform is dynamic, continuously expanding its geographical scope and incorporating diverse nature assets, human impacts, and analytical tools.

This article demonstrates the real-world applicability of the PlanWise4Blue tool through a Baltic Sea case study. The case study highlights three key aspects: ecosystems subjected to multiple human-induced pressures, the transboundary nature of these pressures, and the need for coordinated planning of human activities. As a regional test site, the Baltic Sea emphasizes the importance of a harmonized approach to addressing these challenges, positioning the PlanWise4Blue tool as a rewarding resource for bridging existing gaps in cumulative impact analysis and spatial planning.

2. PlanWise4Blue: Empowering Data-Driven Decision-Making for Sustainable Marine Management

PlanWise4Blue is a digital tool developed to support maritime spatial planning and sustainable marine management. Initially created for the Estonian maritime spatial planning, it has since been adapted for broader European use. The tool employs a unified framework to integrate customized analytical workflows for assessing cumulative effects, filling data gaps, and providing actionable insights through targeted case studies.

PlanWise4Blue employs a data-driven approach, that offers a robust, quantitative foundation for environmental impact assessments. Cumulative impact analysis requires three key components: (a) knowledge of the expected effects of human activities and resulting pressures, (b) spatial data on natural assets, and (c) spatial distribution of human activities defining the analysis scenario (Figure 1). The following section outlines these three key components.

To consolidate scientific evidence on the effects of various combinations of human activities on natural assets, PlanWise4Blue integrates systematic reviews, meta-analyses, and expert input to compile an impact matrix, serving as training data for cumulative impact modelling and effect prediction. Systematic reviews and meta-analyses provide a robust method for synthesizing quantitative data on environmental effects by consolidating evidence from scientific studies and organizing the data in a standardized format (Griffin et al., 2013; Harvey et al., 2013). During data harvesting, effect sizes are determined by calculating the ratio of the effect value to the reference value, reflecting the expected increase or decrease in a natural asset under specific human use combinations. When data are sparse or unevenly distributed across different combinations of human pressures and ecosystem components, extending search terms to include related geographic areas or taxonomic groups can help address data deficiencies at local or regional scales. Moreover, effects can be derived from existing monitoring datasets, such as those collected under the Water Framework Directive or other environmental impact assessments. All available effect sizes are then pooled, enabling comprehensive analyses that uncover overarching patterns, deepen insights into underlying processes and drivers, and highlight knowledge gaps. Importantly, systematic reviews and meta-analyses adhere to a clear, well-defined protocol, ensuring transparency and reliability in assessments. This approach also provides tangible metrics, such as species biomass or habitat loss/gain under different scenarios, rather than relying on arbitrary indices. While some cause-effect interactions continue to rely on expert judgment, PlanWise4Blue increasingly integrates empirical data as it becomes available.

Another persistent limitation of cumulative effect assessments is the lack of spatial detail (Corrales et al., 2020) or reliance on overly coarse spatial resolutions, such as assessments conducted at the scale of entire seas or large sub-basins (e.g., Ojaveer et al., 2023). However, since management decisions often operate at finer spatial scales, such as those required for maritime spatial planning, it is important to improve the spatial granularity of these assessments. The PlanWise4Blue tool integrates distributional data with advanced spatial modelling (Qazi et al., 2022; Robinson et al., 2017) to deliver detailed maps of nature assets for the region of interest. While a comprehensive review of species distribution modelling methods is beyond the scope of this article, numerous tutorials exist to guide the selection of appropriate techniques. Spatial modelling must differentiate between presence-only models, like maxent (Elith et al., 2020; Valavi et al., 2022), and traditional models, which require both presence and absence data. Presence-only models address data biases caused by observational datasets that often lack absence records, while traditional models are suited for taxa with well-documented distributions. Despite their correlative nature and limited ecological insights (Lee-Yaw et al., 2022), species distribution modelling remains essential for conservation and management, offering valuable insights and detailed data that would otherwise take years to compile.

The third component of the PlanWise4Blue tool is the spatial arrangement of human activities, which defines the scenarios for cumulative impact analyses. Users can either use existing datasets, such as human activity maps from the European Marine Observation and Data Network or create custom scenarios to assess the environmental impacts of specific human use patterns on selected natural assets. Climate change can also be integrated into the cumulative effect assessment of the PlanWise4Blue tool. However, due to the complex interactions between different realms (e.g., sea and land), regional or local climate models must first be run to generate scenario-specific maps of climate pressures and natural assets. These climate-specific datasets can then be incorporated into analyses alongside other human pressures.

