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Spatial Cumulative Assessment of Impact Risk-Implementing Ecosystem-Based Management for Enhanced Sustainability and Biodiversity in the Black Sea

Elena Bisinicu [1,*], Valeria Abaza [1], Laura Boicenco [2], Filimon Adrian [1], George-Emanuel Harcota [1,3], Oana Marin [1], Andra Oros [4], Elena Pantea [1], Alina Spinu [5], Florin Timofte [2], George Tiganov [6], Oana Vlas [1] and Luminita Lazar [4,*]

1 Ecology and Marine Biology Department, National Institute for Marine Research and Development "Grigore Antipa", 300 Mamaia Blvd., 900581 Constanta, Romania; vabaza@alpha.rmri.ro (V.A.); afilimon@alpha.rmri.ro (F.A.); gharcota@alpha.rmri.ro (G.-E.H.); omarin@alpha.rmri.ro (O.M.); epantea@alpha.rmri.ro (E.P.); ovlas@alpha.rmri.ro (O.V.)
2 National Institute for Marine Research and Development "Grigore Antipa", 300 Mamaia Blvd., 900581 Constanta, Romania; lboicenco@alpha.rmri.ro (L.B.); ftimofte@alpha.rmri.ro (F.T.)
3 Doctoral School of Ecology, University of Bucharest, 030018 Bucharest, Romania
4 Chemical Oceanography and Marine Pollution Department, National Institute for Marine Research and Development "Grigore Antipa", 300 Mamaia Blvd., 900581 Constanta, Romania; aoros@alpha.rmri.ro
5 Chemical Oceanography and Coastal Engineering Department, National Institute for Marine Research and Development "Grigore Antipa", 300 Mamaia Blvd., 900581 Constanta, Romania; aspinu@alpha.rmri.ro
6 Living Marine Resources Department, National Institute for Marine Research and Development "Grigore Antipa", 300 Mamaia Blvd., 900581 Constanta, Romania; gtiganov@alpha.rmri.ro
* Correspondence: ebisinicu@alpha.rmri.ro (E.B.); llazar@alpha.rmri.ro (L.L.)

Abstract: Marine ecosystems are becoming increasingly vulnerable to cumulative anthropogenic effects and pressures. Therefore, various methodological approaches and tools have been designed to apply cumulative impact appraisal schemes and better assess the dynamics and interactions among pressures affecting marine ecosystems. This study aims to apply the Spatial Cumulative Assessment of Impact Risk for Management (SCAIRM) tool for the Black Sea coastal waters considering human activities, pressures, and effects on different ecosystem components coupled with one management scenario development for actual and new emerging sectors. According to the SCAIRM, the primary pressure on the marine ecosystem was identified as introducing or spreading non-indigenous species from shipping. Additionally, when considering cumulative impact, activities related to coastal defense and flood protection, particularly beach nourishment works, were found to have the highest impact. This is due to the cumulative scores associated with the physical loss from permanent alteration or removal of seabed substrates, and temporary or reversible physical disturbances to the seabed. The scenario development indicated that after shipping, oil and gas exploitation is anticipated to become the second-highest risk sector for additional impact in the Romanian Black Sea. Additionally, the increased military activities related to the war in Ukraine present escalating risks that must be considered in EBM strategies. The results assess the possible effects of human activities and the associated pressures to direct management toward achieving sustainability, biodiversity protection, and the marine ecosystem's integrity.

Keywords: ecological pressures; management scenarios; marine ecosystem; cumulative impact; habitat effects; Black Sea

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1. Introduction

The undeniable importance of marine ecosystems and the significant human-induced pressures they face is broadly acknowledged [1–5]. Coastal zones stand as some of the most productive regions globally, offering a diverse array of ecosystem goods and services.

Given that one-third of the global population resides within a 50 km proximity to coastlines, numerous human activities, both ocean- and land-based, benefit from these services [6–10].

The excessive utilization and insufficient management of ecosystem services, including overexploitation, habitat degradation, and pollution, have imposed immense stress on marine systems [11–13]. The challenges related to the environment become particularly pronounced in coastal areas due to their transitional position between land and sea, coupled with an increased concentration of anthropogenic load from diverse activities [14]. The significance of these environmental issues extends beyond economic considerations, as they directly influence social and ethical aspects of life [15,16]. Consequently, this endangers the future of marine ecosystems and the vital services they provide [12,13]. The outcomes of ineffective traditional management systems, coupled with the aspiration to revive and sustain ecosystem health, have urged a call for change. Although there may not always be unanimity regarding the precise path management should follow, there is widespread agreement on the necessity for enhancements in conventional management practices [5].

There is an urgent need to comprehend the spatiotemporal impacts of both direct factors (such as fishing, sea-use change, and climate change) and indirect factors (including human population growth, per capita income, and technological advances) influencing changes in marine ecosystems. This comprehension is vital for preserving or restoring essential ecosystem functions and associated services, as well as for anticipating future impacts [17,18]. It becomes particularly crucial in our pursuit of the United Nations Sustainable Development Goal 14 (SDG 14), which centers on "conserving and sustainably using the oceans, seas, and marine resources for sustainable development," alongside other interconnected SDGs [19–21]. To direct management efforts toward the objectives of sustainability, the preservation of biodiversity, and the integrity of the marine ecosystem, it is essential to assess all relevant human activities and the pressures linked to them [22].

Ecosystem-based management (EBM) has become a practical strategy that unites organizations and individuals from various industries to manage and safeguard natural resources and biodiversity collaboratively [5]. To support decision-making, EBM utilizes scientific knowledge and integrates crucial elements, including the interrelationships within ecosystems and their connections to social and economic systems. It considers the combined impacts of diverse activities, both within individual actions and across them, employing adaptive management techniques. EBM considers multiple goals across diverse services or sectors and assesses trade-offs [23,24]. Consequently, EBM takes on the characteristics of a dynamic, flexible, and iterative management approach that adapts based on the spatial scale (local, regional, and ecosystem) of the managed natural resources [25,26].

Utilizing data on ecosystem services, functions, and processes, EBM aims to sustainably manage biodiversity and natural resources [27]. Recognizing the dynamic nature of ecosystems and the importance of evaluating the effectiveness of management actions are crucial aspects of EBM because it relies on the principles of sustainable development, acknowledging that our ability to control human activities is limited, while the ecosystem behavior is beyond our direct management [28]. There is widespread consensus that managing the increasing human utilization of the marine environment necessitates an ecosystem-based approach [6,11,12,29]. This understanding is vital for a more comprehensive assessment and definition of the associated socioeconomic benefits [30].

A crucial element in any policy-relevant ecosystem-based management initiative is the regular evaluation of the policy objectives. In Europe, the integration of EBM is embedded in four primary policy instruments for marine governance, which are as follows:

- The Marine Strategy Framework Directive (MSFD; 2008/56/EC) seeks to attain or sustain 'Good Environmental Status' (GES) in European marine waters.

- The EU Biodiversity Strategy to 2030 (COM (2020) 380) attempts to stop the loss of biodiversity and ecosystem services by safeguarding a minimum of 30% of the sea and establishing a network of marine protected areas (MPAs).
- The Common Fishery Policy (CFP, 1380/2013) targets, among other goals, a shift from traditional single-stock management toward ecosystem-based fishery management (EBFM).
- The Maritime Spatial Planning Directive (MSP, EC 2014/89/EU) is established to foster sustainable growth in maritime economies, the sustainable development of marine areas, and the sustainable utilization of marine resources [31].

Incorporating economic and sociocultural factors into integrated ecosystem assessments is crucial, as the MSFD recognizes its pivotal role in guaranteeing the sustainable use of marine resources [32].

The SCAIRM (Spatial Cumulative Assessment of Impact Risk for Management) is a specialized cumulative impact assessment (CIA) designed by Piet et al. 2017 [33] specifically to support EBM. The methodology introduces impact risk (IR) as the central concept, enabling the aggregation of impacts across various pressures. Numerous risk-based approaches to assessing IR in different forms have been proposed in the literature [6,33–36]. Recently, Piet [37] presented a roadmap toward achieving a fully quantitative calculation of the IR, defined as the potential change in the equilibrium state (i.e., biomass or abundance compared to undisturbed) of the receptor caused by a stressor [38].

The goal of the SCAIRM approach is to integrate the benefits of quantitative and categorical risk-based methodologies. To guarantee the conceptual alignment between the IR resulting from cumulative pressures and the results of quantitative procedures, it modifies categorical approaches. The combination of qualitative and quantitative methods into one cohesive strategy is made possible with this integration. Its comprehensiveness allows for accessible quantitative information in data-rich scenarios while making it appropriate for scenarios with minimal data. In the end, this strategy strengthens the ability to provide operationally focused recommendations and inform policy, both of which are essential for sectoral management [38].

Our research focuses on two main inquiries: (a) identifying human activities and pressures with the greatest risk within the Black Sea environment and (b) comprehending the variations in risk levels from human activities and pressures and developing one management scenario for emerging sectors and pressures. We utilize the SCAIRM approach to explore how its adoption can contribute to implementing integrated EBM in the Black Sea, incorporating information about ecological pressures gathered through a literature review and expert judgment.

The Black Sea is a semi-enclosed sea; the only connection to the world's oceans is the narrow Bosphorus Strait. It stretches between latitudes 40°550 and 46°320 N and longitudes 27°270 and 41°320 E. To the south, it joins with the Mediterranean via the Bosphorus, which is one of the world's narrowest straits, with an average width of 1.6 km, a depth of 36 m, and a total length of 31 km [39]. In the north, it links to the Sea of Azov through the shallow Kerch Strait, which has a depth of less than 20 m. The Black Sea is bordered by six countries in Europe and Asia: Bulgaria, Georgia, Romania, Russia, Turkey, and Ukraine. In actuality, the dynamics of the Black Sea are influenced by 17 countries in its basin, 13 capital cities, and approximately 160 million people [39]. Significantly, the second, third, and fourth longest rivers in Europe—the Danube, Dnieper, and Don—flow into this sea, thereby impacting nearly one-third of the entire land area of continental Europe [39].

Given the coexistence of diverse human activities within this semi-enclosed area, effective planning and increased cooperation between countries are imperative due to the limited nature of the basin [40]. To promote the Blue Economy in the region, the Black Sea riparian countries and the Republic of Moldova endorsed the Black Sea Strategic Research and Innovation Agenda (SRIA) and the Common Maritime Agenda for the Black Sea (CMA) in May 2019 [41]. Despite efforts to promote a Sustainable Blue Economy and enforce the European Green Deal to mitigate human impacts on marine ecosystems, along with their associated services and societal advantages [42], there is an expectation that maritime and upstream activities, driven by increasing human demands [43,44], will continue to increase.

The SCAIRM was already used as a tool for evaluating the Black Sea status, within the ODEMM (Options for Delivering Ecosystem-Based Marine Management) project, which concentrated on establishing the necessary structure, tools, and resources essential for the selection and evaluation of management options aligned with the principles of EBM. ODEMM's reports [6] established a knowledge base that outlined the environmental conditions, trends, pressures, and impacts in European regional seas, including the Black Sea. This information is relevant for the description of marine conditions and for addressing issues of Maritime Spatial Planning and marine strategies.

These approaches aid environmental managers in decision-making by providing a versatile, problem-solving solution that establishes links between human activities and ecosystem components [33]. To effectively manage the impacts of pressures on aquatic ecosystems, a fundamental understanding of the pathways through which human activities influence ecosystem components is crucial. When it comes to mitigating the impacts of pressures mediated by activities, it becomes imperative to distinctly identify the connections between activities, pressures, and the affected ecosystem components [36]. Utilizing a specific set of tools and techniques tailored to a given situation can facilitate problem-specific management solutions. However, this approach necessitates careful consideration of the quantity and nature of data, along with the social and ecological context [27].

