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STRATEGIC APPROACHES TO EUTROPHICATION MANAGEMENT IN THE BLACK SEA: SCENARIO TESTING AND POLICY IMPLICATIONS

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ABSTRACT

Marine management involves assessing risks to natural and human systems and implementing measures to mitigate them. Eutrophication, driven by excess nutrients and organic matter, is a major risk in the Black Sea, largely caused by agricultural runoff, urban wastewater, maritime transport, and climate change. This study uses Bow-tie Analysis (BTA) and FCM (Fuzzy Cognitive Maps) to evaluate three IPCC-based management scenarios—Sustainable Future, Moderate Progress, and Deteriorating Conditions—to address eutrophication. These scenarios were assessed for their effectiveness in reducing nutrient runoff, improving water quality, and achieving Good Environmental Status (GES) under Descriptor 5 of the EU Marine Strategy Framework Directive. Key pressures such as agriculture, wastewater, shipping, and low public awareness were linked to targeted controls, including technological improvements, adaptive legislation, and enhanced public engagement. Results show that proactive and integrated measures in the Sustainable Future scenario substantially improve water quality. The Moderate Progress scenario reflects limited success, with some ongoing challenges. The Deteriorating Conditions scenario underscores the risks of weak control measures and policy inaction. The study highlights the importance of coordinated management strategies, adequate policy support, and stakeholder involvement to ensure the Black Sea's ecological resilience—offering valuable insights for other vulnerable semi-enclosed marine systems.

Keywords: Bow-tie Analysis, Fuzzy Cognitive Maps, Water Quality, Environmental Management, Black Sea

INTRODUCTION

The Black Sea, once a productive ecosystem renowned for its biodiversity and economic value to riparian countries, now faces severe environmental challenges due to intensified human activities in the surrounding river basins of the Danube, Dnieper, Dniester, and Bug (Gomoiu, 1992; Zaitsev, 2008). Eutrophication—driven by agricultural runoff, untreated or insufficiently treated urban and industrial wastewater, maritime transport, and climate change—has become a critical threat, leading to biodiversity loss, ecosystem degradation, and risks to human health (Lazăr *et al.,* 2019; Lazar *et al.,* 2018; Y. Zaitsev, 2008). These issues are further aggravated by regional instability, such as the war in Ukraine, and by exogenic pressures such as global climate change (Childs, 2023; Genner *et al.,* 2017).

Marine management is therefore essential to assess both the scale and significance of natural and human-induced hazards, and to prevent, eliminate, or mitigate the resulting risks to ecosystems and coastal communities (Cormier *et al.,* 2019;

Kennish *et al.,* 2024). The European Union Marine Strategy Framework Directive (MSFD) aims to achieve Good Environmental Status (GES) in European marine waters through coordinated assessment, monitoring, and management (European Commission, 2008). In Romania, MSFD implementation involves three stages: the Initial Assessment (2012), a second assessment in 2018, and the upcoming 2024 review (Loizidou *et al.,* 2016). This process is carried out alongside the Water Framework Directive (WFD), which focuses on achieving good chemical and ecological status in catchments, transitional, and coastal waters (Borja *et al.,* 2010).

Given the historical degradation of the Black Sea, achieving GES for Descriptor 5 (Eutrophication) is particularly challenging. Romania's approach is managed by seven ministries and one national agency—the National Agency for Fisheries and Aquaculture (NAFA)—reflecting the cross-sectoral nature of eutrophication management, which spans agriculture, environment, transport, and fisheries. While this structure provides broad coverage, it can also lead to fragmentation and inconsistent enforcement if not carefully coordinated.

Bow-tie Analysis (BTA) is an ISO-accredited qualitative risk assessment method that links causes, central events, and consequences, highlighting points where prevention or mitigation can be most effective (Cockshott, 2005). Fuzzy Cognitive Mapping (FCM), implemented through the Mental Modeler software, complements BTA by capturing the dynamic relationships between activities, pressures, controls, and environmental outcomes.

This combined approach allows both a static view of risk pathways and a dynamic simulation of system responses to different interventions. BTA and FCM can be integrated to provide a more comprehensive understanding of complex systems, especially in risk and environmental management. The bow-tie framework offers a clear, event-focused structure that traces the pathway from hazards through a central "top event" to potential consequences, highlighting preventive and mitigative barriers. FCM, in turn, models the network of causal relationships among system components, incorporating feedback loops, indirect effects, and varying influence strengths. By embedding an FCM within the left side (threats) and right side (consequences) of a bow-tie diagram, analysts can capture the dynamic interdependencies and uncertainties that the static bow-tie alone may overlook. This integration allows for scenario testing—such as simulating barrier degradation or environmental changes—to reveal how risk pathways evolve over time, ultimately supporting more robust decision-making and prioritisation of interventions. Figure 1 presents a conceptual diagram illustrating the integration of BTA and FCM, offering a visual overview of the methodology introduced in this study.