The cumulative effect assessment in the PlanWise4Blue tool is conducted by analyzing the spatial overlap of human activities and natural assets within each grid cell of the study area. The grid cell size is determined by the spatial resolution of natural asset data, typically set at 1 km^2 for regional seas and 50 m^2 for local case studies. Natural asset maps in the tool are sourced from open-access databases, case studies, or generated using spatial modeling algorithms.

The assessment process begins by identifying the intensities of human pressures (e.g., underwater noise and contamination) and the values of natural assets (e.g., species presence, habitat cover, and biomass) within each grid cell. These data are then combined with human use-specific and nature asset-specific effect sizes (sometimes referred to as impact scores) derived from meta-analyses of scientific literature and available datasets. The cumulative effect for each natural asset is calculated as the product of the asset value and the average effect size of specific human pressure–asset combinations. Uncertainty in effect estimates is addressed by incorporating variations in both effect sizes and natural asset indicators, using an expression based on Taylor series expansion (Kotta et al., 2020, 2025; Taylor & Kuyatt, 1994).

Designed to be user-friendly, the tool provides marine managers and policymakers without scientific backgrounds access to high-quality knowledge and data for informed decision-making, presented as interactive maps and summary statistics. By integrating diverse datasets, including global and case-specific environmental data, the tool generates baseline profiles for each case study area. Such baselines serve as essential reference points for assessing the effects of proposed activities or interventions and guiding effective management strategies.

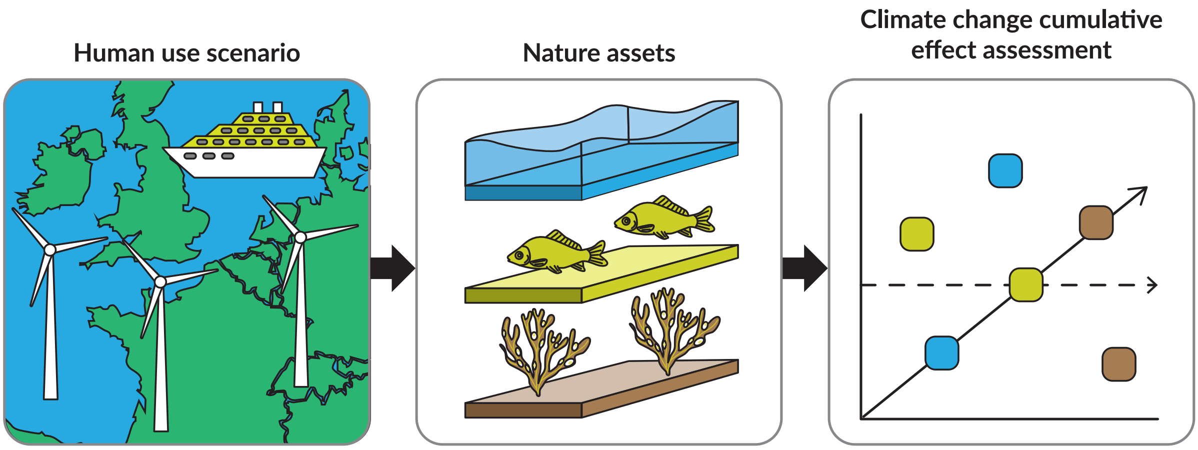

Figure 1. PlanWise4Blue: A tool for quantitative environmental assessment, scenario analysis, and climate megatrend evaluation. Note: PlanWise4Blue enables users to explore climate megatrends, assess the cumulative effects of climate change and human activities, and identify key risks to various natural assets.

3. Assessing the Real-World Applicability of the PlanWise4Blue Tool: A Baltic Sea Case Study

The Baltic Sea is a semi-enclosed brackish water basin in Northern Europe, shared by eight EU countries (Germany, Denmark, Sweden, Finland, Estonia, Latvia, Lithuania, and Poland) as well as Russia. Its limited connection to the open ocean through the Danish Straits restricts water exchange, making it particularly sensitive to external influences. The extensive watershed area further amplifies the ecosystem's vulnerability, causing it to respond rapidly to various pressures.

