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ASSESSING FAIR PRINCIPLES, MSFD READINESS AND GOVERNANCE NETWORKS IN MARINE BIODIVERSITY DATA – A BLACK SEA PERSPECTIVE

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ABSTRACT

The Black Sea, a semi-enclosed basin of high ecological and geopolitical importance, faces mounting pressures from human activities and climate change, requiring robust, interoperable data systems to support biodiversity conservation and sustainable management. This study presents a comprehensive assessment of marine biological data governance across the six coastal states, combining FAIR (Findable, Accessible, Interoperable, Reusable) compliance benchmarking, repository participation analysis, MSFD (Marine Strategy Framework Directive) readiness evaluation, and a fuzzy cognitive map (FCM) analysis of governance dynamics. Data from OBIS (Ocean Biogeographic Information System), SeaDataNet, and WISE-Marine were analysed for phytoplankton, zooplankton, and benthos. Romania and Bulgaria, as EU members, demonstrated full FAIR alignment, strong repository integration, consistent reporting under MSFD Descriptors 1 and 6. Türkiye and Ukraine achieved partial compliance, while Georgia and Russia showed minimal alignment. The FCM revealed National Data Management Policy and Funding Stability as primary drivers improving data interoperability, MSFD Readiness Score as the most central component, and Long-term Sustainability as the main receiver. Positive pathways linked metadata standardisation to interoperability and readiness, while policy fragmentation and unstable funding acted as negative influences. The combined approach identifies priority action enhancing repository interoperability, metadata standardisation, and stable funding—to close governance gaps and achieve basin-wide, coordinated marine biodiversity assessments.

Keywords: harmonisation; biological data; MSFD; environmental governance, transboundary collaboration

INTRODUCTION

The Black Sea is a semi-enclosed basin bordered by Romania, Bulgaria, Türkiye, Georgia, Ukraine, and the Russian Federation. Its unique hydrological structure, characterized by a permanent anoxic deep layer beneath oxygenated surface waters, supports high biological productivity, commercially important fish stocks, and vulnerable habitats (Vespremeanu & Golumbeanu, 2018). This ecological richness, coupled with the region's geopolitical complexity, makes the Black Sea a critical area for biodiversity conservation and sustainable marine management. However, its ecosystems are increasingly exposed to cumulative anthropogenic pressures, including eutrophication, overfishing, invasive species introductions, habitat degradation, and climate-induced hydrographic changes (Lazar *et al.,* 2024a, Lazar *et al*., 2024b, Ristea *et al*., 2025, Bisinicu *et al*., 2024a). These drivers, acting across political boundaries, underscore the necessity for integrated, science-based, and cooperative management approaches.

Robust marine environmental governance depends fundamentally on the availability, quality, and interoperability of monitoring data. In the Black Sea, biological

datasets are frequently fragmented across institutions, inconsistently standardized, and unevenly accessible (Todorova, V. [Ed.], 2021, Boicenco *et al*., 2014). Such heterogeneity hampers the ability to conduct basin-wide ecological assessments, limits comparability across countries, and constrains the implementation of regional and international environmental policies (Serpetti *et al*., 2025).

Two frameworks are particularly relevant for addressing these challenges in the marine data management: the FAIR data principles (Findable, Accessible, Interoperable, Reusable) and the European Union's Marine Strategy Framework Directive (MSFD).

The FAIR principles, formulated to enhance the discoverability, accessibility, and reusability of scientific data, are increasingly recognized as a standard for modern marine data stewardship (Wilkinson *et al*., 2016, Schoening *et al.,* 2022, Kinkade & Shepherd, 2022). In marine science, applying FAIR principles ensures that biodiversity datasets, from plankton to benthic assemblages to higher trophic levels, can be shared across platforms, integrated into models, and repurposed for conservation planning, climate change assessment, and policy reporting (Snowden *et al*., 2019, Owens *et al*., 2022, McQuatters-Gollop *et al.,* 2017). The MSFD, in turn, is a binding regulatory framework for EU Member States that requires the achievement and maintenance of Good Environmental Status (GES) through harmonised monitoring, assessment, and reporting, including biodiversity components (Descriptor 1, 6) (Orejas *et al*., 2020, Bisinicu & Harcota, 2025, Bisinicu & Lazar, 2024).

In the Black Sea context, EU Member States (Romania and Bulgaria) are legally bound by the MSFD and integrated into European marine data infrastructures such as EMODnet and SeaDataNet, while non-EU riparian countries (Türkiye, Georgia, Ukraine, Russia) participate in the regional Bucharest Convention implemented by the Black Sea Commission (BSC). This creates a structural EU–non-EU division in both policy obligations and technical capacity for data governance.

While the FAIR framework addresses the technical dimensions of data stewardship, it does not explicitly cover the ethical, societal, and participatory aspects of marine research. The Open and Responsible Research and Innovation (ORRI) approach complements FAIR by embedding principles of transparency, inclusivity, and shared responsibility in research and monitoring infrastructures (Bisinicu *et al*., 2025, von Schomberg, 2013). Integrating FAIR with ORRI can provide a holistic model of marine data governance that is both technically interoperable and socially equitable, fostering trust among diverse stakeholders and improving regional cooperation.