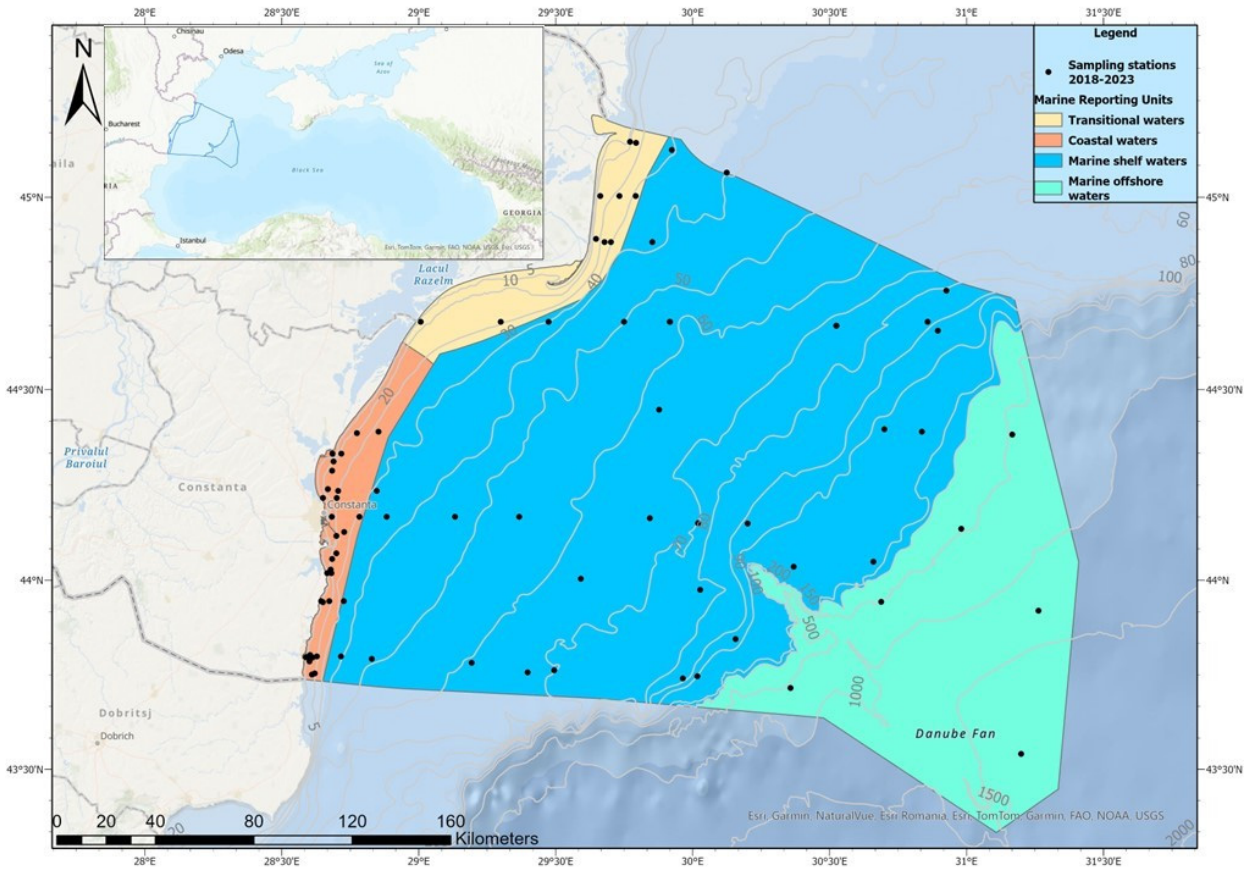
Consequently, this study aims to apply the Spatial Cumulative Assessment of Impact Risk for Management (SCAIRM) tool to assess the impact risks of human activities and associated pressures on different ecosystem components in the Romanian Black Sea.

2. Material and Methods

To address the research questions in this study, we developed inventories for activities and pressures applicable to the Romanian Black Sea (Figure 1a,b), the pressures exerted by these activities, and the ecosystem components affected by those pressures to apply the SCAIRM. In addition, we identified emerging sectors and pressures for one scenario development.

The application of SCAIRM involved identifying sectors and pressures according to the MSFD [45], specifying activities by sector, and detailing the pressures (2.1). Subsequently, for each activity and pressure, the related ecosystem components were defined (2.2). The relationship between activity, pressure, and ecosystem components was established according to the MSFD [45], expert judgment, and the available literature [6,33,35,46,47]. In calculating the impact risk, each activity, pressure, and ecosystem component was evaluated within the impact chain, which included (i) extent, (ii) dispersal, (iii) frequency, (iv) persistence, and (v) severity (2.3). The methodology for assigning scores is described in the Supplementary Materials (Tables S1 and S2).

Data analyses were conducted using PRIMER v. 7.0 [48], and Power BI (Microsoft) was used for data visualization. Multivariate analysis utilizing the Bray–Curtis similarity was carried out on data that had undergone fourth square-root transformation, employing PRIMER 7 [48]. These data were then employed to generate a similarity matrix based on the Bray–Curtis similarity index. Subsequently, these matrices were used in hierarchical cluster analysis (CLUSTER) to evaluate similarities among activities, pressures, and ecosystem components. Maps were produced with ArcGIS Desktop 10.7 [49].



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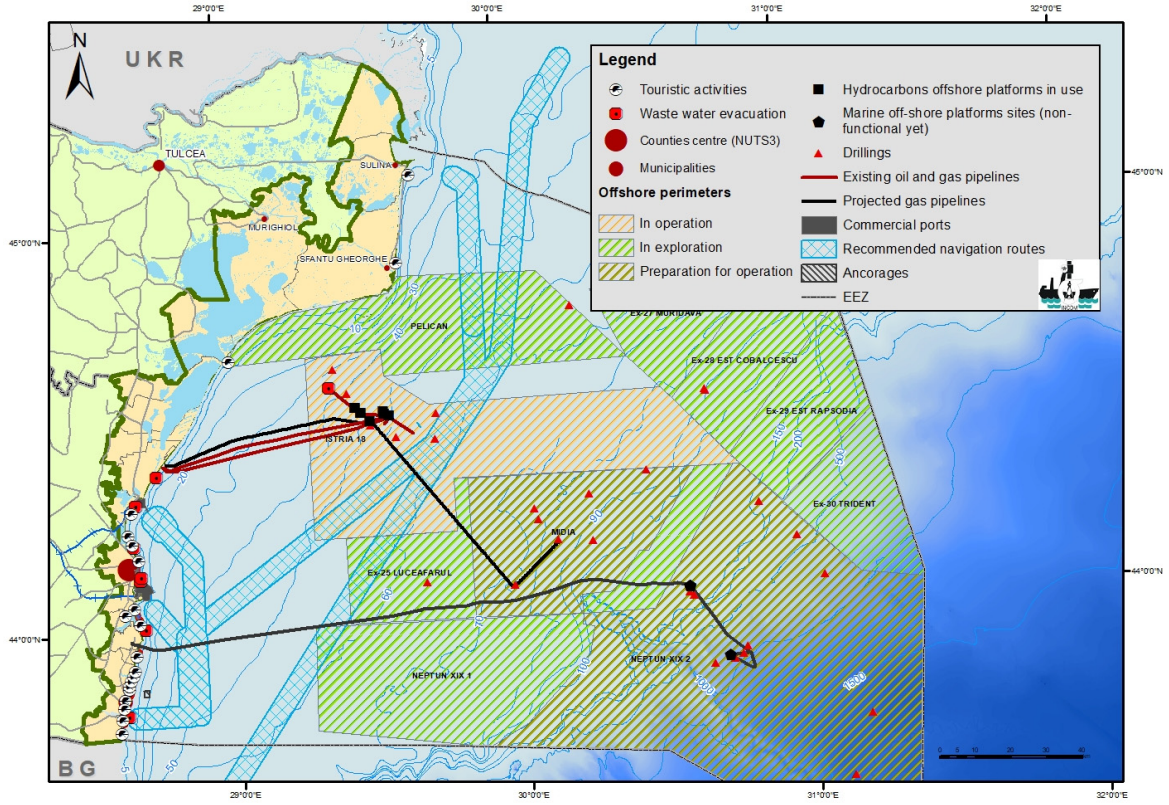

(**b**)

Figure 1. (**a**) Map of the study area; (**b**) activities applicable to the Romanian Black Sea.

2.1. Typologies of Activities and Pressures

To achieve its objectives, this study employed diverse methods to collect data. The analysis began by exploring the coastal, marine, and maritime human activities, as well as economic sectors. Each specific activity and pressure was analyzed by the ecosystem component expert based on the data and expertise achieved in different national and European projects like ANEMONE (Assessing the Vulnerability of the Black Sea Marine Ecosystem to Human Pressures, http://www.anemoneproject.eu/ (accessed on 1 April 2024)) and Administrative Capacity Operational Program 2014–2020 (priority axis IP12/2018 under project code MySMIS 127598/SIPOCA 608 "Improving the capacity of the central public authority in the field of marine environment protection in terms of monitoring, evaluation, planning, implementation and reporting of requirements set out in the Framework Directive Marine Strategy and for integrated coastal zone management"). These factors generate pressures on the marine ecosystem, potentially amplifying their impact on components. We adopted the classifications for activities and pressures by referencing previous categorizations established in the Marine Strategy Framework Directive, specifically the Annex III of the EU Directive 2017/845 amending Directive 2008/56/EC of the European Parliament and of the Council as regards the indicative lists of elements to be taken into account for the preparation of marine strategies and by the designation of seabed conservation features, as mandated by the Habitats Directive 92/43/EEC (Table S1). Thus, the assessment focused on the five most important sectors (urban uses; extraction of oil and gas, including infrastructure; transport; coastal defense and flood protection; and fish and shellfish harvesting). Additionally, it examined seven specific activities within these sectors (wastewater treatment plants, oil and gas exploitation, shipping, coastal protection infrastructure, beach nourishment, benthic trawls and dredges, and harvesting by scuba diving) were used in the assessment.

The assessment evaluated pressures from these activities based on the available expertise—two biological (input or spread of non-indigenous species and extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities)); three physical (physical disturbance to seabed (temporary or reversible), physical loss (due to permanent change in seabed substrate or morphology and the extraction of seabed substrate), and changes to hydrological conditions); and three from substances, litter, and energy category (introduction of nutrients and organic matter and introduction of other substances). To enhance the evaluation and distinction, some of the pressures on ecosystem components were divided into 17 specific pressures (Table S1).

In the scenario of emerging or intensifying activities and pressures, we considered the development of renewable energy sources (wind power), including their infrastructure, as well as marine aquaculture and expansions in oil and gas, shipping, and military operations. Additionally, we identified two new pressures: the introduction of litter (including microsized particles) and other forms of energy, such as electromagnetic fields, light, and heat.

2.2. Classification of Aquatic Ecosystems Considering Components

The hierarchical classification system employed for aquatic ecosystems in this context extends across 11 ecosystem components (ECs) (Table S1), according to MSFD and the Habitats Directive, including broad habitat types of the water column (pelagic) and seabed (benthic), as well as other habitat types. Moreover, for a better evaluation, the ecosystem components were detailed into 31 specific subcomponents (Table S1).