The governance context for the Baltic Sea region is shaped by a complex network of international, regional, and national frameworks. The Helsinki Convention provides the overarching framework for regional cooperation, coordinating the implementation of commitments aimed at protecting the Baltic Sea. Although each Baltic Sea state implements environmental policies in line with regional agreements, national priorities and governance structures differ significantly. These differences can result in diverse approaches to managing trade-offs and conservation efforts, potentially complicating coordinated management across the region.

This is troubling, as the Baltic Sea faces significant management challenges due to the inability to effectively control widespread external pressures, such as eutrophication driven by legacy nutrients, and land-based activities like industrial discharges and agricultural runoff. In addition, transboundary pressures such as wind farm construction and the spread of non-indigenous species through shipping remain inadequately addressed. These issues are further compounded by limited financial and human resources, fragmented datasets, and low stakeholder engagement, hindering effective decision-making and the achievement of biodiversity goals. Despite these challenges, stakeholders recognize the value of data-driven decision-making and the application of cumulative impact tools to integrate pressures across transboundary scales and prioritize mitigation actions. If such analyses are conducted using accessible online tools, targeted training for managers can enhance the capacity for the effective use of spatial tools in future management efforts.

The PlanWise4Blue tool is currently accessible in its consolidated version, PlanWise4Blue Europe, developed under the BlueGreen Governance project. The tool is entirely internet-based, removing the need for downloads. The platform integrates the latest spatial datasets on nature assets, including species, habitats, and ecosystem services. These datasets are generated using advanced modelling techniques such as maxent, boosted regression trees, random forests, and generalized additive models, using the best available biological and environmental data from national and regional monitoring programs, European data infrastructures like Copernicus, and scientific publications. Information about the human pressure layers and nature asset datasets can be found under the guides of the tool.

Users can create new scenarios by defining specific study areas in the Baltic Sea region and setting up workspaces in PlanWise4Blue. Currently, the platform allows the inclusion of 909 nature assets and 44 human activities in cumulative effects assessment. The spatial resolution of the analysis is set at 1 km^2 due to data availability. However, the scale will be refined to 250 m^2 in the next 1–2 years, following the delivery of harmonized key species and habitat maps through the Horizon project Protect Baltic. Human activities can represent current conditions or future management scenarios, with options to adjust spatial arrangements. In the PlanWise4Blue Europe version, users can adjust parameters for specific human activities, allowing the tool to project potential environmental outcomes under various development scenarios. For instance, planners and environmental managers can evaluate the cumulative effects of offshore wind farm development by specifying turbine density and types (e.g., monopile and gravity base), as different configurations are likely to exert varying impacts on marine biota. These specific offshore developments can then be assessed alongside other pressures, such as fisheries or shipping lanes, to identify impact hotspots and quantify the relative effects of different human activities on selected nature assets. Users can also generate a single map that consolidates all the asset-specific effects in nature. However, such an aggregated map may oversimplify the complexity of cumulative effects, potentially overlooking the distinct management needs of different assets. Effective management relies on maintaining the granularity of analyses to address diverse impacts comprehensively.

We demonstrated the PlanWise4Blue tool to stakeholders responsible for nature protection and management in January–February 2025, in the transboundary context of Estonian and Latvian marine waters in the Gulf of Riga. The area is proposed for wind farm development to increase green energy production, yet it is also a significant fishing zone where pelagic trawling for herring and sprat is widespread. The region is also characterized by eutrophication and the presence of multiple non-indigenous species. Stakeholders expressed interest in understanding the relative contribution of wind farm development to cumulative effects, considering interactions between energy infrastructure, fisheries, eutrophication, and invasive species. Specifically, they aimed to identify the nature assets most affected and explore how the negative impacts could be mitigated or avoided (Figure 2).