This study aims to integrate BTA and FCM to assess and manage eutrophication risks in the Romanian Black Sea. By combining the static mapping of risk pathways (BTA) with the dynamic simulation of system responses (FCM), the approach offers a comprehensive framework for evaluating management strategies. Three scenarios, aligned with the IPCC Shared Socio-economic Pathways (SSPs), are developed to examine how varying degrees of policy enforcement, technological advancement, and public engagement can reduce nutrient inputs, enhance water quality, and support the achievement of Good Environmental Status (GES) under the Marine Strategy Framework Directive (MSFD) and Good Ecological Status under the Water Framework Directive (WFD).

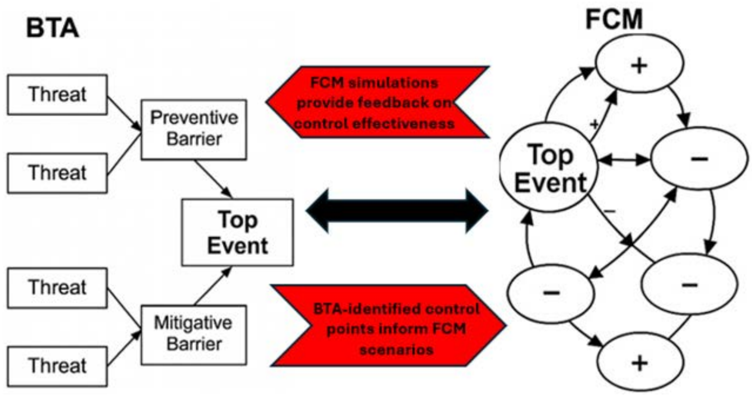

Fig. 1. Conceptual representation of the integration between BTA and FCM

MATERIALS AND METHODS

Study area

The study was conducted along the Romanian Black Sea coast, covering the Danube-influenced northern sector, the central coastal/mid-shelf zone, and the offshore region. This area is strongly influenced by freshwater and nutrient input from the Danube River, which contributes high loads of nitrogen, phosphorus, and suspended matter (Coatu *et al.,* 2020; Damir *et al.,* 2022; Lazar *et al.,* 2024).

The Black Sea (Fig. 2) is a brackish, stratified basin where riverine freshwater overlies saline Mediterranean inflow, with a permanent pycnocline at 100–150 m (Zaitsev *et al.,* 2002). The oxygenated upper layer (to ~50 m) is highly sensitive to nutrient inputs, mainly from the Danube, which delivered on average ~440,000 t nitrogen and ~24,000 t phosphorus annually in 2004–2018—levels still above those of the 1960s. Below 70–100 m, suboxic and anoxic layers with hydrogen sulfide intensify eutrophication effects (Lazar *et al.,* 2021).

Data were collected from Romanian Black Sea environmental monitoring reports, scientific literature on Black Sea pollution, regulatory documents, pollution control case studies (Boicenco *et al.,* 2018; Boicenco *et al.,* 2019; Coatu *et al.,* 2013; Lazăr *et al.,* 2013; Lazar *et al.,* 2011; Lazar *et al.,* 2021; Lazar *et al.,* 2018; Nenciu *et al.,* 2016; Oros *et al.,* 2021, 2012; Rosioru *et al.,* 2016; Ţigănuș *et al.,* 2016; Vasiliu *et al.,* 2010), and expert judgment, offering insights into causal pathways, ecological and health impacts, and management barriers.

Their assessments validated risk scenarios based on oceanographic historical data, guiding the development of practical mitigation strategies. This integration provided a comprehensive, multidisciplinary approach, enhancing the robustness and relevance of BTA in addressing environmental risks in the Black Sea region.

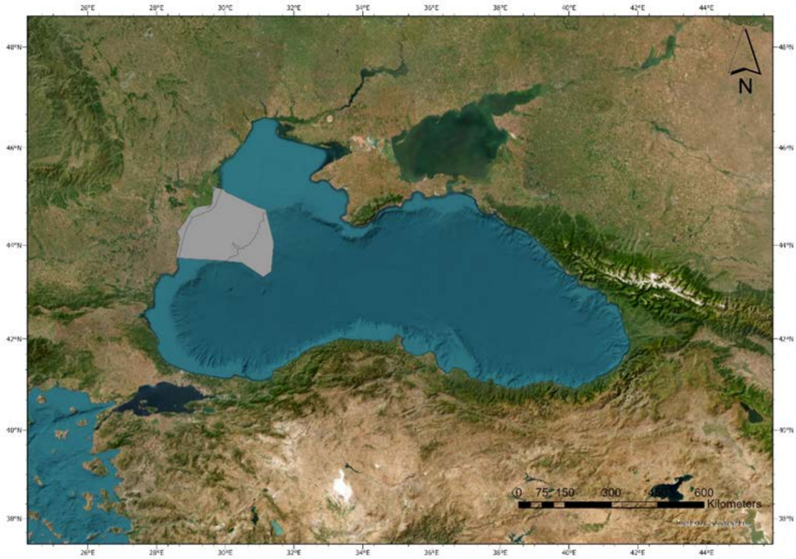

Fig.2. Black Sea – Romanian EEZ (grey) in the Black Sea region

Bow-tie analysis

BTA is an ISO-accredited risk assessment and management technique (IEC 31010; ISO 31000) that links a specific hazard to its causes and consequences through defined prevention and mitigation controls (Astles *et al.,* 2018; Cormier *et al.,* 2020; Gerkensmeier *et al.,* 2018; Kishchuk *et al.,* 2018).