Given the Black Sea's ecological importance, geopolitical complexity, and existing disparities in data governance, a systematic and comparative analysis is needed to assess the degree to which coastal states are aligned with FAIR principles and prepared to meet MSFD biodiversity reporting requirements (Loizidou *et al*., 2016). Such an analysis can highlight systemic gaps and identify best practices. It can also guide the development of coordinated and technically robust governance mechanisms for transboundary marine data management.

This study aims to deliver a comprehensive evaluation of marine biodiversity data governance in the Black Sea by integrating FAIR compliance benchmarking,

repository participation analysis, MSFD readiness assessment, and fuzzy cognitive mapping (FCM). Specifically, it seeks to quantify the degree of alignment of each Black Sea's riparian state with FAIR principles, assess participation in key global and regional biodiversity data infrastructures, determine readiness for MSFD biodiversity reporting, and identify both positive and negative governance and technical leverage points that influence regional data interoperability and long-term sustainability.

MATERIALS AND METHODS

Study approach

This study applied a comparative, conceptual mapping approach to evaluate marine biological data governance across the six Black Sea riparian states: Romania, Bulgaria, Türkiye, Georgia, Ukraine, and the Russian Federation, through the lens of the FAIR principles and their alignment with Marine Strategy Framework Directive (MSFD) requirements. The focus was on governance structures, data management practices, and dataset visibility in recognized international repositories, rather than the ecological content of the datasets.

The assessment covered three ecosystem components: phytoplankton, zooplankton, and benthos. Phytoplankton and zooplankton are relevant to MSFD Descriptor 1 (Biodiversity), while benthos contributes to both Descriptor 1 and Descriptor 6 (Seafloor Integrity). Physical, chemical, and other non-biological datasets were excluded to ensure thematic consistency.

Data sources

Three main infrastructures were used:

- Ocean Biogeographic Information System (Ocean Biogeographic Information System - OBIS) – Global biodiversity database (IOC-UNESCO) integrating standardized marine species occurrence records from national institutions, research projects, and regional platforms such as EMODnet Biology. For this study, marine biodiversity records from 2008–2023 were retrieved directly from the OBIS portal, filtered to the Black Sea region. These records include datasets originally contributed via EMODnet Biology.
- SeaDataNet – Pan-European infrastructure providing multidisciplinary marine datasets in standardized formats (e.g., ODV, NetCDF) and metadata protocols. Metadata for Black Sea coastal states (2008–2023) were retrieved from the Common Data Index (CDI) portal. (SeaDataNet)
- WISE-Marine – European Environment Agency (EEA) platform for official MSFD reporting (WISE Marine). Reporting status for Descriptors 1 and 6 was obtained for Romania and Bulgaria (EU Member States) and contrasted with non-EU countries, which showed absence or partial participation, as they are not legally bound by EU Directives.

Data collection and processing

For OBIS, dataset statistics were obtained by querying the number of marine biodiversity records per country (2008–2023), filtered to Black Sea boundaries, and

aggregated for inter-country comparison. For SeaDataNet, metadata parameters (dataset type, format, access conditions, and licensing) were compiled.

The reporting status for MSFD Descriptors 1 and 6 was retrieved from the WISE-Marine platform. For the second reporting cycle, each Member State's submission was classified as either "full reporting" when official data were available or "no reporting" when no submission was recorded.

Data was processed in R program for comparative statistics and visualizations (e.g., bar charts, repository comparison graphs).

FAIR compliance scoring

Compliance with each FAIR principle was assessed using a structured matrix and three-point ordinal scale:

1 = low compliance (minimal standardisation, no persistent identifiers, not indexed in international repositories)

2 = moderate compliance (partial standardisation, limited metadata and indexing, restricted access, inconsistent licensing)

3 = high compliance (fully standardised formats, open access, clear licensing, persistent identifiers, indexed in global repositories).

Scores were assigned using expert judgement supported by documented evidence from publicly available data portals (OBIS, SeaDataNet) and associated metadata records. Assessment considered the presence of standardized formats, completeness of metadata, licensing, and repository integration for the three ecosystem components.

These scores were then used to generate three-segment pie charts (red = OBIS, blue = SeaDataNet, green = MSFD) representing each coastal country. All spatial processing and visualization were conducted in ArcGIS. Non-EU states were identified as not having MSFD reporting obligations.

MSFD readiness benchmarking

Countries were classified as:

- Ready – minimum score ≥2 for all four FAIR principles.
- Partially Ready – mixed scores, with at least one principle <2.
- Not Ready – scores consistently <2.

MSFD Descriptor 1 and 6 reporting status was obtained from the WISE-Marine platform (WISE-Marine). Reporting was recorded as "full reporting" or "no reporting" based on the presence or absence of official submissions in the second reporting cycle.

