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Research article

Assessing human maritime activities impacts on biodiversity: The case of shipping in the Mediterranean

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Abstract: Maritime transport plays a key role in global trade; yet, in semi-enclosed seas such as the Mediterranean, its growth intersects with exceptionally high marine biodiversity and dense coastal use, creating acute challenges for Maritime Spatial Planning (MSP). Although policy frameworks increasingly require evidence-based mitigation of shipping pressures, implementation is hindered by fragmented and unevenly structured information on shipping activities and biodiversity-relevant variables within geoportals. This research is an approach/framework to indicators' development through a DPSIR based framework and methodological workflow. It could support the development and geoportal structuring of shipping biodiversity indicators for the Mediterranean. The framework was distilled through an interdisciplinary literature synthesis: A DPSIR conceptualisation tailored to shipping–biodiversity pathways; a screening of publicly accessible international and Italian marine geoportals; and some stakeholder workshops and semi-structured interviews to validate operational relevance and feasibility. As a result, we provide a reformulated DPSIR mapping linking shipping drivers, pressures, biodiversity state variables, impacts and responses, and a structured set of qualitative, geoportal-ready indicators with associated metadata requirements. The framework was designed to be applied immediately for qualitative screening and to guide future quantitative operationalisation as harmonised datasets become available, supporting Marine Strategy Framework Directive (MSFD) and MSP implementation in the Mediterranean.

Keywords: marine biodiversity; maritime spatial planning (MSP); geoportal; shipping indicators; marine environmental management

1. Introduction: rationale and purpose

In today's global economy, around 80% of the world's goods are transported by sea, making maritime transport central to international trade and economic development [1,2].

Globally, biodiversity loss is recognized as one of the most significant environmental challenges [3,4], and the Mediterranean is a particularly exposed region: it combines high marine biodiversity and endemism with long-standing and intensifying anthropogenic pressures in a semi-enclosed basin. The basin has experienced centuries-old human use and high coastal population pressure [5–7]. The Mediterranean Sea serves as a nodal point for European and global trade through its connection to key transit points such as the Suez Canal, the Strait of Gibraltar, and the Bosphorus Strait [8,9]. About 1.4 billion tons of products, 30% of the world's oil, and roughly two-thirds of all other energy resources destined for European countries transit through this region, which accounts for approximately 19% of global maritime traffic [10].

Our use of the term "biodiversity" goes beyond a generic reference to species richness and encompasses the variety of genes, species, and ecosystems, as well as the functional diversity and integrity of ecological processes. In the marine context, biodiversity includes plants, animals, fungi, and microorganisms that inhabit the sea, the genetic diversity within each species, and the complexity of ecological relationships among them [11,12]. It also involves dependence on abiotic diversity, or "geodiversity", such as seabed morphology, sediment types, and geomorphological features, which condition habitat availability and ecosystem functioning [13].

In recent decades, the rapid growth and reconfiguration of maritime traffic, including increased trade volumes, ship gigantism, evolving routes, transshipment and short sea shipping, have intensified pressures on marine ecosystems. These pressures include greenhouse gas and pollutant emissions, underwater noise, light pollution, accidental and operational discharges, physical disturbance of seabed and coastal habitats, and the introduction and spread of non-indigenous species (NIS) via ballast water and biofouling [10,14,15]. From this perspective, indicators of shipping impacts on marine biodiversity may refer to impacts on species richness, abundance and composition, the presence or absence of key or sensitive species, trophic structure, habitat condition, and the occurrence of NIS.

Although qualitative links between many of these pressures and biodiversity impacts are conceptually well understood, establishing quantitative cause–effect relationships remain challenging, especially when information on shipping activities is fragmented or incomplete.

Despite the growing attention of National, European, and international authorities, which have introduced increasingly stringent directives to minimize the environmental impacts of shipping, the ability to design proportionate and effective measures depends on robust, spatially explicit information on maritime activities and their ecological consequences.

Geoportals and related spatial data infrastructures are meant to provide such information by enabling users to find, access, and use georeferenced data and service.

We analysed the geoportals listed in Table 1, their data, and metadata to assess the adequacy of information on drivers on marine biodiversity which stems from shipping. As highlighted by Davret et al. [16], the emergence of new geotechnologies enables the collection, analysis, processing, presentation, and dissemination of geoinformation. According to Kloppenburg et al. [17], these advances are particularly important for improving the use of georeferenced data, especially in marine environmental management. Geoportals serve as crucial components of spatial data infrastructures [18], integrate diverse datasets, and analytical methods [19]. Web-based portals enable users to locate and access geographic information and related services, such as visualization, verification, and web-based analysis [16].

Geoportals are indeed designed to integrate heterogeneous datasets collected from various institutions, agencies, and research initiatives, facilitating applications [20]. These features are particularly beneficial when studying complex environmental phenomena, such as the impact of maritime traffic on biodiversity, which requires a multidisciplinary approach.

In practice, our past work [13] showed that, although many geoportals provide extensive information on fisheries and aquaculture activities as well as on certain maritime transport variables such as shipping density, there remains a significant lack of harmonised data on key characteristics of shipping that are directly relevant for biodiversity impact assessment. These include, for example, route configuration, vessel type, size and age, operational profiles, emissions and discharges, dredging activities, and the spatial–temporal resolution necessary to support biodiversity-oriented analysis.

Therefore, we developed a qualitative overview of the major issues related to maritime traffic, such as shipping routes, vessel types, port activities, dredging, exhaust emissions, pollutant discharges, and roadstead stop, and discussed their expected qualitative effects on biodiversity [13].

Consequently, our overarching aim of this article is the development a DPSIR-based framework of indicators and metadata to support the assessment of how shipping affects marine biodiversity in the Mediterranean and how such information could be structured within geoportals.

The methodological DPSIR-based framework was distilled in a research path that included literature synthesis, DPSIR conceptualisation, geoportal screening, and stakeholder validation.

Within the scope of this study, stakeholder engagement plays a key role in ensuring the relevance and applicability of the proposed DPSIR-based indicator framework, as it contributes to the discussion, refinement and validation of drivers, pressures, and information needs related to shipping impacts on marine biodiversity. Because geoportal-oriented indicators inform routing, port management, and regulatory responses, their design must be scientifically defensible and operationally feasible. We therefore need to integrate stakeholder engagement to validate the DPSIR pathways against navigational constraints, regulatory practice, and technological readiness, ensuring that the proposed indicator structure can realistically support MSP/MSFD-oriented decision workflows.

In this paper, we do not compute numerical values of indicators or develop a weighted or operational index of shipping impacts on biodiversity. Instead, the contribution is conceptual and methodological: we formalise a DPSIR-based indicator framework, identify qualitative cause–effect relationships, and specify the types of data and metadata that marine geoportals should host to support future quantitative assessments. Indicator computation, spatialisation, and validation are explicitly defined as future work.

Thus, we provide qualitative outputs (DPSIR mapping; a geoportal-ready indicator structure and metadata requirements) and clarify future quantitative operationalisation for integrating geoportals.

Our results, therefore, have been the outcome of a progressive distil and narrowing of the DPSIR components relevant to shipping, at each research's stage, and after experts' feedback.