2.3. Identifying and Allocating Weights to Impact Chains

We established 45 specific impact pathways from activities to pressures and from pressures to ECs. The identified activity–pressure–EC chains provided a comprehensive list of impact chains according to several studies [33–38,47,50]. Each distinct impact chain was then assessed and assigned weights based on five criteria: (i) extent, (ii) dispersal, (iii) frequency, (iv) hazard, (v) magnitude, (vi) behavior, and (vii) resilience (Table S2) [34–38,47]. The extent

reflecting the overlap of each activity with each EC was evaluated by considering the spatial distribution of human activities and ECs in the area and the degree of spatial overlap between them [36].

Based on these criteria, the methodology uses the following equations for the calculation of the impact risk according to Borgwardt et al. (2019) [36]:

$$Exposure = (Extent + Dispersal) - (Extent * Dispersal)$$

$$Resistance = 1 - Hazard * Magnitude$$

$$Recovery = \frac{ln(50)}{Resilience}$$

$$Depletion = ln(1/If(Resistance > 0.0000001,\ Resistance,\ 0.0000001)$$

$$Effect\ Potential = \frac{Depletion\ Rate\ (yr^{-1})}{Depletion\ Rate\ (yr^{-1}) + Recovery\ Rate\ (yr^{-1})}$$

$$Impact\ Risk\ (IR) = Exposure * Effect\ Potential$$

The *Impact Risk* (*IR*), which is defined as the change in the equilibrium state (i.e., biomass or abundance) of the receptor brought on by a stressor, is the primary output of the SCAIRM that permits cumulation across various pressures [37,38]. "Exposure∗Effect Potential" formula t was used to determine the impact potential for each interconnected activity, pressure, and ecosystem component. It can also be evaluated by looking at the spatial distributions of the receptor (an EC), the stressor (activities and associated pressure(s)), and several population dynamics characteristics. Assessing the risk of impact involves analyzing how various human activities can potentially impact the ecosystem. The impact is considered in terms of how it alters or degrades the ecosystem. Determining the potential risk from exposure and its effects involves evaluating the extent of exposure to these activities and the effect by looking at the magnitude and duration of exposure to the stressors (i.e., activities and pressures). Additionally, factors like population dynamics parameters, including resilience and resistance, contribute to understanding and determining the overall risk (Figure 2).

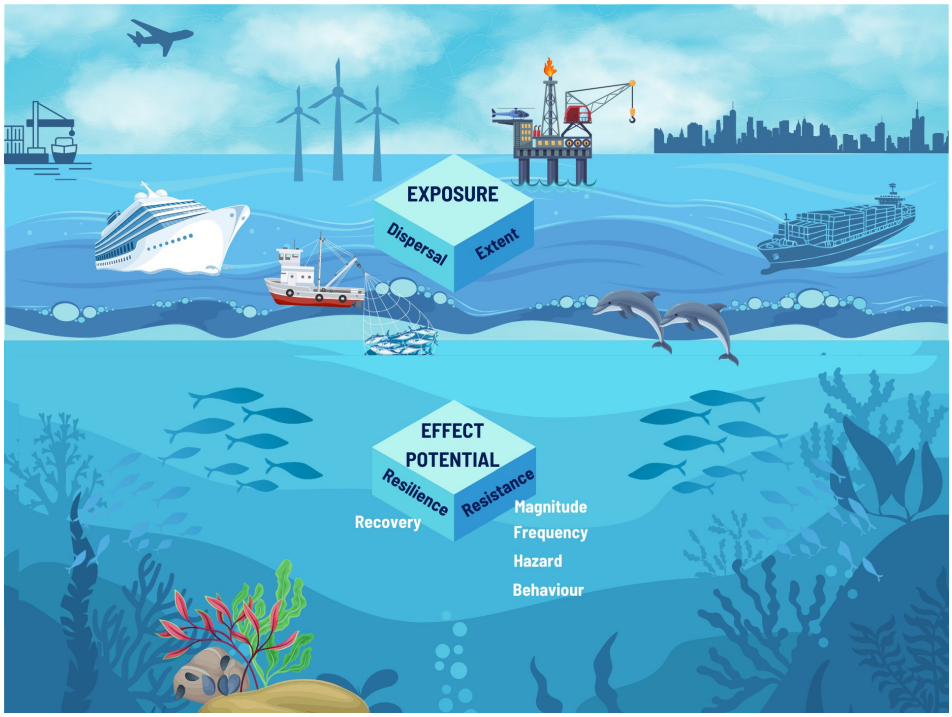

Figure 2. The elements of impact risk assessment for marine ecosystems.

Human activities constantly change ecosystems, making them dynamic rather than static [51]. Climate fluctuations, driven by various factors, constantly affect organisms, and these fluctuations do not follow predictable patterns [51,52]. It is crucial for ecological theories to understand this and not assume that the present reflects the past accurately. We need to be ready for a future shaped by human actions [51,52]. By seeing ecosystems as adaptable and recognizing their history, we can better prepare for the significant changes humans bring and understand that most ecosystems never truly reach a stable balance [51].

Despite the inherent dynamism of ecosystems, managers must still possess tools to assess the potential risks posed by human activities. Such assessments allow for proactive measures to be taken, helping to safeguard ecosystems and the services they provide to both human communities and biodiversity [53]. In essence, while ecosystems are constantly changing, the need for effective management tools remains paramount in navigating the intricate relationship between humans and the natural world [54].

The IR is evaluated through the assessment of scores assigned to seven criteria. These criteria include (1) the spatial (extent), (2) dispersal, and (3) temporal (frequency) overlap between a pressure generated by a particular sector of human activities and ecological characteristic, collectively characterizing the exposure of the ecological component to a sector–pressure combination in terms of their spatiotemporal concurrence; (4) hazard; (5) magnitude; (6) behavior; and (7) the resilience of the ecological characteristic (recovery time in years) [33,34,36–38,47] (Figure 2, Table S2).

3. Results

3.1. Description of the Activities and IR

The key sectors linked to the Romanian Black Sea littoral are related to urban uses, coastal defense and flood protection, maritime transport, fish and shellfish harvesting, and extraction of oil and gas. Specifically, in terms of the main activities, our assessment focused on the impact of wastewater treatment facilities with direct outflows into the Black Sea, including those at Rompetrol, Constanta Nord, Constanta Sud, Eforie, and Mangalia. In 2017, 51% of the total wastewater discharged into the Romanian Black Sea was insufficiently treated and might contribute to the risk of not achieving GES for the eutrophication of the marine waters [55]. In 2018, out of the five WWTPs directly discharging into the Black Sea, only three were compliant with Urban Wastewater Treatment Directive (UWWTD) requirements [55]. Additionally, significant beach nourishment efforts across the central and southern sections of the Romanian coast play a crucial role. In 2020, the significant beach nourishment project conducted by the Romanian water Authorities reported for its first phase an increase of 60.66 ha in beach areas [56]. The principal maritime ports of Constanta, Mangalia, and Midia serve as the main harbors for incoming vessels. However, following the war in Ukraine, the port of Sulina has also gained prominence. As the largest port on the Black Sea, Constanța boasts a handling capacity of approximately 1.8 million twenty-foot equivalent units (TEUs) annually, with the potential to increase to 2.5 million TEUs, thanks to its access to inland transportation and sea navigable routes. The Port of Constanța serves as a crucial maritime and riverine hub due to its connection to the Danube–Black Sea Channel, facilitating substantial cargo movement between Constanța and countries in Central and Western Europe [57]. The national fishing fleet predominantly comprises small-scale vessels, specifically those under 12 m in length. Romania's 2022 registry listed 171 fishing vessels, with 145 of them measuring less than 12 m. Additionally, there were five significantly larger vessels, ranging from 18 to 40 m in length. The total marine catch and landings for the year amounted to 3017 tonnes. The primary species caught was the rapa whelk (*Rapana venosa*), accounting for 77% of the total marine catch volume. The fleet also focused on the Mediterranean mussel (*Mytilus galloprovincialis*), which represents 14% of the catch volume, along with other species like turbot (*Scophthalmus maximus*), European anchovy (*Engraulis encrasicolus*), and red mullet (*Mullus barbatus*), which collectively make up less than 10% of the annual catch volume [58].

In 1975, Romania installed its first offshore platform in the Black Sea at a depth of 84 m to conduct exploration, which revealed no significant oil deposits. It was not until 1987 that the first oil production in the Black Sea commenced with the Lebada East field. Today, the Black Sea contributes to approximately 8% of Romania's total oil production, with OMV Petrom leading the extraction efforts. OMV Petrom is actively involved in both shallow and deep-water operations, producing around 31,000 barrels of oil equivalent daily, and is expected to significantly increase production in the Neptun Deep field from 2027 [59,60].

Additional factors affecting the marine environment are associated with harbor and coastal activities. Processes such as dredging and coastal and offshore construction (such as the development of oil/gas facilities, pipelines, coastal protection structures, wave breakers, etc.) pose threats to benthic communities [39].

Our study revealed that activities such as shipping, followed by coastal defense and flood protection, exert the highest impact on ecosystem components (Figure 3). Among the 45 linkages from 5 sectors, coastal defense and flood protection were observed in 11 instances, while shipping was identified in 28 instances.

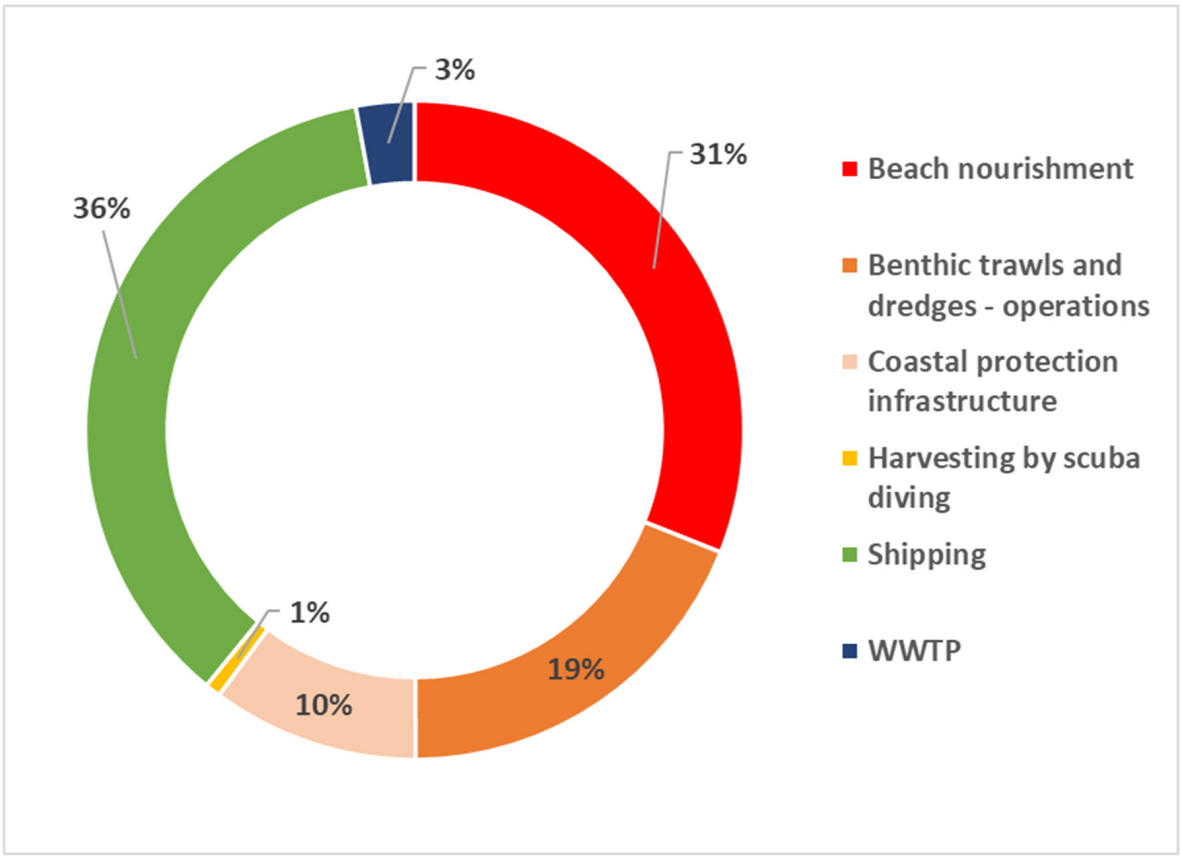

Figure 3. Percentage of IR grand total by activities at the Romanian Black Sea.