A generic Bow-tie structure used in this study is shown in Fig. 3, with the hazard represented by a yellow-striped box, causes on the left (orange), and consequences on the right (red), connected by control measures. Proactive strategies emphasise prevention, while reactive strategies address impacts after the event (Cormier *et al.,* 2019; Saud *et al.,* 2014). Escalation factors (yellow boxes) may weaken controls and require additional safeguards.

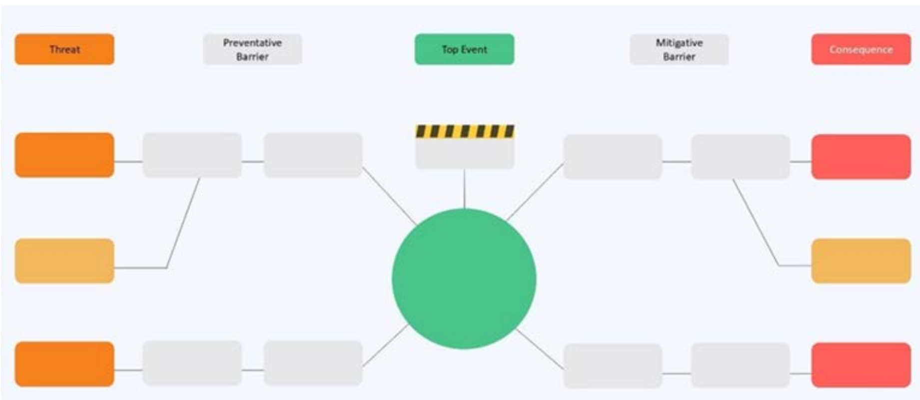

Fig.3. Bow-tie diagram template(https://salus-technical.com/free-excel-and-ppt-bowtie-diagram-template) used for Descriptor 5 in the Romanian Black Sea area

Fuzzy Cognitive Maps

The qualitative modelling was carried out with the Mental Modeler software, a decision support software (open source, https://www.mentalmodeler.com/) (MentalModeler) that helps experts understand the impact associated with environmental changes and develop strategies for reducing unwanted outcomes by capturing, communicating, and representing knowledge (Gray *et al.,* 2014; Jetter *et al.,* 2014; Papageorgiou *et al.,* 2017). Mental Modeler generates semi-quantitative FCMs by defining key components, assigning relationship strengths, and running scenarios to assess system responses (Gray *et al.,* 2013). Positive correlations are shown in blue and negative in orange, with weights based on expert judgment and coefficients were grouped into minor (0.0–±0.3), moderate (±0.3–±0.7), and high (±0.7–±1.0) impact classes.

Scenario development

BTA offers a clear framework for mapping hazards, causes, and preventive measures, but can oversimplify complex systems (Aust *et al.,* 2020; ISO, 2018; Singh *et al.,* 2024). To capture dynamic interactions in Black Sea environmental management, we integrated BTA with FCMs and developed three management scenarios (Intergovernmental Panel on Climate Change (IPCC), 2023; Lazar *et al.,* 2022):

- **Scenario 1 – Sustainable future (SSP1):** Proactive nutrient management, up-graded wastewater treatment, eco-friendly coastal measures, and strong public engagement reduce eutrophication and protect biodiversity
- **Scenario 2 – Moderate progress (SSP2):** Improvements in farming practices and wastewater treatment occur but are hindered by infrastructure gaps, weak enforcement, and limited scalability of measures**.**
- **Scenario 3 – Deteriorating conditions (SSP3/SSP4):** Minimal improvements, weak controls, and rising pollution drive further ecosystem degradation.

The quantitative changes assigned to each forcing factor in the three scenarios—Sustainable Future (S1), Moderate Progress (S2), and Deteriorating Conditions (S3)—were derived from a combination of documented intervention outcomes in the Black Sea and comparable semi-enclosed seas, expert elicitation where empirical data were unavailable, and linkages to specific management controls identified in the BTA and simulated in the FCM. Following IPCC guidance on plausible futures, S1 reflects performance levels achieved in successful real-world interventions, S2 assumes partial adoption due to technical, financial, or governance constraints, and S3 assumes stagnation or decline, sometimes aggravated by unmanaged external pressures such as climate change. Table 1 presents examples of successful remediation and preventive measures (Axe *et al.,* 2016; Friedland *et al.,* 2021; HELCOM, 2017; Jalkanen *et al.,* 2020; Reusch *et al.,* 2018; WWF, 2023), their environmental improvements, and how these values informed the percentage change assumptions for S1, S2, and S3.

In this study, the Scenario interface of Mental Modeler was used to test management interventions by adjusting key variables (e.g., nutrient runoff, untreated wastewater) and modelling their effects on impacts such as eutrophication and environmental degradation. Changes in forcing factors were propagated through a cause–and–effect matrix, allowing scenario comparisons and evaluation of potential trade-offs and benefits to support decision-making.

Table 1. Prevention outcomes guiding scenario % changes.