A fuzzy cognitive map (FCM) was developed in Mental Modeler to link governance mechanisms, FAIR data principles, and MSFD readiness. Thirteen components were identified from literature on FAIR data implementation (Wilkinson et al., 2016b), marine environmental reporting (Magliozzi et al., 2021 ; Boschetti S. T. et al., 2021) and MSFD governance in EU marine regions (Palialexis *et al*., 2021) combined with expert judgement. Directed relationships were weighed from 1 (inhibitory) to +1 (reinforcing); the weighted adjacency matrix was built in Mental Modeler (MentalModeler) which calculated indegree, outdegree, and centrality to classify components as drivers, receivers, or ordinary nodes.

The final network diagram was enhanced to show influence signs using blue arrows for positive and orange arrows for negative relationships, with arrow width proportional to absolute weight and node size scaled to centrality.

RESULTS AND DISCUSSION

The evaluation of FAIR principles across the six Black Sea coastal states reveals marked disparities in performance (Table 1).

Table 1. FAIR compliance for marine biological data in Black Sea coastal states.

Country	Findable	Accessible	Interoperable	Reusable	Relevant Initiatives / Examples
Romania	✅ Indexed through EU platforms (EMODnet Biology, MarineData.ro)	✅ Open access to many datasets	✅ Formats compatible with European standards (ODV, NetCDF)	✅ Compliant metadata, clear licenses (e.g., CC-BY)	EMODnet Biology, MSFD, SeaDataNet,
Bulgaria	✅ Data published in international networks	✅ Online access in standardized formats	✅ Participation in SeaDataNet and other infrastructures	✅ Standards applied under EU framework	EMODnet, SeaDataNet, Black Sea Commission
Türkiye	⚠️ Low visibility in international portals	⚠️ Restricted or request-based access	⚠️ Variable formats, integration difficulties	⚠️ Incomplete licenses or metadata	National projects, collaborations via Black Sea Commission
Georgia	⚠️ Few datasets findable online	⚠️ Data infrastructure is still developing	❌ Low interoperability	⚠️ Limited reuse due to lack of standards	International projects (ENI CBC, ODINAFRICA)
Ukraine	⚠️ Some data accessible through international collaborations	⚠️ Access mainly via partnerships, not direct	⚠️ Some standards respected but not widespread	⚠️ Issues with updates and quality maintenance	Copernicus, participation in EMODnet Biology
Russia	❌ Data not indexed in European platforms	❌ Restricted or non-existent access	❌ Proprietary formats, non-FAIR aligned	❌ Lack of transparency and limited reuse	Internal initiatives, minimally aligned with EU standards

Romania and Bulgaria scored high compliance in all four dimensions. Datasets from these countries are systematically indexed in major European data infrastructures

(EMODnet Biology, SeaDataNet), openly accessible, formatted in standardized structures (ODV, NetCDF), and supported by compliant metadata and clear licensing (e.g., CC-BY). This performance is underpinned by binding obligations under the MSFD and long-term institutional integration into EU marine data workflows.

Türkiye and Ukraine showed moderate compliance, with all FAIR categories marked as partial. Türkiye's data are dispersed across multiple institutes, with low visibility in global portals, limited interoperability due to heterogeneous formats, and incomplete licensing. Ukraine faces similar technical limitations, further exacerbated by the impact of the ongoing conflict on institutional capacity and data continuity.

Georgia recorded low compliance, primarily due to an underdeveloped data infrastructure. Its reporting showed limited findability, partial accessibility, no interoperability, and restricted potential for data reuse.

The Russian Federation also demonstrated low to no compliance. Restrictive data policies, reliance on proprietary formats, and the absence of open access contributed to consistently low scores across all FAIR dimensions.

Analysis of OBIS records for the period 2008–2023 (Fig.1) revealed marked asymmetries in dataset contributions among the six Black Sea coastal states. Bulgaria and Ukraine emerged as the largest contributors, followed by Romania, while Georgia, Türkiye, and the Russian Federation recorded minimal or no entries. The pattern reflects both differences in data governance capacity and the extent of integration into international biodiversity data infrastructures.

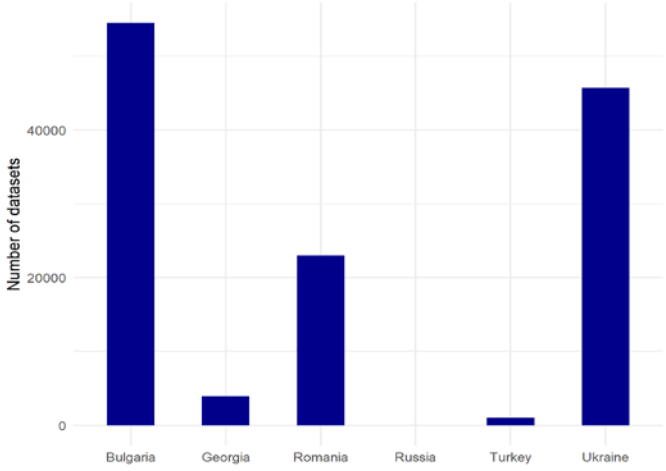

Fig. 1. Number of datasets from the Ocean Biodiversity Information System (OBIS) for Black Sea riparian countries

Bulgaria and Romania demonstrate sustained integration with EMODnet Biology workflows, with national oceanographic centres serving as data nodes that standardize, quality-check, and publish datasets via EMODnet to OBIS in recognized formats. This process not only maximizes completeness and taxonomic resolution but also guarantees compliance with international interoperability standards, resulting in consistent and visible contributions to OBIS.