Clusters showing high similarity (77%) of IR were identified between shipping and beach nourishment. When combined with benthic trawling and dredging operations, these specific activities formed a group with an IR similarity of 97% (Figure 4). However, the formation of the latter cluster does not diminish the importance of other activities but emphasizes prioritizing them.

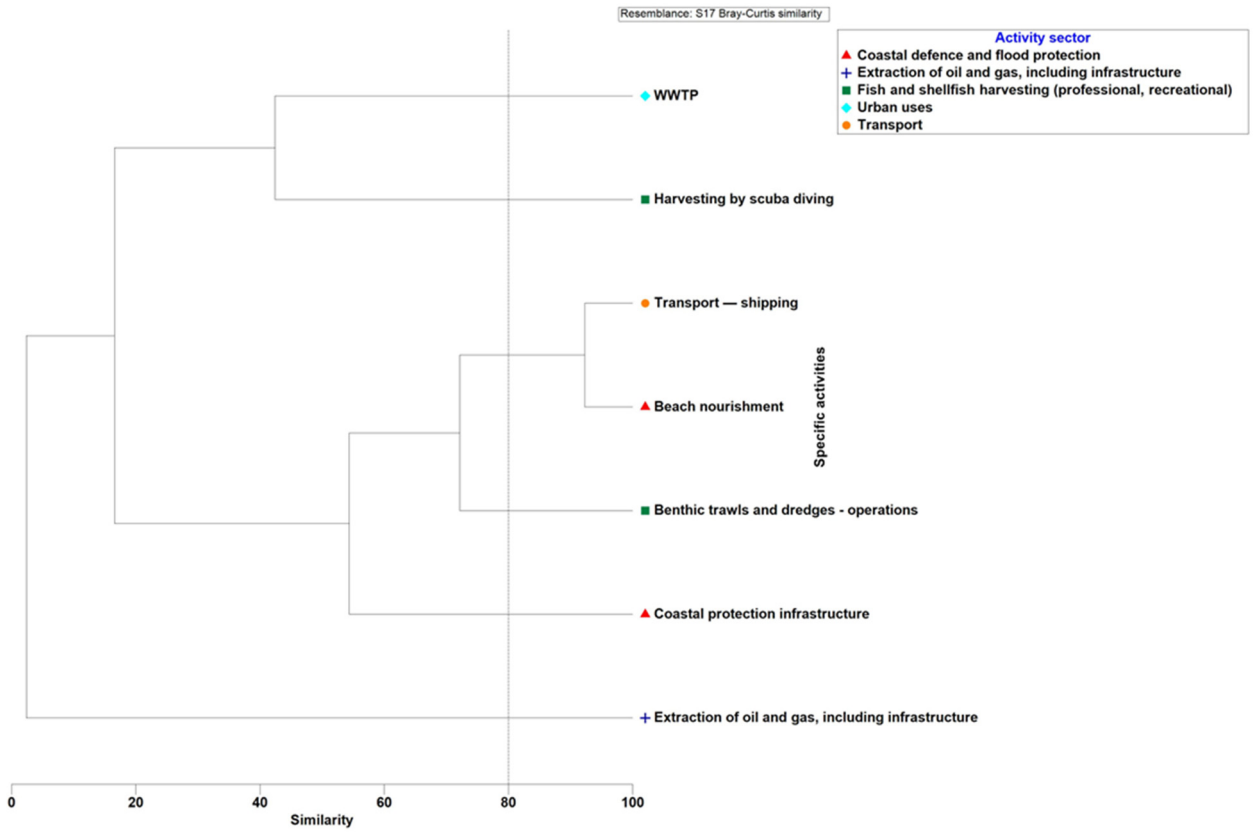

Figure 4. Bray–Curtis similarity based on activities and impacts on the ecosystem components at the Romanian Black Sea.

Over the past decade, soft bottoms in the NW Black Sea, particularly areas near deep-sea mussel beds, have been targeted by beam trawl fisheries for the rapa whelk—an invasive gastropod species *Rapana venosa* (Valenciennes, 1846) that is posing a potentially harmful impact [61]. In 2013, the utilization of beam trawl fishing gear for the commercial harvesting of the rapa whelk was authorized in Romania. Since then, these fishing methods have been widely employed in the central and northern regions of the Romanian coast, primarily on sandy and muddy seabeds [62]. Assessing the sustainability of the impact of beam trawling on benthic species is integral to an ecosystem-based approach to fishery management. Bottom-dwelling species play a vital role in benthic–pelagic coupling, facilitating the transfer of organic matter from the water column to the seabed, representing a crucial food source for demersal fish [61,63,64]. Beam trawling, increasingly common along the Romanian coast in recent years, is considered highly disruptive. Additionally, dredging and associated activities, like the occasional placement of dredged materials, have the potential to harm the marine ecosystem [64]. This harm can manifest through sediment release into the water, habitat disruption, species displacement or disappearance, organic matter enrichment in sediments, and the recycling of pollutants. Unsustainable practices result in ecological losses, such as decreased biological productivity (e.g., depleted mollusk stocks), leading to reduced economic efficiency and incomes [61,64].

3.2. Description of Pressures and IR

The pressures were represented by input of non-indigenous species, physical loss, and physical disturbance of the seabed (Figure 5), because of the main identified activities. The main pressure (introduction of non-indigenous species) was detected in 21 out of 45 instances, followed by physical loss occurring 7 times, and the input of other substances was noted 6 times.

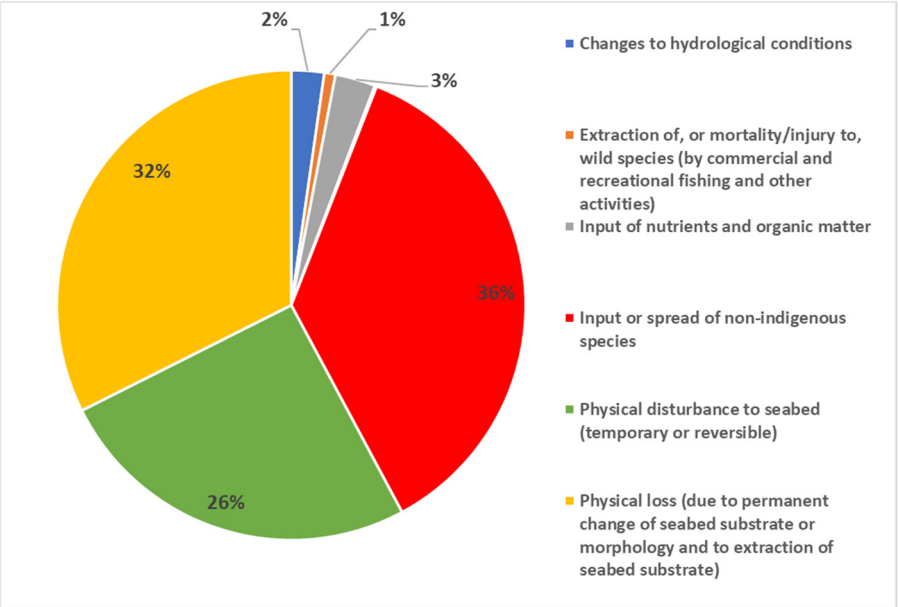

Figure 5. Percentage of IR grand total by pressures at the Romanian Black Sea.

The input of non-indigenous species primarily affects all planktonic organisms and the benthic component (Figure 6). Clusters of high IR similarity were observed between pelagic habitats, infralittoral mud and infralittoral rock, and biogenic reef, as a result of the main identified pressures represented by non-indigenous species, changes to hydrological conditions, and extraction of wild species (Figure 7).

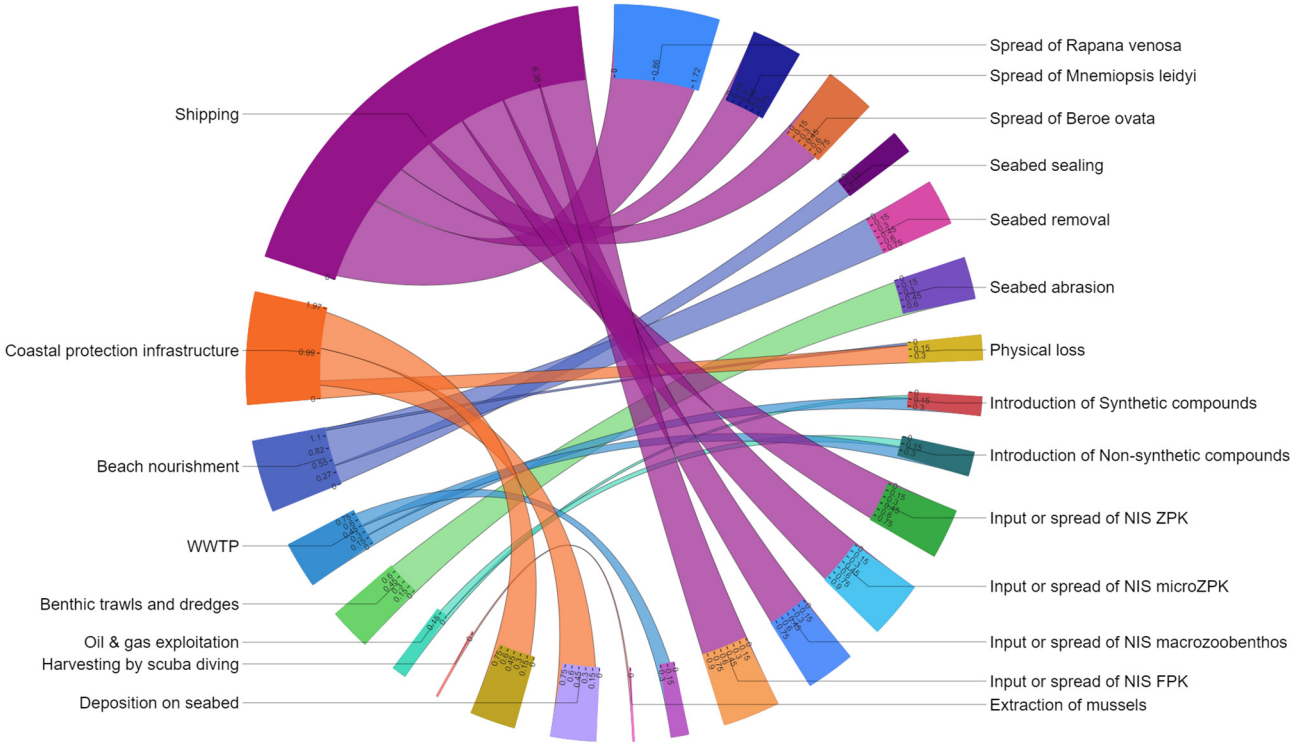

Figure 6. Sankey diagram of specific activities–pressures–ecosystem components in the Romanian Black Sea (2018–2023).