Against this background, in Section 2, we provide a thematic overview of the evolution of shipping in the Mediterranean and of its implications for marine biodiversity, thereby setting the conceptual foundations for indicator development. In Section 3, we describe the materials and methods, including the DPSIR-based framework, the geoportal assessment, and the stakeholder engagement process. In Section 4, we present the results in terms of the proposed indicator framework and its linkage to data availability, and in Section 5, we discuss the implications for marine environmental management and decision-support tools, with reference to the MSFD, the Maritime Spatial Planning Directive (MSPD), and related policies. In Section 6, we conclude by outlining priorities for future research and implementation.

2. Shipping evolution and impacts on marine biodiversity in the Mediterranean: conceptual foundations for indicator development

The strong asymmetries between consuming and producing regions underpin the expansion of international trade and the increasing interdependence of globalized economies. Over the last decades, this dynamic has intensified the spatial reach and structural complexity of maritime transport networks, consolidating shipping as a critical component of socio-economic development and energy security [21,22]. In parallel, recent years have witnessed a marked increase in maritime transport volumes, accompanied by the adaptation and reorganization of both maritime and land-based logistics chains, including port infrastructures, hinterland connections, and intermodal corridors [22,23].

For Mediterranean countries, maritime transport is indispensable from an economic and geopolitical perspective, but it also represents a major source of pressure on one of the world's richest and most fragile semi-enclosed seas. High traffic density, the concentration of major ports and hubs, and the juxtaposition of heavily used routes with ecologically sensitive areas create conditions in which relatively small operational changes can translate into disproportionate environmental consequences. Within this context, it becomes important to develop analytical frameworks capable of capturing the main pathways through which contemporary shipping affects marine biodiversity and of indicating which information layers are needed in geoportals to support biodiversity-oriented assessments.

In this study, we adopted the DPSIR framework to structure a thematic analysis of shipping-related drivers and pressures in the Mediterranean and to derive a set of conceptually grounded indicators. On the driver's side, particular attention is given to the growth in trade volumes and associated intensification of traffic; the increasing size and specialization of ships and ports; and the reconfiguration of major routes and transshipment patterns. These drivers are associated with multiple pressures on the marine environment, including underwater noise, atmospheric, and waterborne emissions, collision risks for large marine vertebrates, biofouling- and ballast-mediated introductions of non-indigenous species, seabed disturbance due to dredging and anchoring, and the release of solid and liquid wastes.

These pressures in turn act upon key dimensions of marine biodiversity, such as species abundance and composition, functional diversity, the integrity and extent of benthic and pelagic habitats, and the spatial distribution of sensitive or conservation-dependent species. Changes in these state variables may manifest as local or regional-scale impacts, including habitat loss or fragmentation, behavioural disturbance, increased mortality of vulnerable taxa, and shifts in community structure linked to climate and pollution stressors.

The qualitative indicator framework proposed in this paper emerges from this thematic and DPSIR-based analysis. Indicators are conceived not as purely theoretical constructions, but as operational elements that can be associated with spatial data and metadata available in existing or future marine geoportals. By qualifying, and in some cases spatially structuring, the relationships between shipping drivers, pressures, ecological states, and impacts, the framework is intended to support the generation of spatial-temporal assessments of how maritime activities influence marine biodiversity. In addition, it provides a basis for identifying information gaps and for prioritizing improvements in geoportal content and interoperability.

In summary, in Section 2, we delineate the conceptual and thematic context within which indicators are defined. The subsequent sections build on this foundation: In Section 3, we translate these concepts into a methodological framework combining DPSIR, geoportal assessment, and stakeholder engagement; in Section 4, we present the resulting qualitative indicator set and its alignment with available datasets; and in Section 5, we discuss how such a framework can inform marine management and policy before the conclusions identify key directions for future empirical and operational work.

3. Materials and methods

In our research, conducted from January 2023 to January 2024 at the regional scale of the Mediterranean Sea, we adopted a qualitative approach aimed at identifying relationships between different aspects of maritime traffic and marine biodiversity. The methodological pathway combined an interdisciplinary assessment of existing knowledge and geoportals with a transdisciplinary process involving stakeholders and sector experts. Conceptually, the study was anchored in the DPSIR framework, which provided the backbone for organising the subsequent phases and for structuring the qualitative indicator set.

The research design comprised four major phases: background research and interdisciplinary literature review; assessment of marine geoportals; stakeholder workshops; and semi-structured interviews. These phases converged in the development of a framework of qualitative indicators and associated metadata structures, organised by drivers, pressures, state, and impacts. In this manuscript, no numerical values or weights were assigned to indicators; such empirical quantification and spatialisation in marine geoportals were explicitly identified as future steps. The present contribution was conceptual and methodological: it defined the indicator framework, the qualitative cause–effect links, and the types of data required to support future, more operational assessments.

To construct a DPSIR framework that was scientifically grounded and suitable for geoportal implementation, we applied an iterative distillation process across the four methodological phases. First, from the interdisciplinary literature synthesis, we extracted an initial, inclusive list of shipping-related drivers and pressures reported in relation to biodiversity-relevant state variables and impacts. Second, we structured these elements within DPSIR and consolidated overlapping concepts into a smaller set of operational categories (e.g., distinguishing route configuration and traffic intensity from fleet composition and port system characteristics). Third, the geoportal screening was used as a feasibility filter, identifying which DPSIR elements could plausibly be represented through existing spatial layers and metadata and where critical gaps persist. Fourth, stakeholder workshops and interviews were used to validate causal pathways and to refine the response dimension in terms of realistic regulatory, technological, and infrastructural measures.

These steps led us to propose the list of qualitative indicators and metadata. The overall methodological path, including these phases and their interrelations, is summarized in Figure 1, which provides the conceptual exemplification of our methods.