Ukraine's substantial OBIS presence, particularly in the early part of the study period, can be attributed to targeted data rescue and mobilization projects undertaken with international partners. These initiatives included digitizing historical datasets, converting them into Darwin Core–compliant formats, and publishing them directly to OBIS. However, the ongoing geopolitical instability has significantly reduced institutional capacity for sustained data curation and publication, leading to a marked decline in new contributions after 2018.

In contrast, Georgia, Türkiye, and Russia exhibit very low OBIS contributions, which closely align with their weak FAIR compliance, particularly in the Findable and Interoperable dimensions. Georgia and Türkiye lack centralized marine data coordination mechanisms, resulting in limited dataset discoverability, inconsistent metadata, and incomplete publication to global portals. Russia's restrictive data policies and reliance on proprietary formats prevent integration with open international repositories, effectively excluding its datasets from OBIS.

The analysis of SeaDataNet metadata for the same period (2008–2023) (Fig. 2) reveals a parallel distribution pattern. Romania and Bulgaria again dominate dataset availability, benefiting from their strong integration into the European marine data management framework, adherence to ISO 19115 metadata standards, and active participation in EU-funded marine monitoring and harmonisation initiatives. These factors ensure that their datasets are not only discoverable but also technically aligned with European interoperability requirements. Meanwhile, Georgia, Ukraine, Türkiye, and Russia remain underrepresented in SeaDataNet. In Georgia and Türkiye, this is due to the absence of national marine data centres and the limited adoption of European metadata and formatting standards. Ukraine's reporting to SeaDataNet was already irregular before the war, with only partial dataset availability and weak metadata alignment. The war has further disrupted monitoring and data submission, resulting in an almost complete interruption of reporting. Russia's restrictive dissemination policies and reliance on closed national archives further preclude effective participation in the SeaDataNet network.

The strong alignment between OBIS and SeaDataNet trends demonstrates that repository participation is not solely a matter of dataset volume but is instead a direct reflection of governance maturity, policy alignment, and technical interoperability. Countries with high FAIR compliance, such as Romania and Bulgaria, are not only more visible in international repositories but also better positioned to sustain long-term contributions. This capability ensures that their marine biodiversity metadata remains accessible, interoperable, and reusable for regional ecosystem assessments and global biodiversity reporting.

The dataset distribution in OBIS and SeaDataNet for 2008–2023 (Fig. 3) reinforces the FAIR compliance trends. Bulgaria contributed the highest number of OBIS datasets (54,504) and had strong representation in SeaDataNet (25,865). Ukraine ranked second in OBIS (45,724) but had minimal SeaDataNet entries, suggesting earlier engagement in biodiversity data mobilization without parallel integration into European metadata systems. Romania contributed with 23,007 datasets to OBIS and 21,413 to

SeaDataNet, reflecting balanced participation in both global and European infrastructures. Georgia's contributions were limited in OBIS (3,889 in OBIS, 69 in SeaDataNet), indicating low interoperability and limited institutional capacity. Türkiye had negligible contributions to both repositories, while Russia had none, illustrating restrictive dissemination policies and reliance on non-interoperable formats.