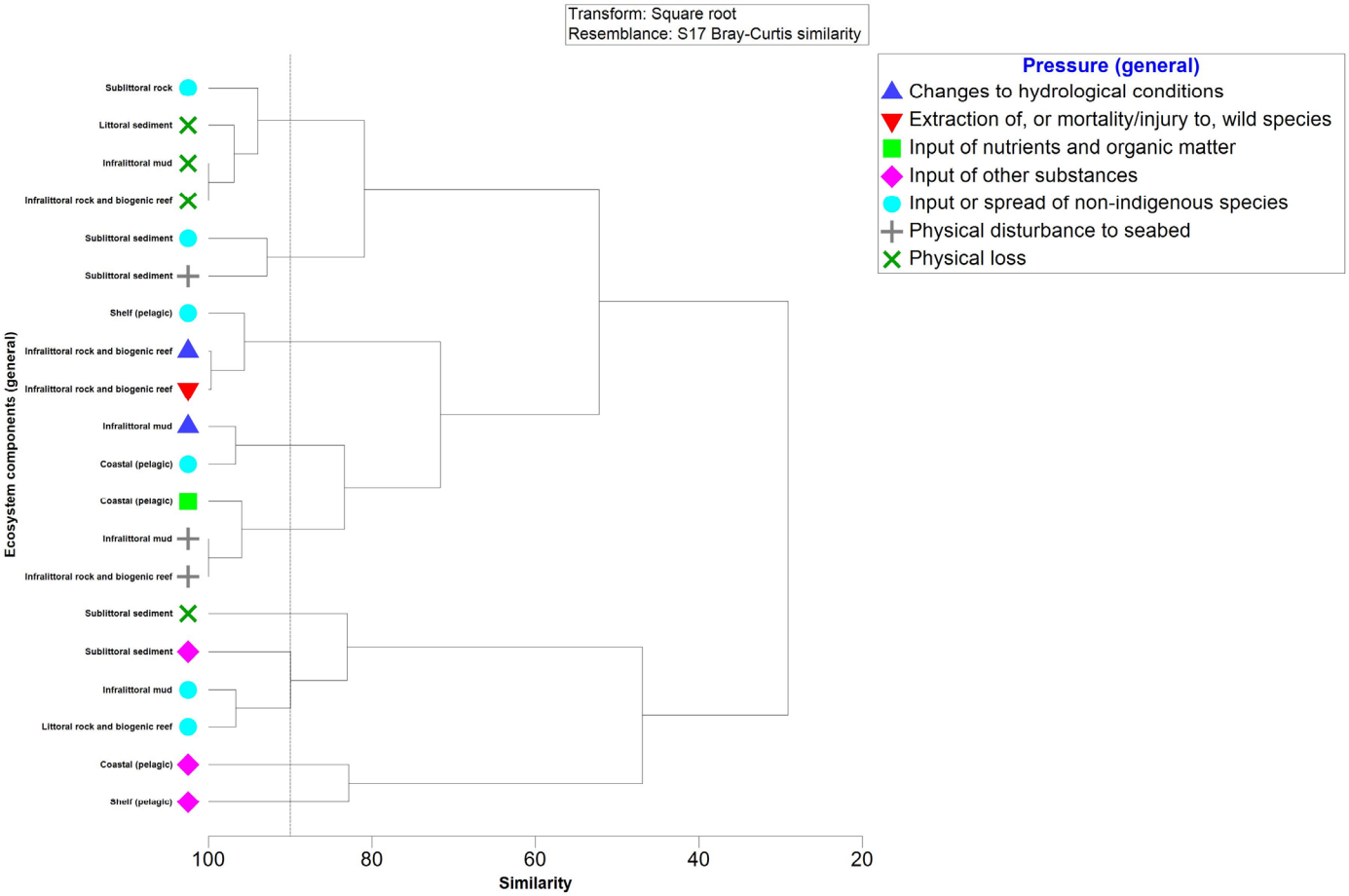

Figure 7. Bray–Curtis similarity based on pressures and impacts on the ecosystem components at the Romanian Black Sea.

3.3. Description of Activities and Pressures Related to Ecosystem Components

Data indicate the minimal effects of urban development and oil and gas extraction on marine ecosystems, which primarily involve the introduction of nutrients, organic matter, and other substances into the water and sediment. The most significant issue along the Romanian coast is the introduction or dispersion of non-indigenous species by the shipping industry. This is followed by the physical loss by permanent alteration or removal of seabed substrates, which primarily occurred during beach nourishment projects. Furthermore, when considering the addition of temporary or reversible physical disturbances to the seabed, coastal defense and flood protection efforts pose the greatest overall risk of cumulative impact (Figure 8). This approach reveals that the benthic component involves higher levels of risk. Additionally, it underscores the significant challenges facing marine biodiversity, particularly the organisms that inhabit the seabed. These species are especially vulnerable to disruptions caused by human activities, such as sediment displacement and habitat degradation, which are often exacerbated by beach nourishment works (Figure 8, Table S3).

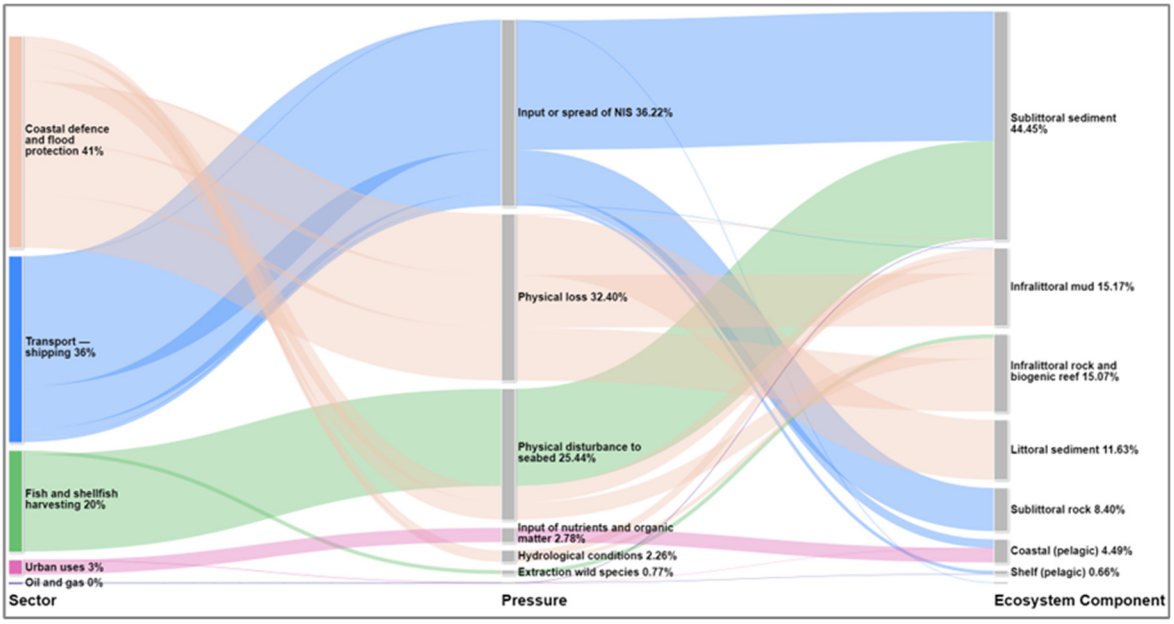

Figure 8. Linkages (45) between sectors (5), their pressures (8), and impacts on the broad ecosystem components (11) at the Romanian Black Sea.

Organizing the ecosystem components based on activities, clusters of 100% similarity of IR for the pelagic habitat, attributed to shipping activities and wastewater treatment plants (WWTPs), were observed based on the introduction of nutrients and organic matter pressure (Figure 9). Similarly, the benthic component formed high-similarity clusters due to shipping, beach nourishment, and WWTPs. Beach nourishment directly and indirectly suppresses benthic macrophytes by depositing substantial amounts of silty mud. Fish and shellfish harvesting pose a threat to the marine ecosystem, and dredging operations and certain fishing practices not only damage bottom landscapes and biocenoses but also exert a significant impact on the overall ecosystem. Notably, WWTPs impact macroalgae and seagrass, with these components also affected by beach nourishment. Shipping activities pose a threat to the benthic community, particularly in the circalittoral and infralittoral zones (clusters of 100% similarity of IR) (Figure 9).

3.4. Scenario Development for Actual and New Emerging Sectors

Scenarios are conceptualized as representations of diverse future potentials, serving to aid decision-makers in navigating uncertainty and predicting the repercussions of their choices. Crucially, scenario planning tools offer significant advantages by challenging the tendency to rely on familiar patterns (anticipating the future to resemble the present) and fostering awareness of the unexpected. This is particularly valuable in situations where planning is hindered by data gaps or where strategic foresight is essential [65].

The scenario developed for the Black Sea is based on information regarding the emergence or intensification of activities such as wind farms [66–68], aquaculture [69–71] military operations [72,73], shipping [74–76], and ongoing beach nourishment works [77,78]. Focusing solely on new emerging sectors, shipping activities have the most pronounced additional impact on the ecosystem due to the increased traffic in the context of the Ukraine war, with oil and gas activities for the new exploitation of the Neptun Deep field following closely behind (Figure 10). Aquaculture and wind farm activities have an insignificant impact risk. In terms of pressures, the introduction of non-indigenous species and synthetic compounds poses the most substantial new threats. It is important to note the escalating risk of impact from military operations, which has intensified due to the ongoing war in Ukraine (Figure 11).