In the PlanWise4Blue tool, users began by creating a workspace, defining the spatial extent of the analysis (e.g., the Gulf of Riga), and selecting relevant human activities and nature assets. After running the cumulative effect model, they accessed the assessment results once the analysis was complete. Outputs were visualized as detailed maps and summary statistics, offering clear insights into cumulative effects and plausible mitigation opportunities (Figure 3). The cumulative effect analysis of the current scenario revealed that all human-induced pressures contributed to changes in nature assets, with wind farm development accounting for an average of 3% of the expected changes. Eutrophication contributed 28%, pelagic trawling 2%, round goby (*Neogobius melanostomus*) 43%, and mud crab (*Rhithropanopeus harrisii*) 25%. However, in absolute terms, the impact of wind farm development was minimal, affecting only a few species and

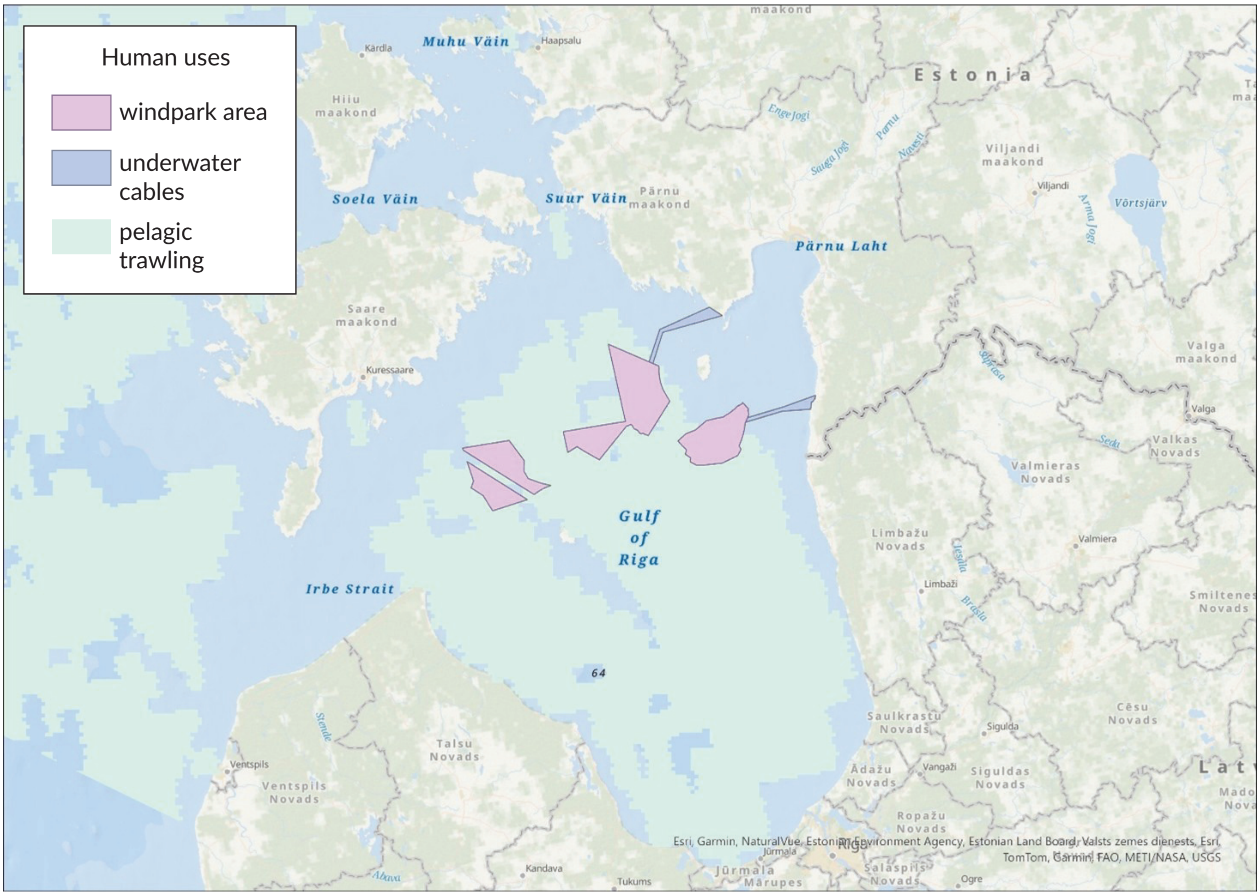

Figure 2. Transboundary case study in the Gulf of Riga: Location of the proposed wind farm and underwater cable areas alongside existing pelagic trawling zones. Notes: Eutrophication effects are evident throughout most of the gulf, while the round goby (*Neogobius melanostomus*) and mud crab (*Rhithropanopeus harrisii*) are the most prominent non-indigenous species in the region; the round goby is widespread across the gulf, whereas the mud crab is primarily concentrated in the southern and northeastern coastal areas.