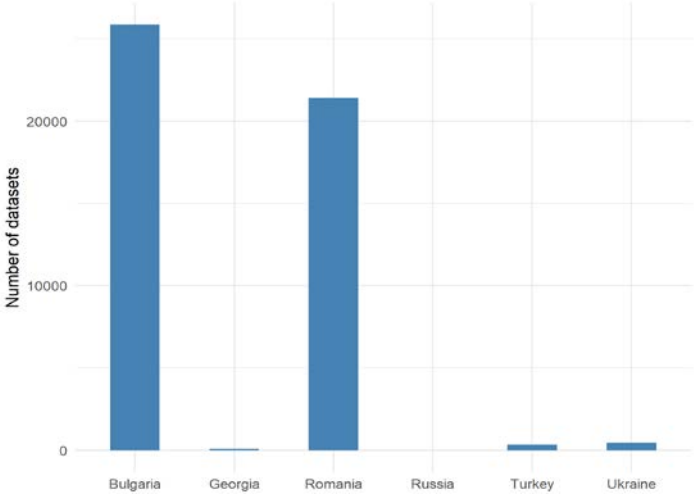

Fig. 2. Number of datasets from SeaDataNet for Black Sea riparian countries

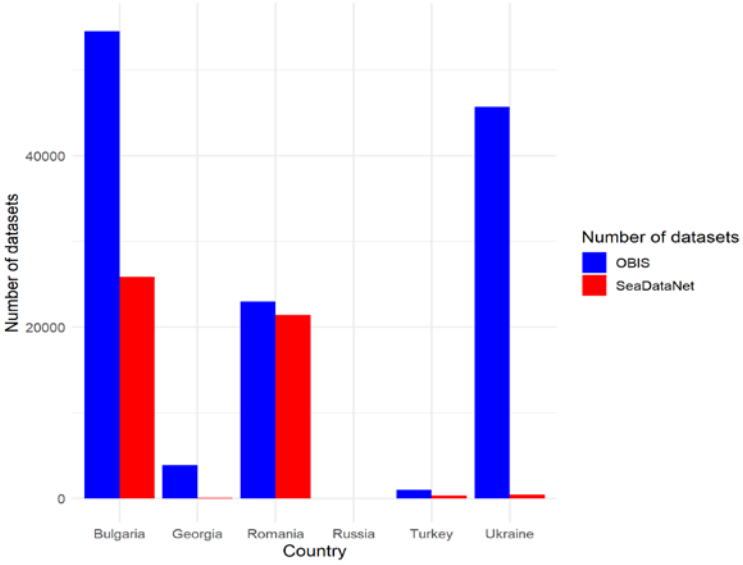

Fig.3. Comparison of the number of data sets from the Ocean Biodiversity Information System (OBIS) and SeaDataNet for Black Sea riparian countries

The FAIR compliance assessment (Table 1, Fig. 4) reveals pronounced contrasts among the six Black Sea coastal states, with a clear separation between EU and non-EU members. Romania and Bulgaria attained the maximum score (3) in all four FAIR

principles, represented as black cells in the heatmap. These results indicate fully compliant marine biodiversity data governance, underpinned by:

- Systematic integration into European marine data infrastructures (EMODnet Biology, SeaDataNet, MSFD reporting).
- Long-term use of standardized formats (ODV, NetCDF) ensuring full interoperability.
- Comprehensive metadata and open licenses (e.g., CC-BY) enabling reuse across research, policy, and monitoring frameworks.

Türkiye and Ukraine, marked in orange (score 2 across all principles), demonstrate partial compliance. Both maintain some level of participation in international networks but lack the systematic processes that ensure persistent findability and metadata completeness. For Ukraine, geopolitical instability since 2014 has disrupted data publication workflows, limiting regular updates and repository integration. For Türkiye, governance fragmentation and institution-specific data policies reduce national-level coherence and visibility. Georgia's performance (light blue, score 1 in three principles; dark blue, score 0 in Interoperability) highlights early-stage infrastructure development. While some datasets have been shared via international projects, the absence of standard formats and harmonised metadata severely constrains cross-system integration. The Russian Federation recorded a score of 0 (blue) in all categories, indicating a complete absence of FAIR-aligned governance. National datasets remain locked within internal repositories, frequently stored in proprietary formats, and are inaccessible to the broader scientific community.

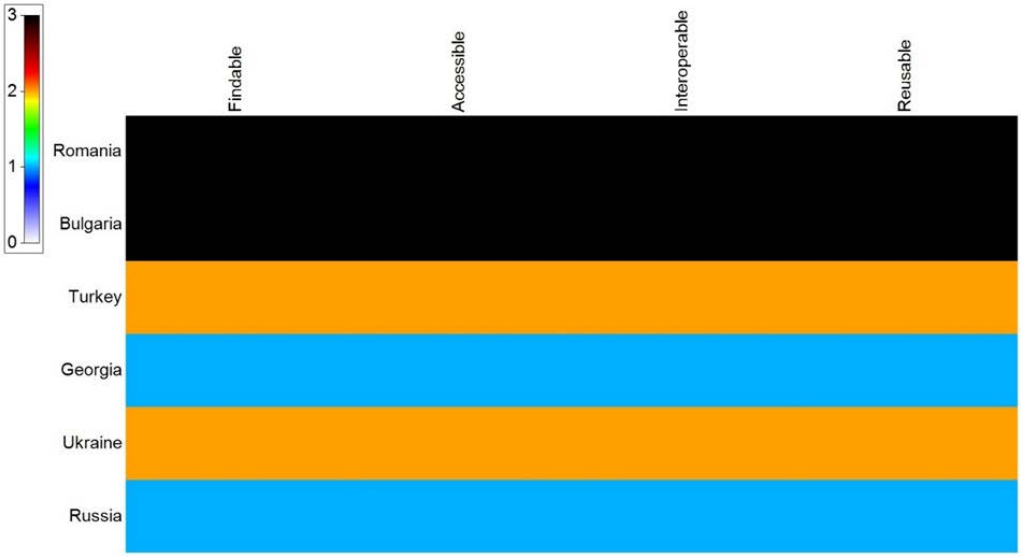

Fig. 4. Assessment of FAIR data principles compliance with marine biodiversity datasets from Black Sea riparian countries