Forcing Factor	Measure / Control Reference	Documented Outcome	Scenario Application
Agricultural runoff	Advanced nutrient management practices (Ctrl 2.2, Ctrl 3.1)	20–25% reduction in nitrogen inputs, improved water clarity	S1: –50%; S2: –20%; S3: +10%
Urban & industrial wastewater	Wastewater treatment upgrades (Ctrl 2.2)	60% reduction in untreated discharges	S1: –70%; S2: –20%; S3: +10%
Shipping	Enforcement of ballast water regulations (Ctrl 1.3.1)	40–50% reduction in nutrient-rich discharges from ballast water	S1: –50%; S2: –20%; S3: +10%
Coastal defence	Eco-friendly erosion control & habitat restoration (Ctrl 1.2.1)	25–35% reduction in sediment disturbance	S1: –30%; S2: –10%; S3: +10%
Public awareness	Regional awareness campaigns (Ctrl 6.1.2)	>70% community participation in sustainable practices	S1: +80%; S2: +40%; S3: +0%

RESULTS AND DISCUSSION

The Bow-tie diagrams for Descriptor 5 (Eutrophication) represent not only the pathways leading to Black Sea eutrophication but also illustrate how a suite of pressures from diverse human activities—such as agricultural runoff, wastewater discharge, and industrial pollution—contribute to this state change. These pressures, arising from sectors like agriculture, urban development, and maritime activities, drive nutrient overloads in the marine ecosystem. The diagrams also highlight the effectiveness of preventive measures and potential escalation factors, offering a comprehensive view of the risks associated with eutrophication. This approach supports the formulation of targeted recommendations for mitigating nutrient pollution and managing the broader impacts of human activity on the Black Sea ecosystem.

Bow-tie Analysis for Descriptor 5: Human-induced eutrophication is minimized, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms, and oxygen deficiency in bottom waters.

Eutrophication is a fundamental response within the risk pathways illustrated in Fig. 4. The Bow-tie diagram illustrates the pathways leading to a flow from the input of nutrients and organic matter threats (nutrient inputs from agricultural, industrial, and urban sources) through the central risk of eutrophication in the Black Sea. It highlights the environmental and health-related events (surpassing ecosystem disturbance thresholds) to the consequences of eutrophication, such as (algal blooms, oxygen depletion, and the decline of aquatic organisms). Preventive measures (the so-called Programmes of Measures in WFD and MSFD), including regulatory enforcement, upgrading wastewater treatment, monitoring programmes, public education, nutrient recovery technologies, precision farming, regional cooperation, and economic incentives, are outlined to mitigate these risks. Additionally, insufficient wastewater treatment infrastructure is identified as a critical escalation factor that could worsen the situation if not properly addressed. This structured approach helps in understanding and managing the risks associated with nutrient pollution in the Black Sea ecosystem disruption. It highlights preventive controls to stop threats from leading to the central event and mitigation controls to reduce the impact (adverse consequences) of the central event if it occurs.

Pressures from the input of nutrients and organic matter and physical disturbance to the seabed drive the degree of ecosystem component disturbance. Controlling these inputs or managing their spatial and temporal distribution can help reduce or eliminate the disturbances. Mitigation and recovery tools (such as ecoengineering and geoengineering) can also be employed to lessen the impacts of eutrophication. Eutrophication is more likely to cause biological disturbances to species (excessive plant growth, harmful algal blooms, more frequent anoxic events, and fish mortality) and impact marine food webs (Boesch, 2019; Dai *et al.,* 2023; Moal *et al.,* 2019). The impact of eutrophication extends beyond just the biological and ecological aspects of aquatic habitats, potentially leading to significant socio-economic losses (Dorgham, 2014).

FCMs offer a dynamic view by modelling relationships among identified activities and pressures—such as agricultural runoff, urban and industrial wastewater, shipping, coastal defence and flood protection, public awareness and education —in a nuanced, interconnected manner (Fonseca *et al.,* 2022; Lavin, 2018).

The obtained FCM (Fig. 5) illustrates the interconnected pathways linking human activities, environmental pressures, ecological state changes, and socio-economic impacts. Activities such as physical restructuring of rivers and coastlines, cultivation of living resources, transport, tourism, and urban or industrial uses generate multiple pressures, including nutrient inputs, untreated waters, and habitat alteration. These pressures contribute to elevated inorganic nitrogen and phosphorus concentrations, leading to human-induced eutrophication, which in turn drives ecological impacts such as algal blooms and a decline in ecosystem services. The resulting environmental degradation cascades into economic impacts, such as increased costs, and societal impacts, including health risks. The model also integrates management measures such as habitat restoration, regulatory limits, improved assessment methodologies, and awareness-raising—which act at different points in the network to reduce pressures or mitigate impacts. This integrative approach not only enhances the understanding of how changes in one driver, activity or pressure can cascade through the system but also supports adaptive strategies to mitigate environmental risks effectively under varying scenarios and uncertainties.