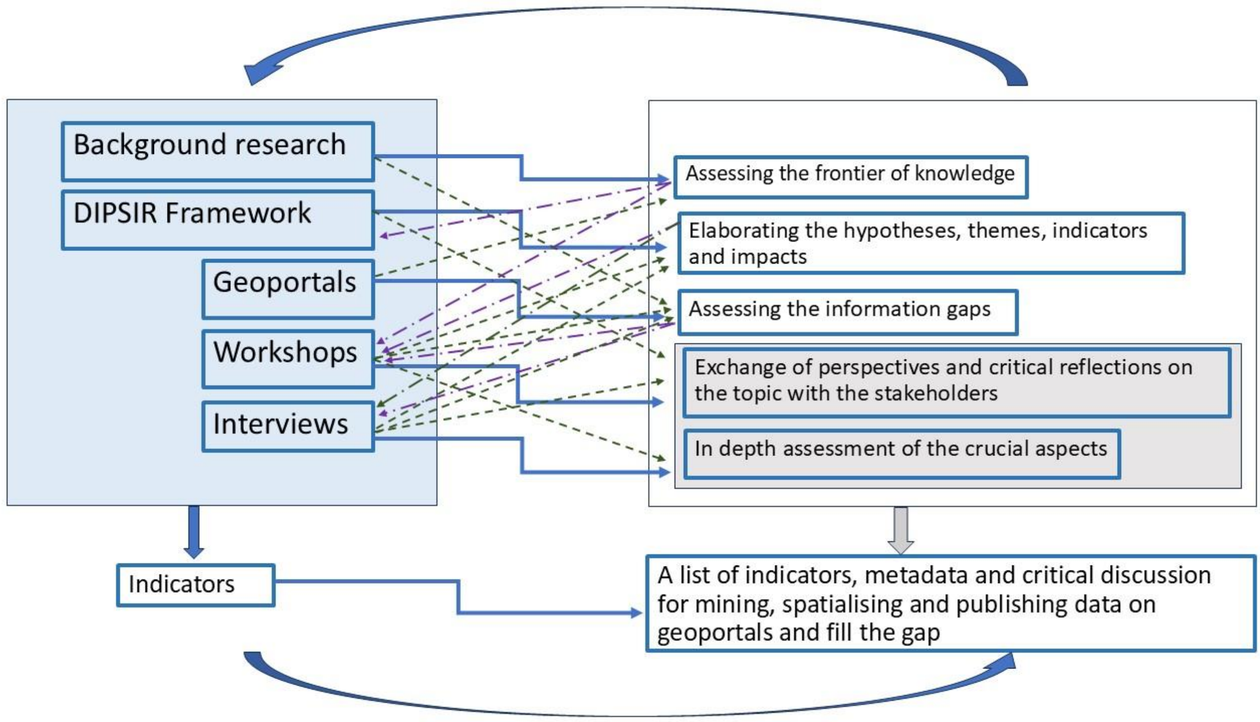

Figure 1. Methodological path. Source: Authors' elaboration.

3.1. Background research and adoption of the DPSIR framework

We reviewed scientific literature across disciplines relevant to shipping–biodiversity interactions, following an interdisciplinary approach. We drew upon Economic Geography and broader geographical scholarship on shipping, and we critically integrated insights from biology, geology, biodiversity science, economics, and marine ecology, particularly studies addressing shipping-related environmental impacts, biodiversity changes, and the economic and ecological consequences of maritime transport [10,14,15,24–31]. Interim results were discussed with natural scientists to refine concepts and definitions used throughout the manuscript and to support the initial DPSIR mapping.

Through this iterative process, information relevant to the DPSIR framework was progressively distilled by identifying shipping-related drivers emerging from the literature; screening associated pressures and ecological mechanisms reported across disciplines, and narrowing state variables and impacts to those most relevant for marine biodiversity in the Mediterranean context.

On this basis, we adopted the DPSIR framework as the conceptual backbone of the study. In the maritime context considered here, the framework was used to structure stakeholder discussions and to support the development of the indicator framework (Figure 2).

Drivers were defined as the underlying socio-economic, technological, and infrastructural forces shaping the maritime transport system. In the Mediterranean context, these included the growth of international and regional trade volumes, the increasing size, specialisation, and number of vessels, the expansion and upgrading of ports and hinterland connections, the opening or intensification of shipping routes (including route reconfiguration and traffic concentration), population growth and coastal urbanisation, and technological developments related to ship design, fuel types, and propulsion systems.

As shown in Figure 2, these drivers (ship traffic: ship types and age, ship size, routes, fuel used; and coastal activities: ports and infrastructures, maritime chokepoints, anchoring areas) generate a range of pressures (ship emissions into the air and water chemical and organic pollutants, noise, lights, ballast water discharge, biofouling, collisions with large marine vertebrates and wildlife disturbance, navigation accidents, groundings, spills, cargo loss, alteration of the seabed and coastlines, and emissions from port activities). They represent the major mechanisms through which maritime transport stresses marine ecosystems, including underwater noise, atmospheric and waterborne emissions, physical disturbance associated with dredging and anchoring, the introduction of non-indigenous species through ballast water and biofouling, dumping, and operational discharges.

State variables (damage to marine species (increased stress and mortality due to injury and disease, difficulty orienting due to noise and light pollution), changes in the substrate and morphology of the seabed due to artificial infrastructure, alteration of the marine environment with increased CO_2 levels, acidification (reduction in pH), change in nutrients and dissolved oxygen, pollution from hydrocarbons and plastics, climate change with rising sea levels, and increased extreme weather events) describe the condition of marine biodiversity and ecosystems, including habitat integrity, species richness, and composition, the presence or absence of key functional groups, and contamination levels in sediments and biota. Changes in these state variables may lead to impacts (biodiversity loss; ecosystem degradation; socioeconomic changes; human health damages), which capture the ecological consequences of shipping-related pressures, such as biodiversity loss (e.g., local declines in abundance, shifts in community structure, and loss of functional diversity), habitat loss and fragmentation, behavioural disturbance, increased mortality of sensitive taxa, and the establishment of non-indigenous species.

Responses (MSFD; MSP; development of new indicators, research focus; effective regulations & enforcement; technological advancements, i.e., cleaner ships; international cooperation) encompass regulatory, spatial, technological, and monitoring measures aimed at mitigating these impacts. These include environmental regulation and governance frameworks (e.g., MSFD, MSPD, and IMO (International Maritime Organization-conventions)), spatial planning, and routing measures, port environmental management, technological solutions such as noise-reduction measures and fuel-related innovations, and indicator-based monitoring systems. As illustrated in Figure 2, the elements associated with each DPSIR component are intended as representative examples rather than an exhaustive list.

Drivers correspond to structural and systemic characteristics of the shipping system that shape the scale, intensity, and spatial configuration of maritime activities. In this study, they included dynamics related to trade volumes and cargo demand, the size, composition and technological evolution of fleets, the development and functional specialisation of ports and hinterland connections, the configuration and concentration of major shipping routes, and the characteristics of fuel and propulsion systems. These drivers determined how shipping activities were organised in space and time and therefore set the conditions under which pressures on marine ecosystems were generated.

Figure 2 operationalises this DPSIR structure for the case of maritime transport in the Mediterranean. It illustrates how key drivers of maritime transport (D), including the growth in trade volumes, the increasing size and specialisation of fleets, the development of ports and hinterland connections, the configuration of major routes, and the characteristics of fuel and propulsion systems, generate the above-mentioned pressures (P) on the marine environment. These pressures modify the state (S) of marine biodiversity as defined above, and changes in these state variables may lead to the associated impacts (I). The resulting impacts, in turn, require responses (R) in the form of regulatory and governance instruments, spatial planning and routing measures, port environmental management, technological solutions (e.g., noise-reduction measures and fuel-related innovations), and monitoring systems based on indicators. The elements listed in each box of Figure 2 are illustrative examples rather than an exhaustive list).