The readiness assessment (Fig.5) provides a policy-relevant synthesis of the FAIR compliance results by mapping them onto the Marine Strategy Framework Directive (MSFD) threshold for effective biodiversity data governance (≥2 in all FAIR

principles). Under this benchmark, Romania and Bulgaria emerge as "*Ready*" (green, score 3), combining advanced technical infrastructure with institutionalized protocols for metadata quality, open licensing, and cross-platform interoperability. Their readiness reflects long-term engagement with European marine data infrastructures, integration of national monitoring datasets into both global (OBIS) and regional (SeaDataNet) repositories, and alignment with MSFD Descriptor 1 (biodiversity) and Descriptor 6) reporting requirements. Türkiye and Ukraine fall into the "*Partially Ready*" category (yellow, score 2). Both states demonstrate basic compliance with FAIR principles but face critical bottlenecks: incomplete or inconsistent metadata, fragmented repository participation, and non-harmonised licensing arrangements. For Ukraine, past participation in data mobilization projects has built a solid OBIS presence, but the absence of robust regional integration into SeaDataNet reduces its effectiveness for coordinated MSFD reporting. For Türkiye, governance is hindered by institution-specific data management practices and limited adoption of EU-aligned metadata standards, resulting in low visibility in both repositories. Georgia and Russia are classified as "*Not Ready*" (red, score ≤1), indicating systemic deficiencies. In Georgia, emerging data initiatives are hampered by weak interoperability frameworks and the absence of national-level mandates for open data sharing. In Russia, strict data access controls, the dominance of proprietary formats, and a lack of engagement with international repositories completely preclude FAIR compliance. In both cases, the absence of standardized and accessible marine biodiversity data not only limits domestic scientific capacity but also creates critical blind spots in regional ecosystem assessments, impeding collaborative management efforts across the Black Sea. Nonetheless, relevant information may exist in the published literature, but it is not systematically accessible and remains insufficiently integrated into interoperable repositories

This classification underscores that EU membership, with its associated policy and funding mechanisms, is a major enabling factor for marine biodiversity data governance in the Black Sea. Non-EU states, lacking these drivers, tend to lag in metadata standardization, repository integration, and legal frameworks for open data, creating asymmetries that weaken basin-wide ecosystem assessments and coordinated management.

While the primary focus of this assessment is on FAIR compliance, the patterns observed also reflect broader aspects of Open and Responsible Research and Innovation (ORRI). Countries with high FAIR scores, notably Romania and Bulgaria, exhibit governance practices consistent with ORRI principles (Bisinicu *et al*., 2025), including transparency in data policies, equitable access to information, and active participation in transnational data-sharing initiatives. These practices foster trust, accountability, and inclusivity, which are essential for collaborative marine research and policy-making. In contrast, the partial or low FAIR compliance observed in non-EU states is indicative of weaker ORRI uptake, particularly in openness, stakeholder engagement, and ethical data stewardship. Strengthening FAIR compliance, therefore, is not solely a technical exercise but also an effective pathway to embedding ORRI principles into

national marine monitoring frameworks, thereby enhancing the legitimacy, reproducibility, and societal relevance of biodiversity data governance in the Black Sea.

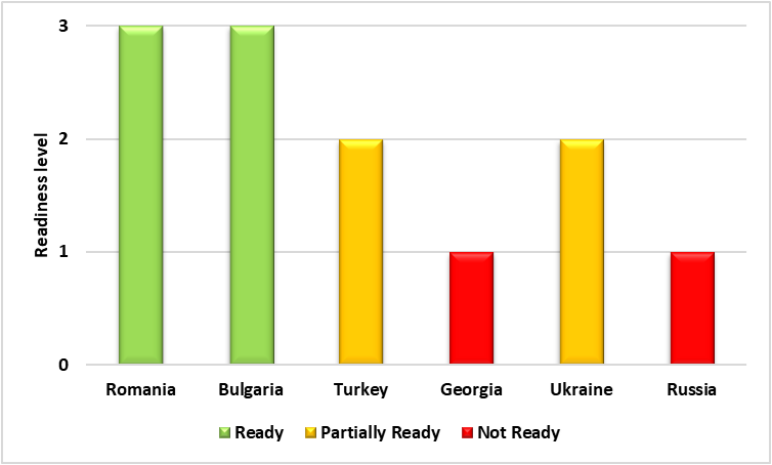

Fig. 5. Readiness level of Black Sea riparian countries for implementing FAIR data principles in marine biodiversity data management

The spatial distribution of data contributions to global (OBIS) and regional (SeaDataNet) repositories, alongside the Marine Strategy Framework Directive (MSFD) reporting status for the Black Sea (Fig. 6), highlights marked geographic disparities between EU and non-EU countries.