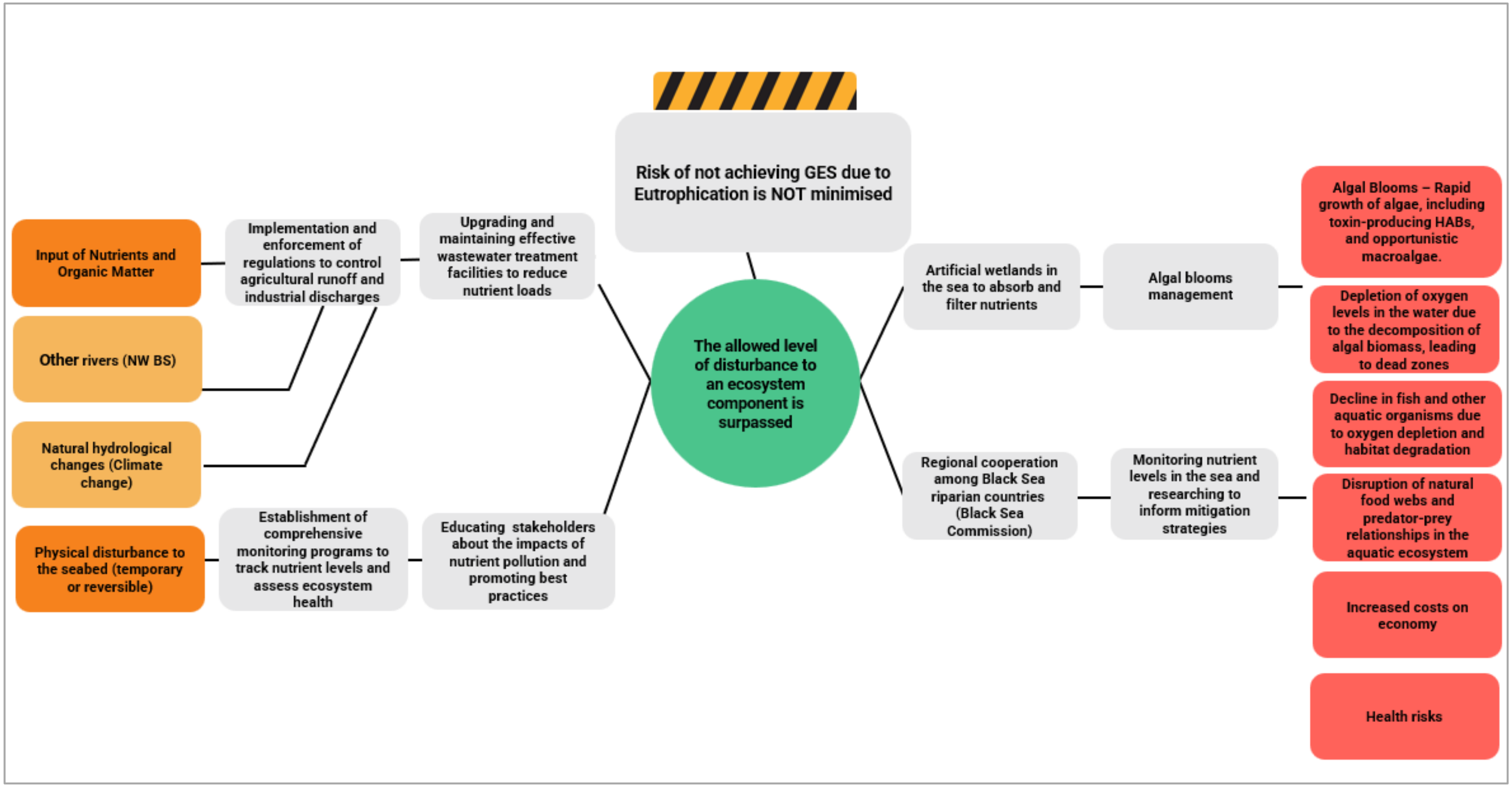

Fig. 4. Bow-tie analysis of MSFD Descriptor 5 - Human-induced eutrophication is minimized, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms, and oxygen deficiency in bottom waters