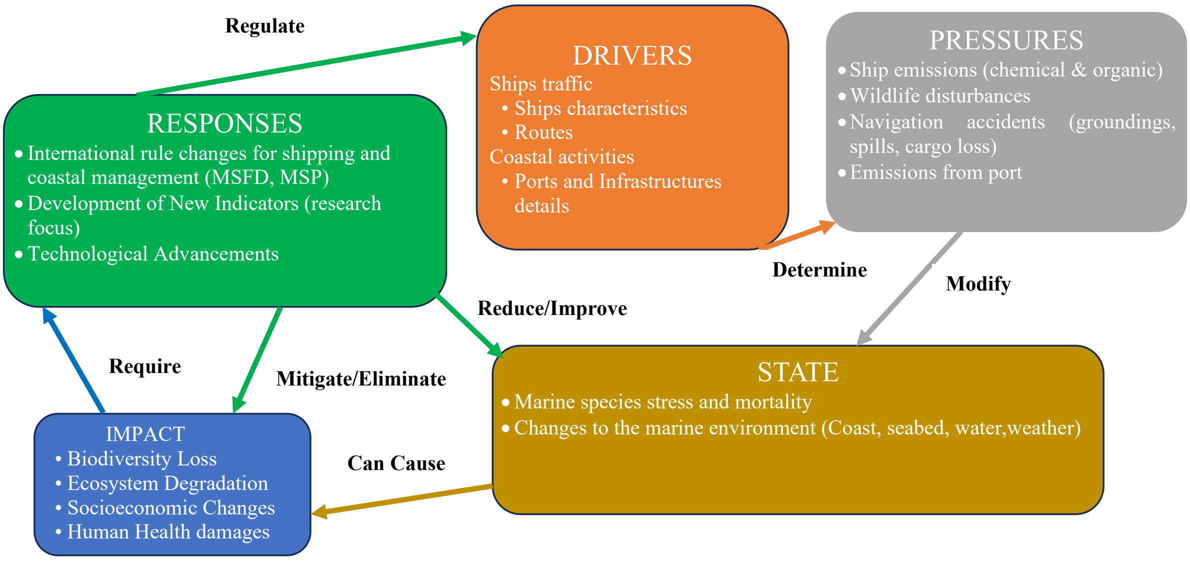

Figure 2. DPSIR-based conceptual structure of the indicator framework for shipping–biodiversity interactions. Source: Authors' elaboration on [10].

The DPSIR framework thus provides a systematic approach to understanding how anthropogenic actions affect ecological systems, how these effects propagate through environmental and socio-economic dimensions, and how society can respond to mitigate or reverse negative outcomes. By explicitly organising shipping–biodiversity interactions into the DPSIR categories, it supports integrated and adaptive management strategies and provides a common language for scientists, environmental managers, and stakeholders.

In our research process, DPSIR offers a clear reference structure for the subsequent phases (geoportal assessment, stakeholder workshops, and semi-structured interviews), helping participants to situate their operational experience within a coherent analytical scheme and guiding them to identify the links between maritime traffic and their impacts on marine biodiversity. Moreover, the elaboration construction of the qualitative indicator set is presented in the results paragraph.

As a result of this process, DPSIR components were progressively distilled and narrowed down to those most relevant to shipping activities in the Mediterranean context. The steps led to the identification and expert-informed refinement of key shipping drivers and their associated pressures, state variables, and impacts on marine biodiversity, which formed the empirical basis of the proposed indicator framework.

3.2. Geoportal assessment

Geoportals were selected as primary data sources because of their ability to integrate heterogeneous datasets from various institutions, agencies, and research initiatives, thus mitigating problems of data fragmentation and facilitating spatially explicit assessments. We addressed, in particular, the lack of information on the impact of shipping on biodiversity within existing geoportals and proposed a structure of indicators and metadata that could be incorporated into these platforms. Quantitative values may be assigned to these indicators in future work, once appropriate empirical data and harmonised datasets are available; here, we focus on the qualitative framework.

The selection of geoportals was guided by criteria aimed at ensuring the relevance and applicability of data for assessing the impact of human maritime activities on biodiversity. The first criterion was accessibility: we chose to assess publicly accessible geoportals that provide comprehensive data on maritime activities and environmental variables. Preference was given to open-access and freely available portals, recognising that information related to maritime transport and logistics is often covered by commercial or security constraints and thus difficult to access for external users. The data used in this study were gathered exclusively from publicly accessible geoportals to ensure transparency and reproducibility. This approach provides a solid foundation for analysis but does not encompass restricted data that may be accessible only through formal request procedures or agreements as some datasets of the European Maritime Safety Agency (EMSA).

The second criterion was data relevance: geoportals needed to contain data related to maritime traffic, emissions, coastal and marine uses, and/or biodiversity and habitat status. The third criterion was geographic coverage, with priority given to platforms providing spatially and temporally comprehensive datasets for the Mediterranean Sea. A further criterion was data usability, in terms of the ease of extracting information and the ability to identify layers corresponding to each DPSIR element.

A "gap" was defined as the absence, insufficiency, or lack of regular updating of data required for the construction of a specific indicator, or as the mismatch between available data and the spatial or temporal resolution needed for biodiversity-oriented assessment. The geoportal assessment was intentionally limited to platforms providing openly accessible geospatial layers and harmonised metadata; therefore, some IMO-related information systems were not included as a stand-alone source within our geoportal screening because the scope of the assessment was intentionally limited to publicly accessible geoportals providing geospatial layers and harmonised metadata through portal-based catalogues and services. Only marine data themes directly relevant to shipping activities and biodiversity-related DPSIR components were reported; themes not pertinent to the Mediterranean context or to shipping–biodiversity interactions (e.g., agriculture, forestry, and polar monitoring) were intentionally excluded.

The selection began with an assessment of geospatial platforms hosted or used by major international organisations and agencies. Many of these actors do not operate a single dedicated geoportal but rather rely on, or link to, specialised geospatial platforms for data sharing. Examples include the United Nations (UN) and the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), which support geospatial platforms functioning as comprehensive marine information systems. Additional examples include the European Union's Space Programme (COPERNICUS), EMSA, networks such as the European Marine Observation and Data Network (EMODNET), the International CO_2 Natural Analogues Network (ICONA), and information systems such as the Ocean Biodiversity Information System (OBIS) and the Global Fishing Watch project. We also analysed Italian geoportals, given Italy's central role in Mediterranean maritime traffic, its geographically articulated port system, and its importance as a trading nation and a tourist destination. Starting from geoportals of Italian Ministries and Agencies, including the Ministry of the Environment and Energy Security (MASE), the former Ministry of the Environment and Protection of Land and Sea (MATTM), and the National Agency for New Technologies, Energy and Sustainable Development (ENEA), we examined the platforms of the National System for Environmental Protection (SNPA), including the Institute for Environmental Protection and Research (ISPRA) and the Regional and Provincial Environmental Protection Agencies (ARPA). Additional geoportals included the National Biodiversity Network (RNB), those of research institutes such as the Stazione Zoologica Anton Dohrn (Naples), the System for the Defence of the Sea (Si.Di.Mar), and the Italian Port Association (Assoporti).

Table 1. List of International and Italian Geoportals Providing Data on Human Activities in the Marine Environment.