impacting less than 5% of their populations in the Gulf of Riga, with recovery considered likely. The most pronounced effects of wind farm development were observed in specific bird species, highlighting the importance of setting wind farms away from key concentration areas. In addition, moderate impacts were noted on soft-bottom seafloor habitats. Given their relatively quick recovery rates, these effects could be mitigated by selecting construction methods that minimize disturbance to benthic habitats. Environmental impact assessments are often conducted sector by sector, without considering the relative contributions of different human activities or the cumulative effects of pressures arising from them. This sectoral focus can overlook pressures not directly associated with a specific sector, such as the influence of non-indigenous species, leading to underestimation or neglect of significant impacts.

The functionality of PlanWise4Blue empowers users to explore future environmental scenarios, evaluate trade-offs, and develop informed, actionable strategies that balance ecological health with human activity. By envisioning and evaluating potential outcomes of future scenarios, these tools stimulate decision-makers' imagination regarding the long-term implications of environmental changes. They also facilitate comparative assessments of various management strategies, providing a valuable framework for informed decision-making (Hukkinen et al., 2024).

The PlanWise4Blue tool does not aim to synthesise objective realities and, in doing so, persuade and inform stakeholders of objectified problem definitions in relation to land–sea governance issues. Instead, it provides an interface for mediating environmental knowledge, enabling stakeholders to access and interpret objective scientific insights from local and regional observations or past experiences (Geurts et al., 2022). Environmental asset indicators are presented through an intuitive interface tailored to the needs of natural resource managers, offering practical support for decision-making (Downs et al., 2023). By bridging the gap between scientific research and practical governance, PlanWise4Blue offers robust, quantitative analyses that move beyond traditional expert-based assessments. Its co-development with stakeholders ensures alignment with real-world challenges, fostering transparency, inclusivity, and sustainability. The tool's versatility and adherence to a common methodological framework make it a valuable resource for policymakers and planners seeking to enhance the governance of coastal and marine environments.