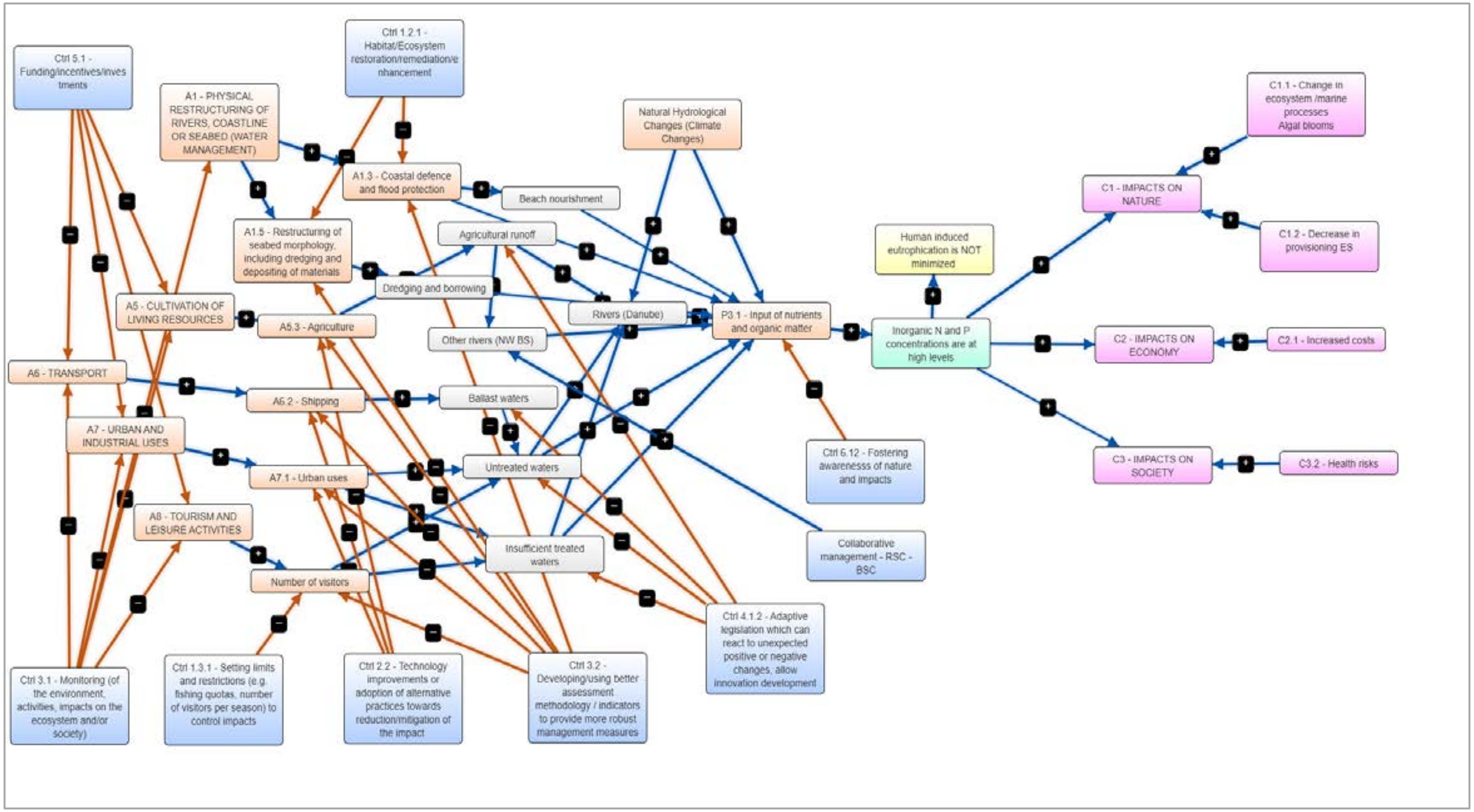

Fig. 5. Mental Model of Bow-tie elements – Romanian Black Sea Eutrophication – Blue – Controls, Orange – Causes, Pink – Consequences, Green-Central event

These scenarios illustrate varying degrees of environmental management effectiveness estimated as the reduction in identified drivers in the Romanian Black Sea region (Annex 1). Thus, it highlights the critical role of policy decisions, resource allocation, and public engagement in shaping sustainable outcomes for marine ecosystems. For Scenario 1 (Annex 1), Romania successfully implements comprehensive environmental management strategies, leading to significant reductions in nutrient runoff, wastewater discharge, and sediment disturbance (Sharpley *et al.,* 2011). The scenario emphasizes the benefits of advanced technologies and strong regulatory enforcement in addressing nutrient pollution and biodiversity threats, while public awareness campaigns drive increased engagement with sustainable practices, showcasing a holistic approach to tackling the Black Sea's environmental issues (Endresen *et al.,* 2007; Larsen *et al.,* 2016; Temmerman *et al.,* 2013).

In Scenario 2 (Annex 1), while Romania makes moderate progress, the persistence of infrastructural and regulatory challenges limits the effectiveness of environmental measures. The partial enforcement of ballast water regulations and difficulties in scaling ecosystem-based coastal protection highlight ongoing complexities (Cîndescu *et al.,* 2023; Henze *et al.,* 2019; Monroe *et al.,* 2016). Despite public awareness campaigns, resource limitations continue to hinder widespread behavioural change, reflecting the need for greater investment and stronger policy coordination.

In Scenario 3 (Annex 1), Romania faces escalating environmental problems due to insufficient control measures. Agricultural practices remain largely unchanged, resulting in increased nutrient runoff, while outdated infrastructure leads to higher levels of untreated wastewater entering the Black Sea (Corcoran *et al.,* 2010). Weak enforcement of ballast water regulations exacerbates nutrient discharges (Nayar *et al.,* 2007), compounded by the impacts of increased maritime traffic (Drake *et al.,* 2007). This scenario underscores the critical need for more robust regulatory frameworks, improved infrastructure, and comprehensive public education programs (Ardoin *et al.,* 2013) to address the growing environmental pressures.

Figure 6 shows the relative changes in selected pressures and impacts under three management scenarios developed using the Scenario interface of Mental Modeler in the FCM analysis. Negative values indicate improvements, meaning that pressures are reduced. In Scenario 1 (Sustainable Future) and Scenario 2 (Moderate Progress), all variables have negative values, reflecting decreased nutrient concentrations, minimised eutrophication, and reduced impacts on nature, society, and the economy—though improvements are less pronounced in Scenario 2. In contrast, Scenario 3 (Deteriorating Conditions) displays positive values for all variables, indicating worsening nutrient levels, eutrophication, and associated impacts. These results emphasize the critical role of comprehensive eutrophication management: Scenario 1 demonstrates that strong controls and proactive measures can deliver substantial environmental, societal, and economic gains; Scenario 2 shows that partial measures yield moderate benefits but leave challenges unresolved; and Scenario 3 underscores the risks of inadequate control, highlighting the urgency of enhanced management to prevent further degradation.