INTERNATIONAL GEOPORTAL		
Source	Marine Data theme	Data on Human activities in the marine environment
COPERNICUS (Earth observation component of the European Union's Space Programme)	Boundary (spatial reference layers): Coastline and geographic; boundaries Extreme sea level; Sea level rise; Sea state; Sea water temperature; BLUE MARKETS: Coastal services; Conservation & biodiversity; Extremes, hazards & safety; Policy & governance; Trade & marine navigation.	Area management/designation; Cables construction and structures; Mining; Pipelines; Pollution; Transport;
Ocean Biodiversity Information System (OBIS)	Bathymetry; Marine environment flag; Fish abundance & distribution; Hard coral cover & composition; Invertebrates' abundance & distribution; Macroalgae canopy cover & composition; Mangroves cover & composition; Marine birds' abundance & distribution; Marine mammals' abundance & distribution; Marine turtles' abundance & distribution; Microbes' biomass & diversity; Phytoplankton biomass & diversity; Seagrass cover & composition; Zooplankton biomass & diversity	
Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO)	Environment; Linked: International Oceanographic Data and Information Exchange (IODE), ODIS, OBIS, World Ocean Database (WOD), Copernicus marine data store, Institute for Marine and Antarctic Studies (IMAS), Pan-European infrastructure for ocean & marine data management (Seadatanet)	
International CO2 Natural Analogues Network (ICONA)	Marine Biodiversity	

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INTERNATIONAL GEOPORTAL		
United Nation (UN) The United Nations Environment Programme (UNEP)	Conserve and sustainably use the oceans, seas and marine resources; Protected Marine Area; Marine Key Biodiversity Areas; Pollution; Hazards. Linked: UNEP (UNEP Digital Library, UNEP GPML Digital Platform, UNEP World Conservation Monitoring Centre), UNEP Ecosystem Management, UN-OCEANS, UNESCO Intergovernmental Oceanographic Commission, UNDP Water and Ocean governance, IMO, UN Division for Ocean Affairs and Law of the Sea, UNDP–Oceans	Microplastic Pollution; Commercial Activity (Shipping Lanes); Ocean Pollution (Shipping Lanes, Ports); Threats posed to Marine Life (including Ship strikes); Emissions; Marine exposure due to marinas and recreational shipping; Sectoral Guidelines for Marine Litter Management: Passenger Ships; Merchant fleet by flag of registration (Container ships); Number of Passengers at Cruise Ship Ports; Intensity of pollution by maritime transport; Cumulative Pressure Indicator (pressure categories): climate change (Marine pressure of climate change), maritime transport (Intensity of pollution by maritime transport), coastal tourism (Marine exposure due to marinas and recreational shipping) and marine litter (by population and transport influence).
Global Fishing; Watch (Project that creates and publicly shares knowledge about human activity at sea regarding marine sustainability)	Transshipment Anchorages Vessel identity	Transshipment and carrier vessels track Anchorages areas, port visits and vessel voyages
European Marine Observation and Data Network (EMODNET)	Bathymetry; Human Activities; Seabed Habitats	Aggregate Extraction; Cables; Dredging; Oil and Gas; Main Ports; Maritime Spatial Planning; Forms of Area Management/Designation; Pipelines; Shipping Density; Waste Disposal
European Maritime Safety Agency (EMSA)	Oil spill monitoring service; Long Range Identification and tracking vessel; Historical vessel tracks; Linked: SafeSeaNet, CleanSeaNet	Automatic Identification System (AIS) Long range identification and tracking Additional ship and voyage information

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INTERNATIONAL GEOPORTAL		
European Environmental Agency (EEA)	Emissions of air pollutants from transport in Europe; Marine non-indigenous species in Europe's seas; Marine protected areas in Europe's seas; Status of marine fish and shellfish stocks in European seas; Changes in fish distribution in Europe's seas; Global and European sea level rise; Chlorophyll in Europe's transitional, coastal and marine waters; Oxygen concentrations in Europe's coastal and marine waters; Hazardous substances in marine organisms in Europe's seas; European sea surface temperature; Ocean acidification; Nutrients in Europe's transitional, coastal and marine waters; Extreme sea levels and coastal flooding in Europe	Emissions of air pollutants from transport in Europe; Changes in fish distribution
ITALIAN GEOPORTAL		
National System for Environmental Protection (SNPA)	Biodiversity; Reclamation and contaminated sites; Emissions and air quality; Sea and swimming areas; Radioactivity; Waste; Linked: Italian Environment Information System (SinaNet), Biodiversity Italian Network (ISPRA), The Regional Agency for Environmental Protection (ARPA)	
Institute for Environmental Protection and Research (ISPRA)	Bathing waters; Italian coastal structure; Marine species protected in Marine Protected Areas and Natura 2,000 sites in Sicily; Forecast of the sea conditions; Mareographic Network of the Venice Lagoon; National Mareographic Network; National Wave Metric Network; Marine Protected Species; Invasive Alien Marine Species	
Ministry of the Environment and Energy Security (MASE) – National Geoportal	Bathymetry; Protected areas; Sites of Community Importance (SIC); Special Conservation Zones (ZSC); Special Protection Zones (ZPS); Ecological Protection Zones (EPZ); Nature 2000 areas; Coastline project; Minor Island ports;	Ports
System for Defence of the Sea (Si.Di.Mar)	Distribution of alien species in the Mediterranean Coastal mapping of Posidonia oceanic meadows in Italy Location, zoning and boundaries of established Marine Protected Areas Strandings of cetaceans, sharks and marine turtles in Italy	
National Biodiversity Network (NNB)	Bathymetry; Posidonia oceanic meadows; Coastal marine sediments; Sites of Community Importance (SIC); Special Conservation Zones (ZSC); Special Protection Zones (ZPS); Nature 2000 areas; Coastal erosion; Dumps; Important bird and biodiversity areas; Linked: MASE, ISPRA, National Geoportal	

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INTERNATIONAL GEOPORTAL		
National Agency for New Technologies, Energy and Sustainable Development (ENEA) Ministry of the Environment and Protection of Land and Sea (MATTM)	Sites of Community Importance (SIC) Special Conservation Zones (ZSC) Special Protection Zones (ZPS) Nature 2000 areas	
Anton Dohrn Zoological Station	Bathymetry; Marine laboratories areas; Linked: Marine Coastal Information System	
ASSOPORTS (Association of Port Authorities) *	Ports data; Maritime transport in major Mediterranean and Black Sea Ports; Foreign trade by sea; Linked: Marine Traffic, EUROSTAT	Port activities

Note: * It uses geographic data for port management and planning, but it does not provide a web portal to access geospatial data. Source: Authors' elaboration.

In this paper, we reformulated a DPSIR-consistent framework to clarify how different data sources can be integrated, and we used this framework as the basis for stakeholder workshops. A further limitation of this study concerns the scope of the geoportal screening. For the assessment, we focused on openly accessible datasets with harmonised metadata that could be readily interpreted within a DPSIR-based indicator framework. As a result, some datasets available in major platforms may not have been fully captured or operationalised for biodiversity impact assessment. This limitation reflects the methodological focus and selection criteria of the study rather than the absence of such data per se.

3.3. Stakeholder workshops

The transdisciplinary component of the research began with a series of workshops designed to connect the DPSIR-based conceptual framework and the geoportal assessment with the practical experience of actors operating in maritime and environmental sectors. Our use of DPSIR helped participants situate their contributions within a coherent set of categories (drivers, pressures, state, impacts, responses) and thereby directly contributed to the refinement of the indicator framework. We organised 11 workshops at the University of Naples "Federico II" between April and May 2023 with key experts from the maritime and environmental domains. Our objectives were to identify, from operational and regulatory perspectives, the major criticalities of the shipping sector in relation to marine biodiversity, and to evaluate the technical and economic feasibility of different mitigation measures and management options.