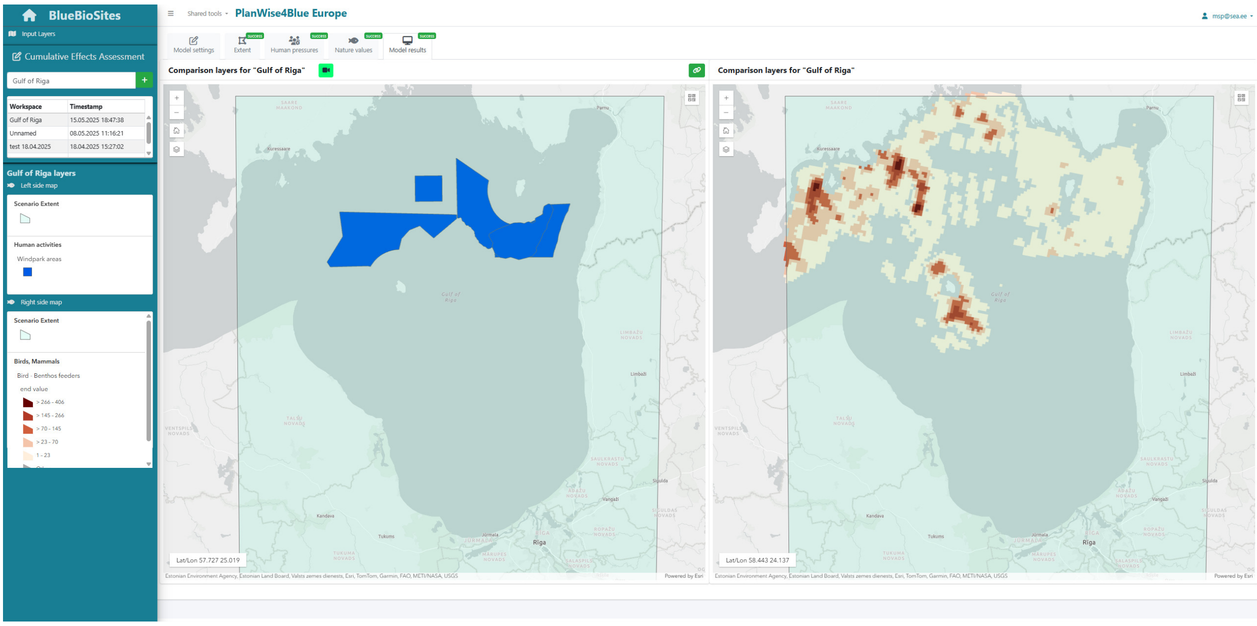

Figure 3. The PlanWise4Blue tool interface guides users through key steps in cumulative effect analysis, including defining the spatial extent, selecting human activities, choosing nature assets, and running the analysis. Notes: The results display provides various indicators, such as human use scenarios and changes in nature assets (e.g., benthos-feeding birds) based on the selected human activities; each scenario is saved in the user workspace, allowing for later modification; in addition, users can download the results as maps and summary statistics for further analysis and reporting.

4. Addressing Barriers and Unlocking Opportunities for PlanWise4Blue in Maritime Spatial Strategy and Environmental Management

Ensuring effective use of a web-based tool requires a clear understanding of barriers, constraints, and enabling factors. While technology holds significant potential, its successful implementation involves addressing challenges related to data management and integration, advanced modelling, stakeholder engagement, and institutional alignment.

From a data perspective, the PlanWise4Blue tool integrates information from various local to global repositories (e.g., Copernicus and the Ocean Biodiversity Information System), with regular updates reflecting current environmental conditions. However, the spatial resolution of these datasets may not be sufficient for local-scale analyses, necessitating the inclusion of locally specific maps. Employing machine learning algorithms and spatial modelling techniques can improve data accuracy, particularly in areas with sparse observational data, resulting in a more comprehensive depiction of marine ecosystems.

A persistent challenge is the lack of harmonized data products across European seas, leading to discrepancies that may reflect inconsistencies in datasets rather than true ecological differences. This issue is being addressed through initiatives like the European Digital Twin, which aims to provide more detailed and harmonized products in the future.

However, nature asset data in public repositories remains limited. While extensive datasets on physical and chemical conditions are accessible, comprehensive, fine-scale, pan-European data on underwater habitats, fish, birds, and mammals are scarce. Although the European Marine Observation and Data Network offers harmonized human activity data, its spatial resolution may be insufficient, and some layers may not be fully updated. To mitigate these limitations, PlanWise4Blue users can upload custom datasets or adjust existing human activity layers to better align with specific project needs.

Until now, data extraction for cumulative effect assessments has been performed manually, a process that is highly time-consuming and impractical for handling large datasets. However, with the rapid increase in available information and published evidence, there is an urgent need to transition to automated digital solutions. Future developments of the PlanWise4Blue tool will include an AI-driven multimodal information retrieval system to extract and process effect-related data from scientific publications for seamless integration into predictive models. While such AI systems are not yet available, our development team is currently working on designing the analysis pipeline. Current systems face challenges in processing visual and textual data together. To overcome this, the enhanced tool will batch-process PDFs, extracting data from tables, figures, captions, and text, aligning it within studies or experiments, and converting it into structured numerical formats. By employing a state-of-the-art AI retrieval pipeline validated through active learning with expert feedback, this system will significantly improve the efficiency and accuracy of environmental impact assessments.

One of the key social challenges is the disparity between the theoretical benefits of participatory processes and their actual implementation in practice. Many initiatives struggle to move beyond formal agreements, with participation often limited to paper-based commitments rather than active involvement. Inconsistent or sporadic engagement, particularly when certain stakeholder groups dominate discussions or when some are excluded, can lead to power imbalances and ineffective decision-making. These discrepancies hinder the potential of digital tools to foster equitable and inclusive governance.

Moreover, there are practical barriers to ensuring that technology is accessible to all relevant stakeholders. A lack of trust or willingness to engage with scientific data and models may prevent some groups from participating in the decision-making process. This is particularly true when stakeholders feel that their values and concerns are not adequately represented, leading to scepticism or even resistance. In such cases, overcoming these barriers requires careful management of expectations and the establishment of trust through transparent communication and ongoing dialogue. Addressing these challenges can be achieved by providing intuitive, user-friendly interfaces, implementing transparent methodologies, and actively incorporating stakeholder input throughout the process.

An essential factor for successfully implementing digital tools is establishing robust, multi-sectoral networks that promote collaboration across diverse stakeholder groups. Whether operating at local, national, or transboundary levels, these networks are important for integrating varied perspectives and values into the assessment process. By fostering these connections, the digital tool can act as a central platform for collaborative decision-making, combining data-driven insights with local and traditional knowledge.