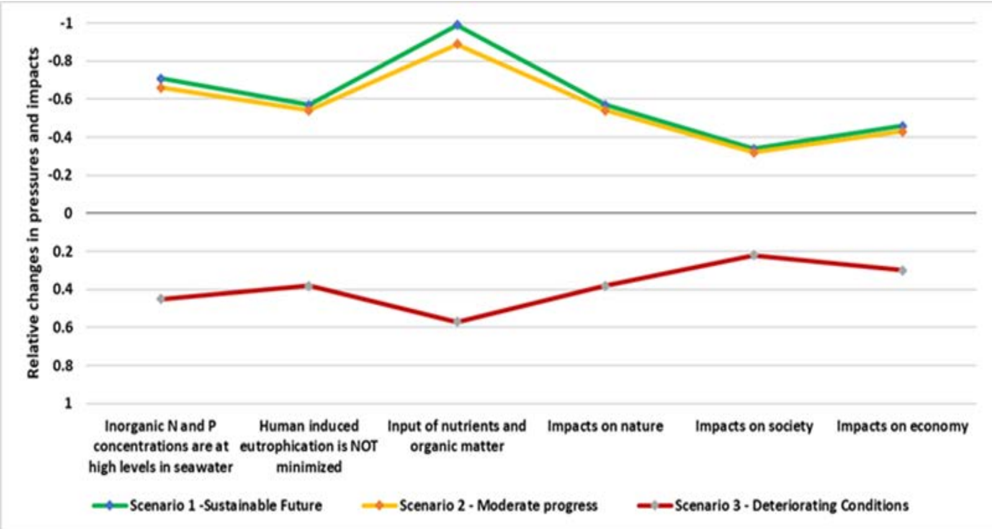

Fig. 6. Impact of Eutrophication Management Scenarios on Environmental, Societal, and Economic Factors in the Romanian Black Sea (negative values indicate improvements through variables reduction, while positive values indicate worsening conditions)

The scenario results highlight the critical role of comprehensive eutrophication management. Scenario 1 (Sustainable Future) shows that strong controls and proactive measures can deliver significant environmental, societal, and economic gains. Scenario 2 (Moderate Progress) indicates that partial measures yield some improvement but fail to address persistent challenges. Scenario 3 (Deteriorating Conditions) underscores the risks of insufficient control and escalating pressures, stressing the urgency of enhanced management.

Improvements in the Black Sea's health require reducing upstream nutrient inputs through coordinated implementation of the WFD for catchments and the Marine MSFD for marine areas. Given the transboundary nature of the basin, harmonized policies among all riparian and Danube countries are critical to avoid fragmented efforts and ensure equitable contributions to pollution reduction (Elliott, 2023).

Management coordination measures must align input, spatial, and temporal controls with output controls that define acceptable levels of ecosystem perturbation at the regional scale (Cormier *et al.,* 2010). Bow-Tie Analysis (BTA) highlights that failing to meet these thresholds will prevent achieving or maintaining GES descriptors (Cormier, 2019).

Programmes of Measures, as output controls, are essential for evaluating whether existing legislation remains effective in meeting ecological targets, ensuring older regulations are still relevant in protecting marine environments. Integrating BTA into this process can help stakeholders better visualize and manage eutrophication risks, enabling more effective achievement of MSFD objectives.

The need for coordinated transnational action is well recognized (Cormier *et al.,* 2022)as managing eutrophication across national boundaries requires a shared understanding of pressures and harmonized policies.

Without collective engagement from all riparian states, isolated national efforts—such as those by Romania—will be insufficient. Aligning nutrient management, wastewater treatment, and agricultural practices through joint implementation of the WFD and MSFD is therefore essential to ensure equitable contributions to pollution reduction and long-term restoration of the Black Sea ecosystem.

This study, while comprehensive and innovative, has several limitations. The use of BTA and qualitative modelling involves a degree of subjectivity, relying on expert judgment and available data that may not fully capture the complexity of the Black Sea ecosystem. The scenarios developed—Sustainable Future, Moderate Progress, and Deteriorating Conditions–provide a useful framework but as noted by the IPCC, represent plausible futures rather than definitive predictions. Many pressures can be managed locally (endogenic pressures), while others, such as climate change (exogenic unmanaged pressures), require global action, with local efforts focusing only on mitigating their consequences

Data limitations are also present, as the 2012–2017 monitoring dataset may not capture recent trends or site-specific variations in nutrient levels. Moreover, the focus on the Romanian coast may restrict the direct applicability of results to other regions. Nevertheless, it offers a representative case of the challenges faced by urbanised and industrialised semi-enclosed seas worldwide.

Future research should integrate more recent, high-resolution data across national boundaries and apply combined qualitative–quantitative approaches to strengthen risk assessments. Socio-economic analyses are needed to weigh the costs and benefits of measures such as nutrient controls, which may impact agriculture and employment. Research into public perception and behavioural responses can improve community engagement. Climate change impacts on eutrophication dynamics and management effectiveness require adaptive frameworks. Finally, interdisciplinary, systems-based research (Elliott *et al.,* 2020) that unites ecological, economic, social, and policy perspectives, supported by multi-sector collaboration, will enhance the sustainability and resilience of the Black Sea ecosystem.