Participants included senior Navy and Coast Guard officers, Port Authorities, Harbour Masters, shipowners from different segments, port terminal operators, technical-nautical service providers, and experts in maritime research and Mediterranean economics, as well as researchers and academics with expertise in shipping. Many are also engaged in implementing environmental and safety regulations or in verifying their compliance through their activity as shipowners, ship managers, or consultants.

The workshops facilitated the exchange of perspectives among scientists, shipping operators, regulators, and researchers, fostering a reflective process aimed at identifying perceived environmental priorities and practical constraints. They also provided qualitative insights into how measures are evaluated by those responsible for applying and enforcing them, and into how the sector perceives the timing, scope and feasibility of regulatory and technological changes [32].

3.4. Semi-structured interviews

Table 2. Topics covered during interviews with experts in the maritime sector.

TOPICS	QUESTIONS
Maritime traffic monitoring	• How do maritime traffic routes in the Mediterranean determine areas that are most affected by high traffic intensity? • How do areas most affected by maritime transport overlap with important sites for the conservation of marine species? • Which routes primarily coming from tropical countries contribute to the probable sensitive areas for the settlement of alien species? • What are the peculiarities of maritime traffic in the Mediterranean straits? • Through which channels can official data and information on maritime traffic routes in the Mediterranean be obtained?
Electrification of engines and ports	• To what extent are electric motors used in navigation, and how are ports in the Mediterranean Sea being electrified? • What are the pros and cons of electrification in maritime transport?
Naval gigantism	• What are the advantages of developing naval gigantism within the Mediterranean Sea? • How are the impacts related to collisions with marine vertebrates considered in maritime transport studies concerning naval gigantism? • Which sectors and companies most frequently utilize naval gigantism? • What are the sustainability differences between small and large vessels? • How do the environmental impacts differ between cruise ships and cargo vessels?
Other sustainability innovations	• What technologies are being developed in the maritime transport sector to limit environmental impacts, with a focus on energy transition and decarbonization? • What technologies are available to limit anchoring and grounding problems, particularly concerning naval gigantism? • Are there sensors that can be used on ships to monitor and limit noise pollution? • How significant is noise pollution considered within the maritime sector? • What existing technologies are available for ballast water management to limit the impact of alien species? • How are the regulations, as per the Ballast Water Management Convention, enforced effectively?

Note: Source: Authors' elaboration.

Given the complexity of the maritime sector and the diversity of actors involved, semi-structured interviews were conducted to deepen specific topics that emerged from the DPSIR-based analysis and the workshops, and to explore in more detail issues related to naval gigantism, technological innovation, regulatory implementation, and data availability. We conducted semi-structured interviews with four maritime entrepreneurs and one maritime research manager, selected as key national experts with international experience.

Interview topics guided the formulation of questions aimed at eliciting expert insights on spatial patterns and ecological pressures associated with shipping routes, on technological and infrastructural developments for decarbonisation and electrification, on the consequences of increasing vessel size, and on emerging solutions addressing broader sustainability challenges, including noise pollution, ballast water management and invasive species. A detailed breakdown of the critical topics and corresponding information needs is presented in Table 2.

The interviews enabled us to critically examine practical perspectives from maritime entrepreneurs and managers, whose first-hand experience contributed to a more nuanced understanding of the challenges and opportunities associated with maritime traffic and environmental sustainability. We followed established qualitative research protocols in human geography and social sciences [32,33], including careful sampling procedures, clear explanation of the research aims, informed consent, and systematic transcription and checking of interview notes. A flexible, semi-structured format was adopted, enabling spontaneous additions and comments beyond the initial question list. Interviews were conducted at the university and at the respondents' premises; in addition to audio recording (with permission), a note-taker was present to minimise the risk of misunderstandings and to facilitate rapid verification of transcripts immediately after each interview [34,35].

Insights from these interviews were used to verify the relevance and feasibility of the proposed indicators (e.g., availability of data on routes, ship types, fuel use, port infrastructure, and ballast water management) and to refine the formulation of response variables so that they reflected realistic technological and regulatory trajectories in the Mediterranean shipping sector.

4. Results: construction of the qualitative indicator framework

The Results section is organised to progressively present the conceptual DPSIR framework into a structured and interpretable indicator system. Tables and figures are presented as complementary elements: Table 3 synthesises the causal relationships between drivers, pressures, state variables, and impacts, Table 4 operationalises these relationships into a coherent set of qualitative indicators.

To improve interpretability and avoid redundancy, drivers are grouped according to their functional role within the shipping system rather than treated as independent or additive variables. Specifically, routes, ships, ports, and fuels are considered distinct analytical dimensions that capture different pathways through which shipping activities exert pressure on marine biodiversity. Routes describe the spatial configuration and intensity of maritime traffic; ships represent technological and operational characteristics influencing emissions, noise, and collision risk for large marine vertebrates; ports capture the spatial concentration of activities and infrastructure-related pressures; and fuels reflect energy choices that directly affect atmospheric and waterborne emissions.

Although these drivers are inherently interconnected, they are analytically separated to prevent double counting in indicator development. For example, the risk of non-indigenous species introduction is attributed either to route-related exposure (spatial connectivity and frequency) or to ship-related mechanisms (ballast water and biofouling), depending on the causal pathway considered. Similarly, greenhouse gas emissions are distinguished between ship-related technological performance and fuel-related energy characteristics. This analytical separation ensures conceptual clarity while preserving the possibility of integrating drivers in future quantitative assessments.

The integration of the four methodological phases, interdisciplinary background research, DPSIR conceptualisation, geoportal screening, and transdisciplinary engagement through workshops and interviews, enabled the progressive translation of the analytical problem into a structured framework for assessing shipping–biodiversity interactions. Table 3 represents the first outcome of this process: a systematic organisation of the major drivers of maritime transport and their associated pressures, ecological states, and impacts within the DPSIR architecture after the series of workshops and our reflexive elaboration.

Thus, Table 3 serves as the conceptual interface between the theoretical foundation of the study and the subsequent development of operational indicators. The structure of Table 3 highlights the causal pathways linking distinct components of maritime activity (e.g., fleet characteristics, routing patterns, anchorage behaviour, dredging operations) and energy-system characteristics (fuel mix and emission controls) to specific mechanisms acting on marine ecosystems. By organising these relationships according to the DPSIR logic, it was possible to identify recurring links, cluster pressures by their mode of action, and distinguish direct and indirect pathways affecting biodiversity. This articulation also clarified the location of each phenomenon within the analytical model; for instance, recognising that underwater noise constitutes a pressure, while collision-induced mortality represents an impact, or that port expansion may function as a driver and a pressure depending on the spatial and temporal scale considered.

The analysis of geoportals summarised in Table 1 reveals a heterogeneous coverage of data relevant to assessing shipping-related impacts on marine biodiversity. With respect to shipping, some key drivers and pressures are partially captured, particularly through datasets on shipping density, port locations, dredging activities, and emissions. For instance, platforms such as EMODNET include layers on shipping density and other maritime uses, which constitute an important basis for characterising traffic intensity and spatial patterns of maritime activity. However, these datasets are not consistently linked to biodiversity-oriented state or impact variables, nor are they always available at the spatial and temporal resolution required to assess ecological consequences.