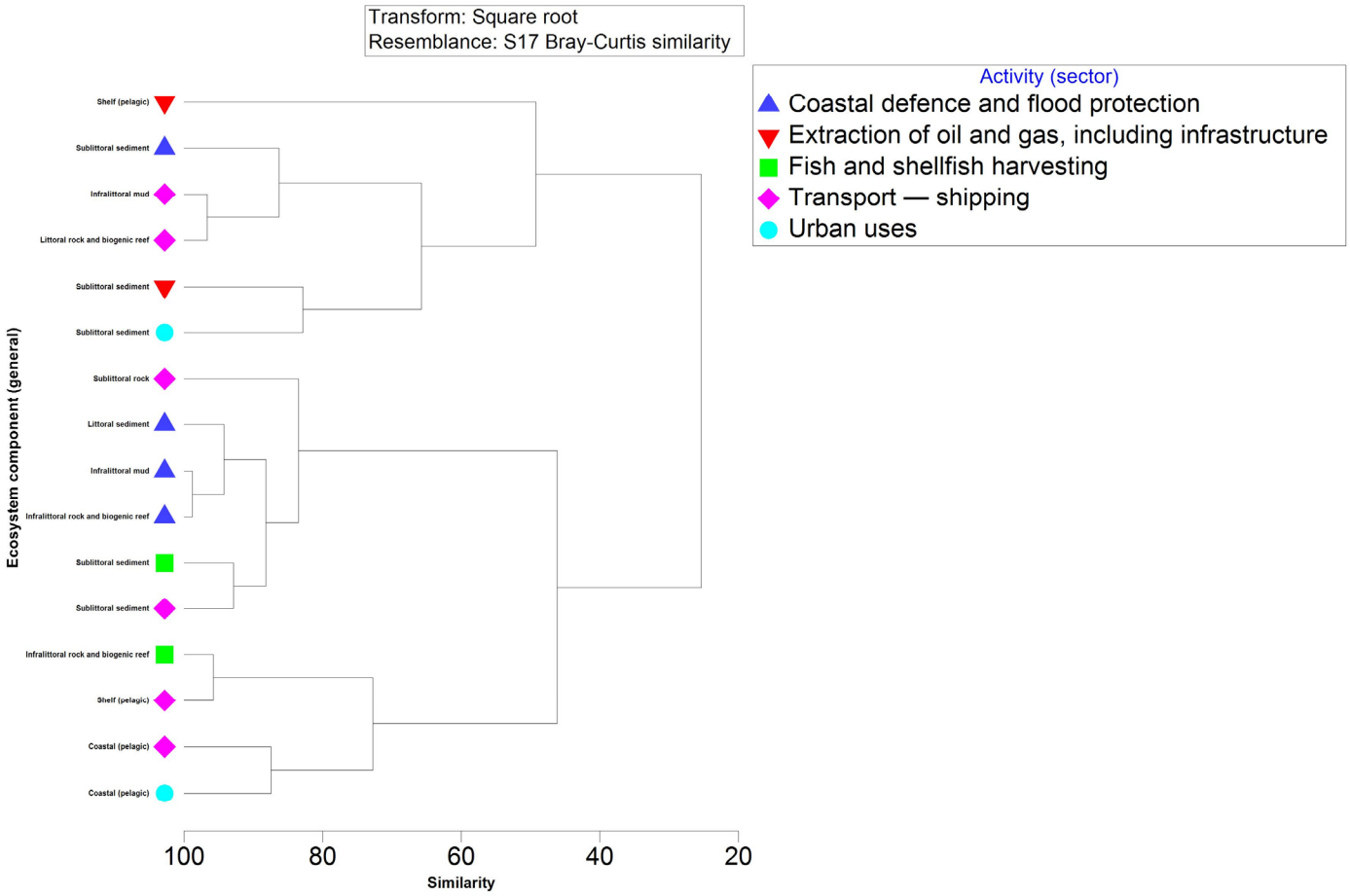

Figure 9. Bray–Curtis similarity based on activities and impacts on the ecosystem components at the Romanian Black Sea.

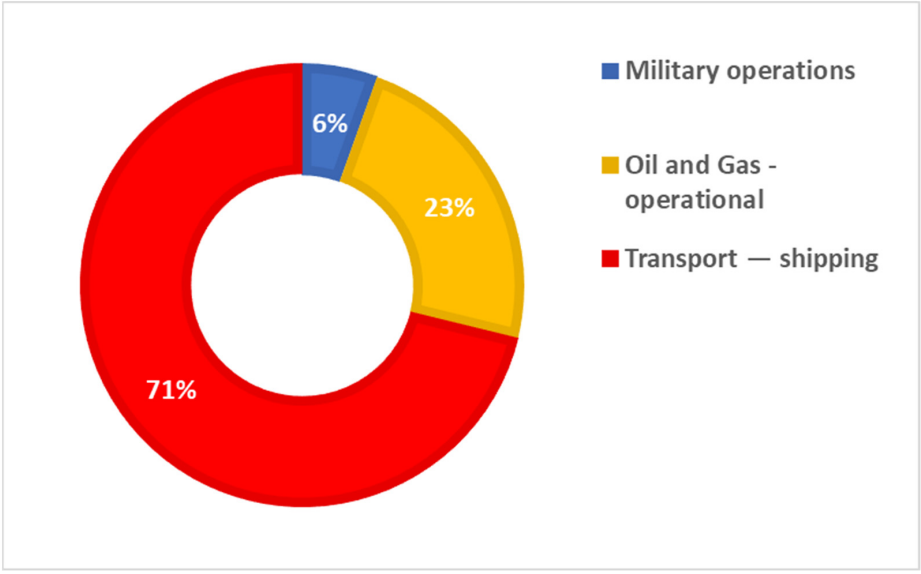

Figure 10. Scenario development—percentage of IR grand total by sectors at the Romanian Black Sea.

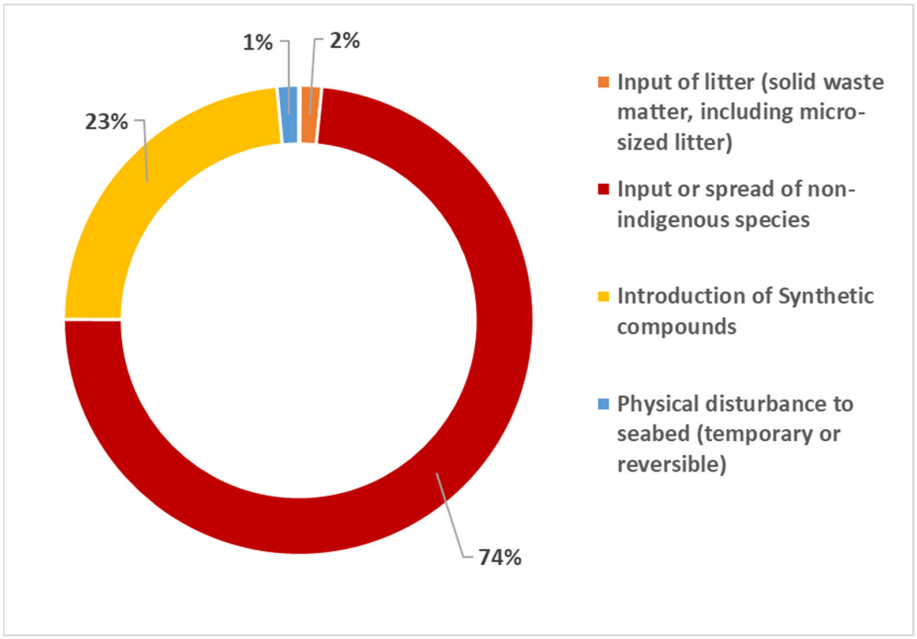

Figure 11. Scenario development—percentage of IR grand total by pressures at the Romanian Black Sea.

Organizing impact chains according to ecosystem components and sectors revealed that shipping activity results in the formation of closely related clusters for pelagic habitats and benthic components (Figure 12). In terms of pressures, the formation of these highly similar clusters is caused by the introduction of non-indigenous species, which clusters the primary ecosystem components represented by pelagic habitats and benthic components (Figure 13).

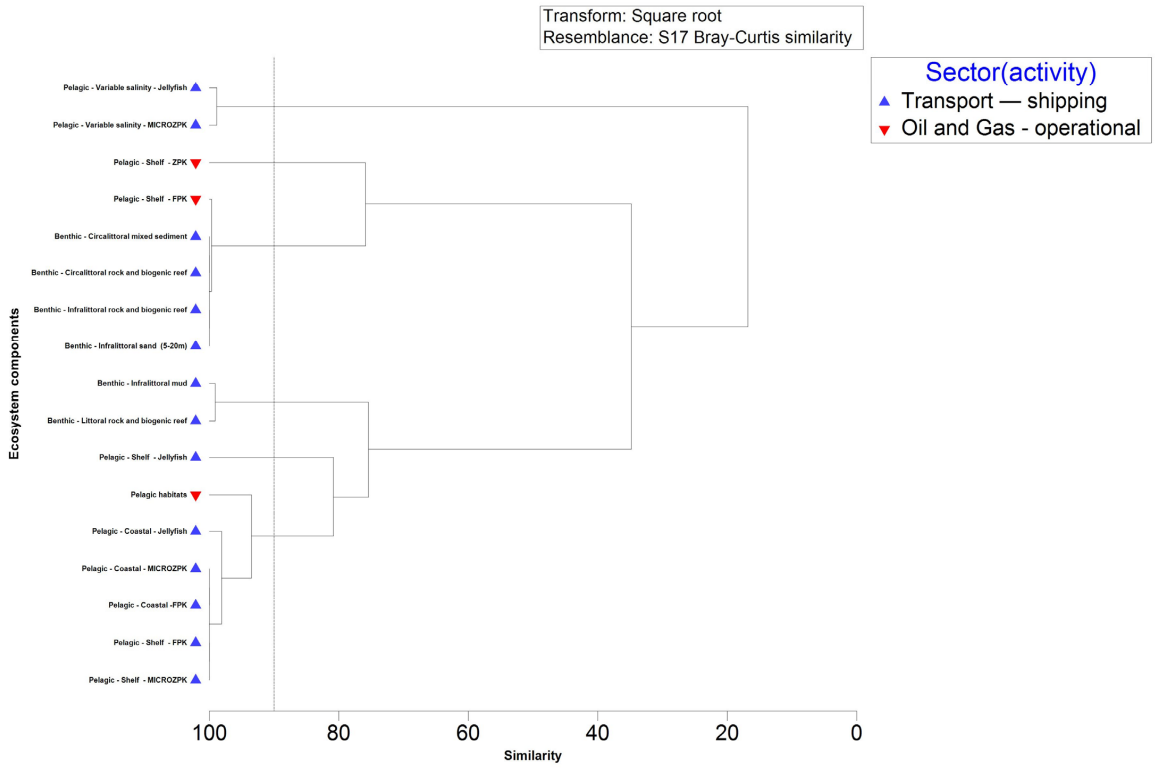

Figure 12. Scenario development—Bray–Curtis similarity based on sectors and impacts on the ecosystem components at the Romanian Black Sea.

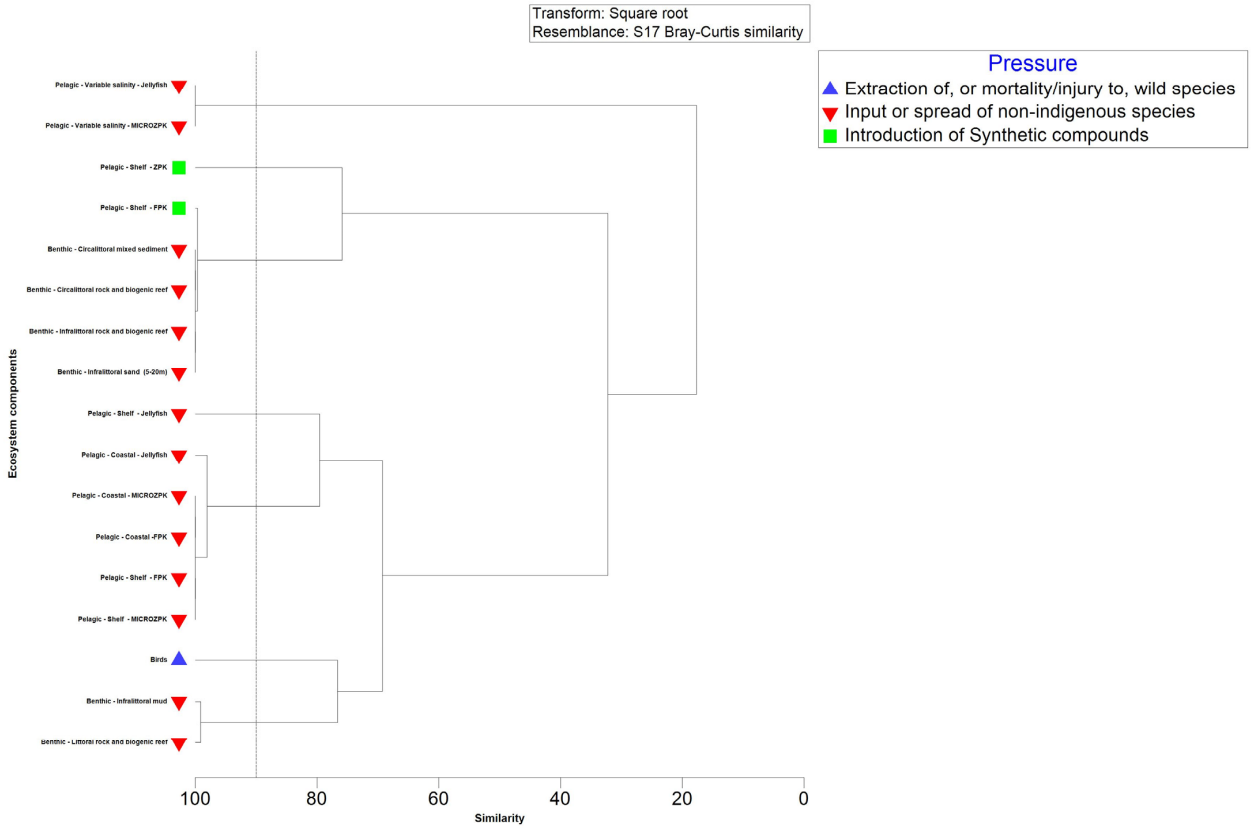

Figure 13. Scenario development—Bray–Curtis similarity based on pressures and impacts on the ecosystem components at the Romanian Black Sea.