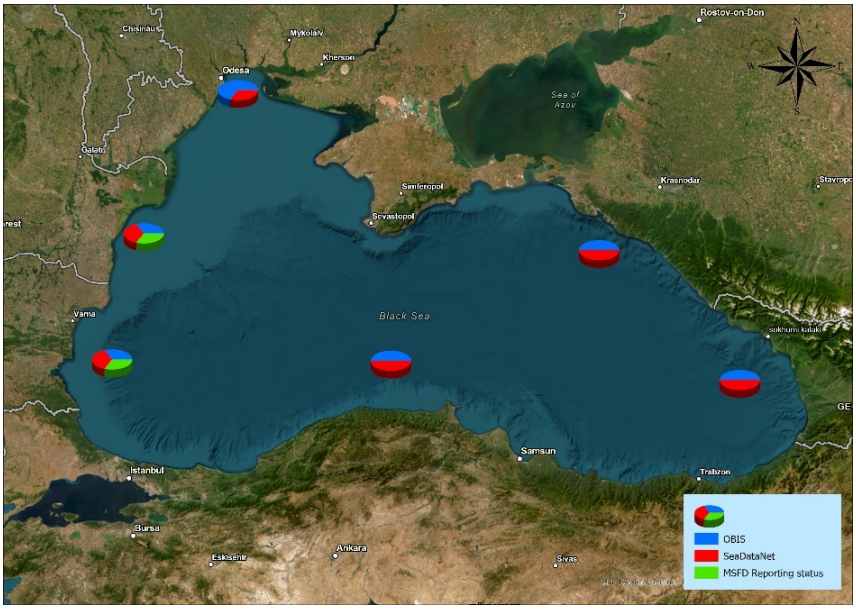

Fig. 6. Spatial distribution of contributions to global OBIS, SeaDataNet, and MSFD reporting in the Black Sea

Romania and Bulgaria, as the only EU member states in the region, display a balanced and substantial presence across all three categories: OBIS, SeaDataNet, and MSFD reporting (green sectors), reflecting their comprehensive biodiversity assessments under MSFD Descriptors 1 and 6. This alignment with EU environmental frameworks is underpinned by robust governance, standardized monitoring protocols, and effective integration into international data-sharing networks. In contrast, non-EU riparian states, which are not bound by MSFD reporting obligations, show contributions largely concentrated in regional repositories, highlighting both voluntary engagement and existing gaps in alignment with EU-driven marine assessment and FAIR data principles. These findings align with basin-wide patterns identified at the European scale (Nikolaou *et al*., 2025) who reported that despite the MSFD framework, data coverage and reporting remain incomplete and inconsistent across many European seas, with significant gaps in non-EU neighbouring regions. Our results for the Black Sea provide a concrete case study of this broader trend, illustrating how political alignment, institutional capacity, and technical infrastructure determine both FAIR compliance and MSFD reporting. In particular, the limited integration of benthic and planktonic indicators in non-EU states mirrors the pan-European underutilization of these biological components noted by Nikolaou *et al*., 2025, reinforcing the need for targeted cross-border cooperation to close monitoring and assessment gaps.

Our findings also resonate with regional observations from the Todorova, V. [Ed.], 2021, which identified persistent data gaps, particularly in biological and plankton components, across Black Sea riparian countries. These issues align with governance gaps management studies emphasizing the need for robust monitoring and coordination (Hassoun *et al*., 2024). Lastly, sea level monitoring networks reflect similar inconsistencies, indicating broad infrastructural fragility across the region (Seyhan et al., 2025).

The fuzzy cognitive map (FCM) of 13 governance and FAIR data components revealed 21 causal relationships, with National Data Management Policy and Funding Stability acting as primary drivers and Long-term Sustainability as the sole receiver (Fig. 7). MSFD Readiness Score showed the highest centrality (3.6), integrating inputs from both policy and technical levels. Strong positive pathways, such as Metadata Standards Compliance → Data Interoperability (+0.9) → MSFD Readiness (+0.8), highlight the efficiency gains from technical standardization. Conversely, negative links, including policy fragmentation reducing Regional Harmonisation (–0.6) and unstable funding undermining Long-term Sustainability (–0.7), expose governance bottlenecks. The network suggests that aligning governance frameworks, enhancing repository interoperability, and stabilizing funding would yield cascading benefits for MSFD reporting readiness and cross-border harmonisation.

The findings underscore that readiness for FAIR-compliant marine biodiversity governance is influenced not only by technical capacity but also by political alignment, binding legal frameworks, and sustained institutional cooperation.

The lack of reporting from non-EU states perpetuates a fragmented regional assessment framework, whereby EU member states generally provide more robust,

interoperable datasets to support MSFD implementation, while non-EU neighbours remain largely excluded from coordinated, basin-wide monitoring and evaluation efforts. However, even within the EU, reporting is not without gaps and challenges, although a detailed examination of these issues lies beyond the scope of this paper and may be addressed in future assessments. This asymmetry undermines the capacity to produce integrated, transboundary ecosystem assessments for the Black Sea, ultimately constraining the effectiveness of regional marine environmental policy.