As a result, while shipping density can be identified as a relevant driver of pressure on marine ecosystems, the translation of this information into indicators of biodiversity state or impact remains constrained by data fragmentation, limited interoperability between thematic layers, and gaps in biodiversity-related datasets. In contrast, biodiversity state variables (e.g., habitat condition, species distribution, and sensitivity) and impact-related information are often hosted in separate portals and are not systematically connected to shipping-related drivers and pressures.

The geoportal assessment, therefore, highlighted that the main limitation does not lie in the complete absence of shipping-related data, but rather in the difficulty of integrating datasets into a coherent analytical framework suitable for biodiversity impact assessment. This finding provided the empirical basis for the DPSIR-based indicator framework proposed in this study, which aimed to bridge the gap between available information on maritime activities and the requirements of biodiversity-oriented monitoring and decision-support tools.

This conceptual mapping highlighted two important features relevant for indicator development. First, existing geoportals provide uneven coverage: some drivers and pressures (e.g., ship traffic density, vessel type distribution, air emissions) are represented, whereas others (e.g., underwater noise, benthic disturbance, ballast-water dynamics, habitat condition, and biodiversity state variables) remain poorly documented. Second, several pressures exhibit strong spatial concentration, particularly in narrow straits, approaches to major ports, anchorage areas, and dredged zones, making them suitable candidates for spatially explicit indicators once more detailed datasets become accessible.

Table 3. Reformulated DPSIR linking the main drivers of maritime traffic with their impact on marine biodiversity.

<table>
<tr><th>Driving elements</th><th>Pressures</th><th>State</th><th>Impacts</th><th>Responses</th></tr>
<tr>
<td>Routes
- Origin location
- Destination location
- Marine waters crossed
- Trade routes
- Routes frequency</td>
<td>- Release of alien species
- Release of litter and pollutants in sea/air
- Release of GHG and acids
- Production of noise and light
- Additional artificial infrastructure</td>
<td>- Increase in marine animals' stress levels
- Collisions with large marine animals
- Reduction of indigenous species
- Increase of invasive alien species
- Alteration of hydrological conditions
- Animals' orientation problems due to light/noise pollution
- water turbidity
- Loss of seabed habitat
- Death of benthic organisms
- Sea level rise
- Increase of extreme weather events</td>
<td rowspan="2">- Loss of biodiversity
- Trophic chain alteration
- Alteration of seabed and coastal habitat
- Alteration in species distribution
- Loss of benthic organisms
- Adverse effect on organisms that build calcium carbonate shells or skeletons
- Adverse effect on organisms due to hypoxia or unavailability of nutrients
- Damages to exposed organisms
- Mutation of behaviour of organisms</td>
<td rowspan="2">- Loss adoption of environmentally aware technologies
- Encourage the sustainable planning of port areas, anchorage and waiting areas at straits, canals and locks
- Encourage the sustainable planning and design of new port infrastructure
- Encourage the adoption of green management practices
- Efficiency improvement of port operations
- Monitoring and control of anchorage areas
- Monitoring and control of sensitive areas such as waiting areas near canals
- Monitoring and control of waste released in ports from ships and nearby activities
- Monitoring and control of noise pollution</td>
</tr>
<tr>
<td>Ship
- Traffic sector
- Numbers
- Size
- Speed
- Fuel consumption
- Waste/sewage produced</td>
<td>- Release of alien species
- Release of litter and pollutants in sea/air
- Release of GHG and acids
- Production of noise and light
- Additional artificial infrastructure</td>
<td>- Increase in marine animals' stress levels
- Collisions with large marine animals
- Reduction of indigenous species
- Increase of invasive alien species
- Animals' orientation problems due to light/noise pollution
- water turbidity
- Death of benthic organisms</td>
</tr>
</table>

		- Increase in extreme weather events		- Monitoring and control of water turbidity - Monitoring and control of dredging activities - Reducing the environmental impact of ships by improving propulsion efficiency (hull, engines and thrusters) and using the most appropriate alternative fuels according to the ships' type, routes and trading areas - Monitoring and control of intentional discharges - Monitoring and control of accidental discharges - Analysis of discharged products
Ports - Hub/Multipurpose - Ancient/New - Public/Private - Freight/passengers volumes - Number of Ships calls - Free Trade Area volumes - Oil consumption in port area - GHG emissions in Port Oper. - Occupied areas - Garbage/Waste produced - Cold ironing availability - Alternative fuels availability - Efficiency (for operations)	- Release of litter and pollutants in sea/air - Release of GHG and acids - Production of noise and light - Additional artificial infrastructure	- Reduction of indigenous species - Increase of invasive alien species - Alteration of hydrological conditions - Animals' orientation problems due to light/noise pollution - water turbidity - Sea level rise - Increase of extreme weather events		
Dredging activity - Maintenance - Incremental - Constructive	- Release of litter and pollutants in sea/air - Need for artificial infrastructure - Release of GHG and acids - Production of noise and light - Changes in nutrients and dissolved oxygen - Release of waste substances - Changes or damage to the coastal habitat - Changes or damage to the seabed substrate and morphology	- Increase in marine animals' stress levels - Alteration of hydrological conditions - Animals' orientation problems due to light/noise pollution - water turbidity - Loss of seabed habitat - Death of benthic organisms		

	- Alteration of hydrological conditions	
Fuel	- Release of litter and pollutants in sea/air - Need for artificial infrastructure - Release of GHG and acids	- Loss of seabed habitat - Sea level rise - Increase of extreme weather events
Dumping/disposal	- Release of litter and pollutants in sea/air - Need for artificial infrastructure - Release of GHG and acids - Production of noise and light - Changes in nutrients and dissolved oxygen - Release of waste substances - Changes or damage to the coastal habitat - Changes or damage to the seabed substrate and morphology - Alteration of hydrological conditions	
Anchoring Areas	- Release of litter and pollutants in sea/air - Need for artificial infrastructure - Release of CO2 and acids - Production of noise and light - Changes in nutrients and dissolved oxygen - Release of waste substances - Changes or damage to the coastal habitat	

	- Changes or damage to the seabed substrate and morphology - Alteration of hydrological conditions	

Note: Source: Authors' elaboration.

On this basis, we developed the operational extension of the DPSIR mapping (Table 4). While Table 3 demonstrates *how* shipping activities interact with biodiversity components, Table 4 addresses *how such interactions can be assessed* through a structured set of qualitative indicators. Each indicator was linked to a specific DPSIR element and formulated to enable expert-based evaluation even in the absence of harmonised quantitative datasets. The qualitative monitoring logic embedded in the table enabled consistent comparison across components of maritime activity, while providing the foundation for future integration into geoportals and subsequent quantitative refinement.