Sustaining these networks requires adequate financial and human resources, as well as integrating the tool into broader initiatives such as the European Digital Twin. This would ensure continued support for the platform's operations and long-term impact. Furthermore, to maximize the effectiveness of digital tools, there is a need to develop a shared understanding among stakeholders. Creating a common narrative around key challenges and opportunities can bridge differing viewpoints and facilitate consensus on mutually beneficial solutions. While scientific data integration is important, presenting this information in a clear, accessible manner is equally vital. Effective communication ensures that technology becomes an inclusive tool for informed decision-making rather than a barrier to stakeholder engagement.

5. Conclusion

Coastal ecosystems are increasingly impacted by overlapping human-induced pressures, leading to cumulative effects that can undermine ecosystem resilience and push systems toward ecological tipping points. Addressing these complex interactions requires comprehensive, data-driven assessments that consider both direct and indirect effects over time and space. The PlanWise4Blue tool provides a valuable framework for integrating scientific data, predictive modelling, and stakeholder input to assess cumulative effects across marine and coastal environments. By enabling spatially explicit analyses of human activity scenarios and their potential environmental impacts, the tool supports evidence-based decision-making for sustainable marine management. The Baltic Sea case study illustrates the tool's capacity to identify impact hotspots, quantify stressor interactions, and inform strategic planning efforts, highlighting its potential as a valuable resource for harmonizing environmental management across regional seas.

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Conflict of Interests

The authors declare no conflict of interests.

Data Availability

This study did not generate any new data. All analyses were conducted using previously published or publicly available datasets.

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About the Authors

Jonne Kotta is a professor in marine ecology at the Estonian Marine Institute of the University of Tartu. His research focuses on benthic ecology, species interactions, nonindigenous species, GIS modelling, linking ecosystem functioning to services, bioeconomy, and climate change. He leads the development of digital decision-making tools to quantify the cumulative impacts of human activities on different nature assets.

Jean-Marc Douguet is a senior lecturer in economic sciences at the Paris-Saclay University. His research areas are part of an ecological economics and post-normal science perspective. He mainly focus on environmental evaluation, integrative analysis, circular economy, risk and environmental governance, knowledge mediation, and deliberative e-tools.

Elis Vollmer is a project manager at the Institute of Ecology, University of Tartu, and the head of the Centre of Renewable Energy at the Estonian University of Life Sciences. She has an MSc in environmental protection. She is a board member of CEESEN and leads the UN SDG workgroup at EMU.

Mihhail Fetissov is a research software engineer at the Estonian Marine Institute of the University of Tartu. His work focuses on the development of spatial decision support systems for ecosystem-based marine management, contributing both to their conceptual design and technical implementation.

Elisa Furlan is a senior scientist at Euro-Mediterranean Centre on Climate Change (CMCC) and scientific coordinator of the EU Mission projects DesirMED and GRACE. Her research focuses on transformative climate adaptation, nature-based solutions, and territorial resilience, with expertise in risk modelling and co-design. She also teaches at Ca' Foscari University of Venice.

Gea Grassi is a junior researcher at the RAAS (Risk Assessment and Adaptation Strategies) Division of CMCC, where she works on the BlueGreen Governance and TRANSEATION projects. Her research focuses on strategic foresight, generative AI, and climate change adaptation in marine-coastal ecosystems, with a focus on land–sea interface.

Federica Zennaro is a postdoctoral researcher at the Euro-Mediterranean Centre on Climate Change (CMCC), where she works on European projects focusing on blue-green governance and nature-based solutions. Her work advances innovative land–sea governance frameworks based on scientific evidence and societal input and monitors the effectiveness of marine and coastal nature-based solutions.

Hector Charles Pagan MPA is the executive director of CEESEN and has taught and conducted research on stakeholder engagement for almost 20 years. He has also worked in the civil society sector for over 25 years and has led or participated in multiple applied research projects focused on local governance and sustainability.

Helen Orav-Kotta is a marine ecologist and associate professor of marine biology at the Estonian Marine Institute at the University of Tartu. Her activities focus on marine conservation and climate change, blue economy development, and teaching blue literacy to various stakeholders and dissemination to the public (policymakers, students, companies, and communities).