CONCLUSION

This study has practical relevance for policymakers and stakeholders involved in managing eutrophication in the Black Sea. The application of BTA and FCM provides a structured approach to understanding and addressing the complex interplay of factors contributing to eutrophication.

By evaluating three management scenarios—Sustainable Future, Moderate Progress, and Deteriorating Conditions, the study offers some guidance on the potential effectiveness of different strategies for reducing nutrient runoff, improving water quality, and achieving GES under the EU MSFD and Good Ecological Status under the EU WFD.

This study highlights the need to integrate advanced nutrient management into agricultural policies, focusing on reducing diffuse pollution from farming. Measures such as fertiliser limits, precision farming, and nutrient recovery technologies can cut runoff significantly if supported by targeted subsidies and incentives. Upgrading urban and industrial wastewater treatment to higher standards, paired with strict discharge limits and regular monitoring, is equally vital to reducing nutrient inputs.

Nature-based coastal defences, including habitat restoration in shallow bays and lagoons, can reduce sediment disturbance, trap nutrients, and strengthen ecosystem resilience. Public awareness campaigns linked with community monitoring can encourage behavioural change and increase local participation in conservation.

Finally, tackling eutrophication in the Black Sea requires coordinated action across all riparian countries, ensuring both EU and non-EU states adopt compatible measures. Only through combined efforts in agriculture, wastewater management, habitat restoration, and public engagement can long-term improvements in water quality and ecosystem health be achieved.

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Annex 1. Management measures identified for each forcing factor in the three scenarios

Forcing Factor	Scenario	Key Measures/Actions	% Change	Control Numbers	Details
Agricultural runoff	Scenario 1: Sustainable Future	Advanced nutrient management practices in agriculture	50% reduction in nutrient runoff	Ctrl 2.2, Ctrl 3.1	Driven by technology improvements and continuous monitoring to mitigate eutrophication risks.
	Scenario 2: Moderate Progress	Moderate adoption of best farming practices	20% reduction in nutrient runoff	Ctrl 2.2, Ctrl 3.1	Progress has been made, but it has been limited due to ongoing infrastructural and regulatory challenges.
	Scenario 3: Deteriorating Conditions	Minimal changes in farming practices	10% increase in nutrient runoff	Ctrl 2.2, Ctrl 3.1	The lack of adoption of sustainable practices exacerbates nutrient runoff, which is worsened by climate impacts.
Urban and industrial wastewater	Scenario 1: Sustainable Future	Upgrades to urban/industrial wastewater treatment facilities	70% reduction in untreated wastewater	Ctrl 2.2	Substantial improvements in wastewater treatment through technological upgrades.
	Scenario 2: Moderate Progress	Improvements in wastewater treatment plants	20% reduction in untreated wastewater	Ctrl 2.2	Challenges in upgrading wastewater management infrastructure continue to slow progress.

	Scenario 3: Deteriorating Conditions	No improvement in wastewater treatment facilities	10% increase in untreated wastewater	Ctrl 2.2	Outdated infrastructure and weak regulations increase discharges.
Shipping	Scenario 1: Sustainable Future	Enforcement of ballast water management regulations	50% reduction in nutrient discharges	Ctrl 1.3.1	Strict regulation enforcement to reduce nutrient discharge and prevent invasive species.
	Scenario 2: Moderate Progress	Partial enforcement of ballast water management regulations	20% reduction in nutrient discharges	Ctrl 1.3.1	Regulatory challenges limit the full enforcement of ballast water management.
	Scenario 3: Deteriorating Conditions	Weak enforcement of ballast water management regulations	10% increase in nutrient discharges	Ctrl 1.3.1	Increased maritime traffic, partly due to geopolitical factors, exacerbates nutrient discharges.
Coastal defence and flood protection	Scenario 1: Sustainable Future	Eco-friendly coastal defence measures	30% reduction in sediment disturbance	Ctrl 1.2.1	Habitat restoration to reduce erosion and nutrient release along the coastline.
	Scenario 2: Moderate Progress	Eco-friendly coastal defence measures	10% reduction in sediment disturbance	Ctrl 1.2.1	Limited scale-up of ecosystem-based coastal protection measures.
	Scenario 3: Deteriorating Conditions	Minimal coastal defence measures	10% increase in sediment disturbance	Ctrl 1.2.1	Escalating environmental pressures highlight the inadequacy of current coastal defence measures.

Public awareness and education	Scenario 1: Sustainable Future	Public awareness campaigns	80% increase in public engagement with sustainable practices	Ctrl 6.12	Extensive public campaigns promoting sustainable practices throughout the region.
	Scenario 2: Moderate Progress	Public awareness campaigns	20% increase in public engagement with sustainable practices	Ctrl 6.12	Moderate progress in public engagement due to resource constraints and limited outreach.
	Scenario 3: Deteriorating Conditions	Sporadic awareness efforts	10% increase in public engagement	Ctrl 6.12	Limited collaboration and public education result in marginal public involvement in sustainable practices.