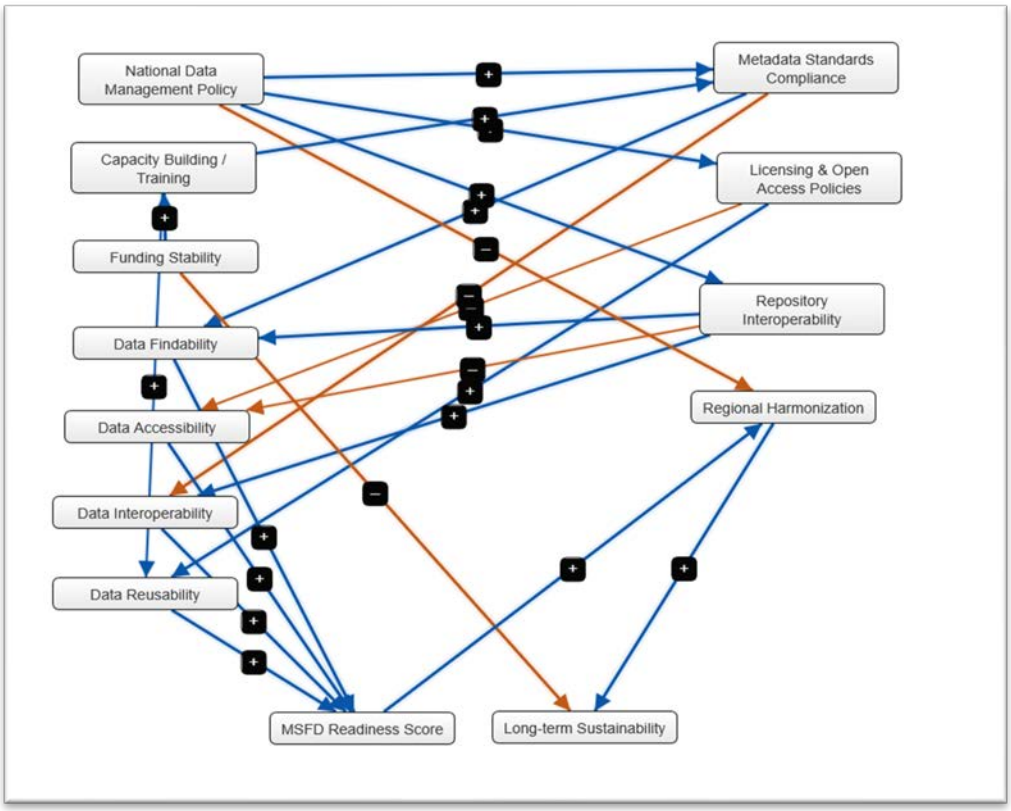

Fig. 7. Fuzzy cognitive map (FCM) showing causal relationships between governance levers, FAIR data principles, and MSFD readiness for marine biodiversity data governance in the Black Sea

The FCM results reinforce the quantitative benchmarking by revealing how governance levers and technical enablers interact to shape MSFD readiness in the Black Sea. National Data Management Policy and Funding Stability emerge as high-leverage drivers, capable of triggering positive cascading effects when aligned with robust technical standards. In particular, the chain Metadata Standards Compliance → Data Interoperability → MSFD Readiness illustrates a direct and efficient pathway for improving regional reporting capacity. Conversely, the negative influences of policy fragmentation and unstable funding highlight vulnerabilities that can erode long-term

sustainability, even in technically capable systems. These network insights underline that closing the EU–non-EU gap will require not only technical upgrades but also coordinated policy reforms and stable investment mechanisms, including adequate financing for joint monitoring initiatives to ensure basin-wide, interoperable, and sustainable biodiversity data governance.

The integration of FAIR compliance assessment, repository participation, readiness classification, and MSFD reporting performance provides a comprehensive diagnostic of the Black Sea region's marine biodiversity data governance. This multi-layered approach demonstrates that technical standards, institutional capacity, and political alignment are deeply interconnected, and that deficiencies in any one domain can cascade into reduced visibility, limited reusability, and ultimately, non-participation in regional and international monitoring frameworks. The findings highlight that without harmonised data policies, interoperable infrastructure, and sustained cross-border cooperation, the Black Sea will remain a data-fragmented marine basin, constraining its ability to produce the integrated, science-based assessments required for effective ecosystem-based management. Addressing these gaps is therefore not only a matter of improving scientific data quality, but also of strengthening the governance mechanisms that underpin transboundary marine conservation and sustainable resource use.

CONCLUSIONS

This study assesses marine biodiversity data governance in the Black Sea, linking FAIR compliance, repository participation, MSFD-aligned monitoring, and the integration of Open and Responsible Research and Innovation (ORRI) principles. Strong data policies, stable funding, and MSFD readiness drive progress, while policy fragmentation and unstable funding remain major barriers. Improving metadata standards and interoperability presents key opportunities for long-term sustainability.

The findings show that FAIR compliance depends not only on technical capacity but also on political and institutional commitment, aligning with ORRI values of openness and inclusivity. Bridging governance gaps will require interoperable infrastructure, harmonised metadata and licensing standards, and stronger Regional Sea Convention mechanisms to enable full participation of non-EU states. Advancing FAIR and ORRI together can improve biodiversity data quality and accessibility while ensuring socially responsible and inclusive governance.

Future efforts should embed FAIR and ORRI principles into regional governance frameworks, backed by stable funding and political will. Strengthening cross-border collaboration, building shared data infrastructures, and aligning with MSFD standards will be essential to transform the Black Sea into an integrated and resilient monitoring region capable of supporting sustainable marine policy.

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