4. Discussion

The Black Sea, characterized by its enclosed nature and specific ecosystem, stands out as one of the most environmentally threatened regional seas. It faces vulnerabilities resulting from the continuous overexploitation of fish stocks, oil pollution, human activities on land, and the introduction of invasive species [79], thus encompassing the largest anoxic basins globally [80,81]. This unique physical characteristic makes it highly susceptible to human-induced alterations, as pollutants persist in the water for extended periods and in elevated concentrations [82]. Furthermore, no living organisms exist below a depth of 150 m due to hydrogen sulfide presence. Consequently, the layer of seawater supporting Black Sea biodiversity becomes even more susceptible to the adverse effects of anthropogenic pollution. Disrupting the natural balance between these two layers could lead to irreversible losses in the Black Sea ecosystem [83,84]. The health of the Black Sea's environment is adversely affected by unsustainable historical, current, and anticipated maritime, coastal, and terrestrial activities [85]. These include pollution, marine litter, wastewater, and unsustainable practices. Sectors such as agriculture, coastal infrastructure, fishing, shipping, tourism, recreation, and wastewater treatment contribute significantly to the pressures on the Black Sea ecosystem [6,86]. Due to the loss of fishery stocks, there is a noticeable shift from primarily fishing activities toward coastal tourism, while the oil and gas sector remains a significant and ongoing presence in the Black Sea with the potential to increase in the next years [87]. With the implementation of new oil and gas exploitations, there is an evident expansion in the energy sector [88,89]. Conversely, the absence of economic mechanisms in the region fails to stimulate interest in eco-tourism development among both entrepreneurs and residents. Additionally, there is a notable lack of environmental advertising, promotion, and advocacy in the region [16,90].

Each activity operates within a designated area, forming an activity footprint, which subsequently generates pressure footprints (mechanisms of impact) and footprints with

effects on natural and social systems [91]. These paths require attention, by utilizing management response footprints [92]. Currently, the primary challenge in marine management lies in addressing the cumulative footprints of all activities and their associated pressures to mitigate the risk of adverse effects resulting from their combined impacts on ecosystem structure and functions [44,93,94].

Our approach relies on a comprehensive representation of the connections between human activities, their pressures, and various components of marine ecosystems, including waters with variable salinity (transitional) and coastal and marine regions. Such inclusive methodologies hold significance for numerous environmental policies, including the EU Biodiversity Strategy, the EU Marine Strategy Framework Directive, and the EU Water Framework Directive. We utilized a risk assessment framework encompassing various sectors, pressures, and fundamental ecological components, typical in Black Sea marine ecosystems. These ecological components, considered representative of a healthy ecosystem [95], have been recognized as relevant attributes of Good Environmental Status (GES) under the MSFD. Consequently, the analysis enables a direct interpretation of ecosystem risks resulting from different sectors [96,97]. The evaluation also succeeded in identifying and prioritizing sectors and pressures that specifically concern the region.

Through the application of this risk assessment framework, we identified the sectors and pressures representing primary drivers of change in the ecosystem and its constituent elements. These approaches aid environmental managers in decision-making and impact mitigation by providing a versatile, problem-solving solution that establishes links between human activities, pressures, and ecosystem components [33]. To effectively manage the impacts of pressures on aquatic ecosystems, a fundamental understanding of the pathways through which human activities influence ecosystem components is crucial. Utilizing a specific set of tools and techniques tailored to a given situation can facilitate problem-specific management solutions. However, this approach necessitates careful consideration of the quantity and nature of data, along with the social and ecological context [27,98].

The evaluation also successfully identified and prioritized sectors and pressures that are of particular concern within the Black Sea region, with coastal defense and shipping representing the highest threat to ecosystem components at this moment.

Our study revealed that, due to the significant beach nourishment efforts across the central and southern sections of the Romanian coast, coastal defense causes temporary or reversible disturbances to infralittoral rock and biogenic reefs through physical disturbance to the seabed and leads to physical loss by inducing permanent changes in seabed substrate or morphology. Human intervention, including the construction of coastal protection structures, ports, and leisure infrastructure, significantly affects coastal areas both directly, by altering shore morphology, and indirectly, by modifying the natural hydrological regime. The shoreline responds dynamically, continuously adjusting to the characteristics and influences of both natural and human-induced factors [99,100]. The presence of alongshore protecting structures impacts the coast, resulting in a significant loss or elimination of natural habitats [101]. The transformation of habitats due to coastal development can influence biodiversity, distribution patterns, trophic interactions, community compositions, and the quality of nursery habitats within the estuarine ecosystem [101]. Beach nourishment was carried out in the area between Constanta and Mamaia, as well as in the touristic resort Eforie North, on five beach sectors (Figure 14). The cumulative length is about 7.3 km, and the area of the five beach sectors has been increased by 60.66 ha. On 12 October 2020, the National Administration "Romanian Waters" announced in a press release that works have started for the second phase of the project, as well as for the first stage of beach nourishment in Navodari and Mamaia, and stated that following these works, the width of the beaches would increase to 100 m. In the absence of official explanations, it is difficult to understand the reason why the width of the extended beaches ultimately exceeded 200–250 m, even 300 m, in some places [56].

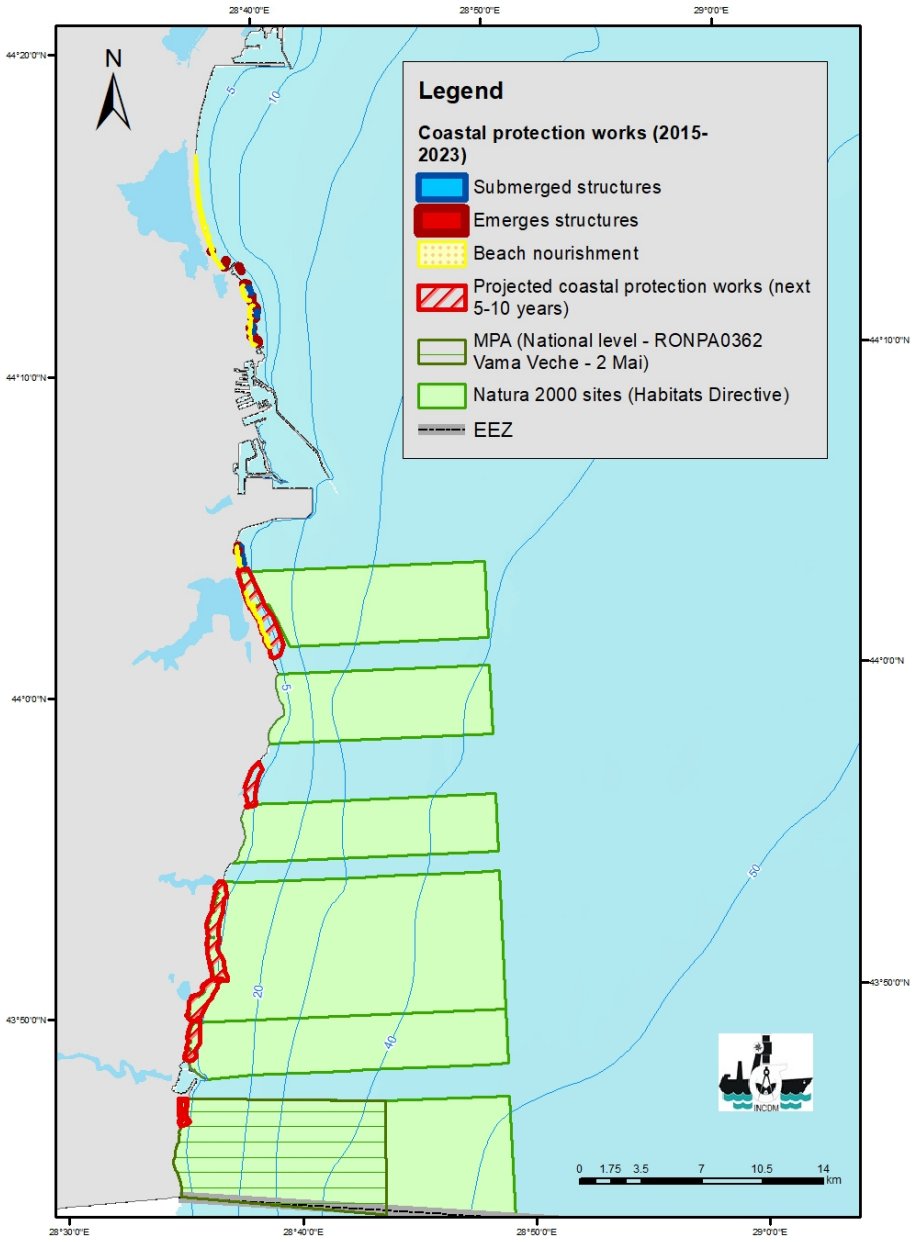

Figure 14. Coastal protection works at the Romanian Black Sea.

Erosion control structures directly impact benthic flora and fauna. Algal macrophytes, predominantly found at depths of 1–5 m, primarily inhabit hard substrates. These macroalgae play a crucial ecological role, serving as biological nutrient processors, providing shelter for epiphytic algae and associated fauna, and forming the trophic foundation for invertebrates and marine fish. Environmental shifts lead to alterations in hydrochemical parameters, substrate clogging, increased detritus and metabolite levels, reduced water transparency, and the presence of petroleum residues. Consequently, these changes foster the proliferation of opportunistic macrophyte species such as *Ulva*, *Cladophora*, and *Ceramium*. Notably, there is a significant decline in the number of perennial marine plant species like *Cystoseira*, *Phyllophora*, and *Zostera* in the Black Sea [102].

The Romanian Black Sea coast witnesses a positive trend in biodiversity growth within the zoobenthic community, reflecting improved environmental conditions [102]. During coastal protection works, the benthic substrate experiences adverse effects or potential loss [102]. Loss of habitat, alterations in habitat quality, and decreased availability of alternative sandy habitats may lead to diminished distribution and survival of benthic

invertebrates such as bivalves, whelks, and isopods, on open-coast beaches, particularly in lower shore areas [102]. Within the Black Sea's sandy shores, *Donacilla cornea*, a bivalve mollusk, was a noteworthy inhabitant known for its sensitivity to environmental changes. The habitat preference of *D. cornea* includes coarse-to-medium-grained sands and is highly responsive to changes in substrate structure caused by human activities such as engineering projects and sand extraction. These activities lead to increased turbidity and alterations in the granulometric composition of sand by reducing interstitial spaces between grains. Historical records provide insights into their population densities [103]. In the 1960s, densities of *D. cornea* ranging from 5100 to 21,700 individuals per cubic meter were observed on northwestern sandy beaches, while densities exceeding 3000 individuals per square meter were reported in the splash zone of Crimean sandy beaches during the 1950s [103]. In the southern Romanian littoral, *D. cornea* was common until the late 1970s, predominantly found in the midlittoral zone with coarse sands, reaching densities of up to 10,000 individuals per square meter. However, after 1980, *D. cornea* became exceedingly rare, and by the 1990s, it was no longer recorded across its former habitats. In 2004–2005, it was rediscovered only in the Eforie area [104–106]. The decline in *Donacilla* serves as a poignant illustration of ecological degradation within the modern Black Sea psammocontour. Human-induced impacts have led to the shortening and transformation of this habitat over time [103].

The effects of coastal protection measures on the environment can be examined in terms of both short-term impacts (during the construction and maintenance phase) and long-term effects (during operational phases) [102,107]. During the maintenance phase of coastal protection works, these new species may face temporary disturbances, leading to negative repercussions [102]. Over time, the biodiversity in the vicinity of these projects experiences shifts. This includes the formation of new habitats that may eventually provide suitable conditions for different plants and animals linked to them [107]. Nevertheless, there is a decline in the original habitat, which could hold greater ecological significance than the newly developed habitat [102,107].

In comparison to Ref. [108], our study showed that the input of nutrients and organic matter is continuous, mainly due to the WWTP discharge, and it affects both the pelagic coastal habitat and benthic coastal ecosystems, including macroalgae and seagrass, potentially preventing the GES for the MSFD's descriptor 5 (Eutrophication). The same situation was observed for the introduction of non-synthetic and synthetic compounds, affecting pelagic habitats and infralittoral mud, potentially preventing the GES for the MSFD's descriptors 8 and 9 (contaminants in the environment and seafood).

Changes in water quality can result in hampering fishing, recreational activities, and industrial water usage, consequently affecting the economy. Furthermore, the disappearance of vulnerable species and the proliferation of more resilient ones pose a threat to ecosystems [109]. Addressing pressure-related challenges, such as the proliferation of invasive species, to safeguard vulnerable ecosystems requires collaborative efforts transcending borders. Strengthening cooperation among stakeholders within the sea basin is imperative to support the conservation of coastal and marine ecosystems. This collaborative approach fosters harmonious coexistence and mitigates conflicts arising from competing economic activities in marine and coastal zones [108].

Shipping and deliberate introductions are the primary means by which non-native species are introduced into the Black Sea. Shipping is particularly prevalent in the Black Sea, primarily driven by the transportation of Caspian oil from Novorossiysk, Russia, to Mediterranean nations via the Turkish straits [110] and recently by opening a new corridor for cereals transport due to the war in Ukraine [111,112].

Given the enclosed nature and relatively low biodiversity of the Black Sea, several non-native species pose significant threats to indigenous biota [113]. A prime example is the comb jelly *Mnemiopsis leidyi*, which was transported to the Black Sea via ship ballast water [79,114]. This species has caused considerable ecological and economic harm to coastal fisheries by primarily preying on the larvae and eggs of small pelagic fish, such as

anchovy, horse mackerel, and sprat [115,116]. The introduction of its predator *Beroe ovata*, which came from either the Mediterranean Sea or the eastern coast of the North Atlantic through ballast waters in 1997, helped the later recovery of the ecosystem [117]. *B. ovata* was first encountered in the western shelf [118] and the northeastern basin in the summer of 1997 [119].

Another non-native invasive species, the sea snail *R. venosa*, has gained notable commercial importance in the Black Sea since the 1980s and has been exported to Asian countries. However, its impact on native fauna, particularly mussel and oyster beds, has been detrimental. Among these non-native invasive species, the rapa whelk (*R. venosa*), a type of sea snail, is the most heavily harvested and commercially exploited by countries bordering the Black Sea [113].

The Ukraine–Russian conflicts in the Black Sea region have brought attention to the significant impact of military operations on marine biodiversity and conservation. This conflict has resulted in both immediate and subsequent environmental repercussions in the Black Sea [120,121]. Direct consequences such as oil spills, the discharge of harmful substances, and habitat degradation have had detrimental effects on marine ecosystems, resulting in the loss of crucial breeding grounds [120].

Additionally, the fragile balance of marine life in the region is further threatened by indirect effects arising from fishing activities, increased maritime traffic, and the construction of coastal infrastructure prompted by the conflicts [122].

Notable changes in ecosystem components lead to declining ecosystem health encompassing shifts from naturally diverse habitats to artificially reduced diversity environments, the accumulation and expansion of invasive species [123], and the increased prevalence of harmful occurrences like harmful algal blooms (HABs) and jellyfish outbreaks [124]. These alterations pose significant challenges for the management of human activities within these ecosystems [44,124].

In developing scenarios for the Romanian Black Sea region, it is essential to factor in both emerging and existing activities and pressures. In the short term, several significant developments are anticipated. Among these are plans for windfarm and aquaculture expansion, reflecting a growing emphasis on renewable energy and sustainable food production. Additionally, the discovery and development of the Neptun Deep oil and gas field present significant opportunities for the region's energy sector. However, alongside these advancements, there are also challenges, such as the escalation of maritime traffic due to the conflict in Ukraine and associated military actions. This increased activity poses risks, including potential environmental impacts.

The scenario development indicated that shipping activities are expected to have the most significant additional impact on the ecosystem of the Romanian Black Sea. The multitude of services provided by boats and ships underscores their value to humanity and economic prosperity. Whether it is supplying food through fishing, serving as transportation for commercial and recreational purposes, facilitating leisure and sporting activities in developed nations, or enabling global commodity distribution, their importance is undeniable. However, routine operations; onshore activities like maintenance or ship demolition; and accidental incidents such as explosions, groundings, or cargo losses (e.g., oil spills or lost merchant containers) all pose potential environmental risks [125,126]. These impacts can detrimentally affect aquatic ecosystems, leading to reduced water quality, the introduction of invasive species, habitat disturbance or destruction, and alterations to ecosystem structure and function, as well as atmospheric pollution inputs [125].

Moreover, these impacts can be either direct or indirect and can occur over varying spatial and temporal scales, influenced by factors such as vessel size and density (e.g., cumulative impacts from clustered vessels), movement patterns, specific operational activities, and environmental conditions. A comprehensive understanding of these impacts on aquatic ecosystems is crucial, both in the short term and over extended periods, to inform effective management and mitigation strategies [127].

5. Conclusions

While this paper aims to contribute to understanding the cumulative impacts on marine ecosystems and guide management strategies, it is important to acknowledge several limitations. Firstly, the effectiveness of the Spatial Cumulative Assessment of Impact Risk for Management (SCAIRM) tool relies heavily on the availability and quality of data and information. Incomplete or inaccurate data could compromise the accuracy of our assessments and subsequent management recommendations. Additionally, the complexity of marine ecosystems presents challenges in fully capturing all interconnections and dynamics, particularly considering the vast array of factors influencing ecosystem health. Moreover, the application of the ecosystem-based management (EBM) approach, while recognized as valuable, may face practical challenges in implementation, particularly in terms of stakeholder engagement and resource allocation. Despite these limitations, our study provides valuable insights into the potential impacts of human activities on marine ecosystems and highlights the importance of adopting holistic management approaches to ensure their long-term sustainability.

The outcomes of this study reveal the impact risks of human activities and associated pressures, aiming to guide management strategies toward achieving sustainability, biodiversity protection, and the overall integrity of the marine ecosystem. Using SCAIRM, the primary pressure on the marine ecosystem was identified as the introduction or spread of non-indigenous species from shipping. Additionally, when considering the cumulative impact, activities related to coastal defense and flood protection, particularly beach nourishment works, were found to have the highest impact. This is due to the cumulative scores associated with the physical loss from permanent alteration or removal of seabed substrates and temporary or reversible physical disturbances to the seabed. The scenario development indicated that the introduction or spread of non-indigenous species from increased shipping activities due to the war in Ukraine had the most significant impact risk, thus requiring targeted management actions. New oil and gas exploitation is anticipated to become the second-highest risk sector for impact in the Romanian Black Sea. Both sectors require targeted management actions for sustainability in the Black Sea.

This study strengthens the scientific capability to assess cumulative pressures and outcomes through quantitative methodologies along the Romanian Black Sea coast by employing a sequence of interlinked matrices to portray the complex connections between human activities influenced by the socioeconomic system and ecological components. Establishing connections between human activities and environmental pressures is crucial for understanding ecosystem service supply. This kind of assessment is crucial for informing policy and conservation efforts aimed at reducing the negative impacts of human activities on marine ecosystems.

Global climate change and the increasing activities and pressures in the marine environment call for immediate evaluations of the effects on ecosystem service supply and long-term sustainability. By identifying areas where human activity may impact the provision of services, this approach offers guidance for management measures to achieve maximum effectiveness, efficiency, and equity. Moreover, this will enable the promotion of the sustainable utilization of marine resources and make informed decisions through ecosystem-based management (EBM).

The continuous nature of these pressures indicates a persistent input that could lead to long-term impacts on marine ecosystems if not managed properly. The data emphasize the importance of monitoring and mitigating the effects of human activities on marine environments to ensure their sustainability and health.

Our study underscores the critical need for improved legislation and information regarding the environmental impact of human activities in the Romanian Black Sea. Better legislation is required to regulate and manage emerging activities such as wind farm development, aquaculture expansion, and oil and gas exploration, ensuring that environmental concerns are adequately addressed.

Additionally, there is a pressing need for enhanced data collection and dissemination regarding the environmental impacts of these activities. This includes comprehensive assessments of the potential risks posed by activities, as well as ongoing monitoring of environmental indicators to inform decision-making processes.

By strengthening legislative frameworks and access to environmental information, policymakers can more effectively safeguard marine ecosystems, promote biodiversity conservation, and achieve sustainable management of the Black Sea region.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16114449/s1, Table S1: The classifications for activities and pressures by referencing previous categorizations established in the Marine Strategy Framework Directive, Tabel S2: Risk evaluated through the assessment of scores assigned to criteria, Table S3: Specific activities and ecosystem components—IR%.

Author Contributions: Conceptualization, E.B. and L.L.; methodology, E.B., L.L., V.A., L.B., F.A., G.-E.H., O.M., A.O., E.P., A.S., F.T., G.T. and O.V.; software, E.B. and L.L.; validation E.B. and L.L.; formal analysis, E.B., L.L., V.A., L.B., F.A., G.-E.H., O.M., A.O., E.P., A.S., F.T., G.T. and O.V. investigation, E.B., L.L., V.A., L.B., F.A., G.-E.H., O.M., A.O., E.P., A.S., F.T., G.T. and O.V.; resources, E.B., L.L., V.A., L.B., F.A., G.-E.H., O.M., A.O., E.P., A.S., F.T., G.T. and O.V.; data curation, E.B., L.L., V.A., L.B., F.A., G.-E.H., O.M., A.O., E.P., A.S., F.T., G.T. and O.V.; writing—original draft preparation, E.B. and L.L.; writing—review and editing, E.B. and L.L.; visualization, E.B. and L.L.; supervision, E.B. and L.L.; project administration, E.B. and L.L.; funding acquisition, E.B. and L.L. All authors have read and agreed to the published version of the manuscript.

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