When applied to the geoportal screening, the indicators revealed a marked asymmetry between well-documented exposure/pressure variables (e.g., corridor traffic intensity SR1, emissions intensity ST4, and dredging pressure P2) and comparatively weaker coverage of state, impact, and response dimensions (B1–B3; P4; A4; D2). For example, high values in route-related indicators (SR1–SR5) often coincided with ecological sensitivity classes (B1) and documented or inferred disturbance signals (B2), particularly in straits, port approaches, and narrow channels where navigation constraints and species distributions overlap. Ship-related indicators (ST1–ST5) showed how fleet composition and onboard performance act as modifiers of corridor exposure, highlighting the role of vessel classes and technologies in amplifying or mitigating underwater noise and collision risk with large marine vertebrates (ST2–ST3), emission intensity (ST4, including fuel and controls), and non-indigenous species transfer via ship-based vectors (ST5), which was kept distinct from route-based connectivity exposure (SR5). Port, anchorage, and compliance indicators (P1–P5; A1–A4; D1–D4) showed coastal nodes where pressures concentrate and where management and enforcement readiness (P4; A4; D2) may lag ecological vulnerability.

Overall, the shift from Table 3 to Table 4 translates the conceptual DPSIR pathways into an operational assessment tool. Table 4 is organised by accounting unit (routes/corridors, ships, ports/anchorages, compliance, and biodiversity context) to make interconnections explicit while preventing double counting in future quantitative operationalisation. In this structure, route indicators captured spatial exposure, ship indicators captured onboard mechanisms and mitigation capacity, and port/anchorage indicators captured localised operational sources; compliance indicators were attributed to either at-sea corridors or port vicinities (not both), and biodiversity layers provided the ecological context for interpretation. This organisation provided a transparent basis for geoportal integration and later refinement once harmonised datasets became available.

In Table 4, indicators are grouped by accounting unit to prevent double counting in future quantitative applications: routes captured corridor-scale exposure, ships captured onboard mechanisms and technological performance, and ports/anchorages captured localised operational sources. NIS risk was separated into route-based connectivity exposure versus ship-based vectors (ballast water and biofouling), and fuel was treated within ship emissions (as an energy-system attribute) rather than as a standalone driver to avoid duplicating GHG indicators.

Table 4. Structured Set of Qualitative Indicators for Shipping-Related Impacts on Marine Biodiversity.

Accounting unit (group)	DPSIR element	Indicator		What it captures (brief)	Anti doublecounting rule	Example qualitative scale
		code	name			
ROUTE/ CORRIDOR (spatial exposure)	Driver	SR1	Route traffic intensity	Relative density of vessel movements along a corridor/segment.	Do not sum with ship counts; use as exposure context for ship/port indicators.	Low/Medium/ High/Very high
ROUTE/ CORRIDOR (spatial exposure)	Pressure/ Impact	SR2	Overlap with biodiversity hotspots	Spatial coincidence of corridors with sensitive habitats/species areas.	Use once per corridor; do not repeat at port-scale unless analysing ports separately.	Minimal/ Moderate/ Extensive
ROUTE/ CORRIDOR (spatial exposure)	Pressure/Impact	SR3	Collision risk	Likelihood of ship–megafauna collisions based on corridor traffic and species presence.	Attribution is route-based (where encounters occur); do not also count as ship-based unless using ship class as modifier.	Low/Medium/ High
ROUTE/ CORRIDOR (spatial exposure)	Pressure	SR4	Underwater-noise exposure	Chronic low-frequency noise exposure associated with corridor traffic intensity.	Route indicator = exposure field; ship indicators may explain contributors. Avoid adding both as totals.	Low/Medium/ High

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Accounting unit (group)	DPSIR element	Indicator		What it captures (brief)	Anti doublecounting rule	Example qualitative scale
		code	name			
ROUTE/ CORRIDOR (spatial exposure)	Pressure/Impact	SR5	NIS connectivity exposure	Exposure linked to route connectivity (origin–destination patterns and frequency) increasing probability of NIS arrival.	Counts ‘where introductions may arrive’; do not duplicate with ballast/biofouling compliance indicators.	Low/Moderate/ Elevated
SHIP (onboard mechanisms & performance)	Driver	ST1	Dominant fleet composition	Prevalent vessel types/size classes operating in an area.	Use as a modifier for route exposure (SR1–SR4), not as an additive pressure.	Container/ Tanker/Mixed
SHIP (on board mechanisms & performance)	Pressure	ST2	High-noise/high-speed segment prevalence	Share of vessels likely to generate higher noise/collision risk due to speed/power profile.	Do not double count with SR3/SR4; treat as contributor explaining corridor exposure.	Low/Moderate/ High
SHIP (on board mechanisms & performance)	Response	ST3	Noise-reduction technology uptake	Adoption of quieting measures (propeller/hull/engine retrofits; operational measures).	Response metric; not additive with noise exposure. Use to evaluate mitigation capacity.	Absent/ Emerging/ Moderate/ Widespread
SHIP (on board mechanisms & performance)	Pressure/Response	ST4	GHG/air-emission intensity & controls (incl. fuel)	Emission profile driven by fuel mix, engine efficiency and after-treatment/control technologies.	Fuel is embedded here; do not create a separate ‘fuel’ driver when computing emissions indicators.	High/Medium/ Low (or: Absent/ Partial/Advanced controls)
SHIP (on board mechanisms & performance)	Response	ST5	Ballast & biofouling management performance	Effectiveness of onboard measures reducing NIS transfer via ballast water and hull biofouling.	Counts ‘how introductions happen’; keep distinct from SR5 (connectivity exposure).	Weak/Moderate/ Strong

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Accounting unit (group)	DPSIR element	Indicator		What it captures (brief)	Anti doublecounting rule	Example qualitative scale
		code	name			
PORT / COASTAL NODE (localised operations)	Driver	P1	Port traffic & connectivity	Role and intensity of port activity (calls, volumes, connectivity).	Use as local intensification context; do not add to corridor intensity unless modelling network flows.	Local/Regional/ Hub
PORT/ COASTAL NODE (localised operations)	Pressure	P2	Dredging pressure	Frequency and magnitude of dredging operations affecting turbidity and seabed disturbance.	Port-scale pressure; separate from corridor exposure.	Low/Episodic/ Recurrent/ Intensive
PORT/ COASTAL NODE (localised operations)	Pressure/Impact	P3	Coastal transformation due to port expansion	Extent of habitat alteration linked to port expansion/infrastructure.	One-off/phase-based; do not combine with dredging as the same indicator.	None/Planned/ Ongoing/ Completed
PORT/ COASTAL NODE (localised operations)	Response	P4	Environmental management capacity	Strength of monitoring, waste reception, enforcement and environmental management systems.	Response metric; evaluate mitigation readiness rather than adding as pressure.	Basic/ Intermediate/ Advanced
PORT/ COASTAL NODE (localised operations)	State/Impact	P5	Habitat sensitivity near port areas	Vulnerability of habitats/species near port infrastructure and approaches.	Context layer for port pressures; not additive with port traffic.	Low/Medium/ High sensitivity
ANCHORAGE (subset of coastal nodes)	Pressure	A1	Anchorage intensity	Frequency and duration of anchoring events.	Local pressure; do not add to corridor intensity.	Occasional /Regular/ Persistent
ANCHORAGE (subset of coastal nodes)	State	A2	Benthic sensitivity under anchorage zones	Ecological sensitivity of habitats beneath anchorage footprints.	Context for A1; not additive as a second pressure.	Low/Moderate/ High

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Accounting unit (group)	DPSIR element	Indicator		What it captures (brief)	Anti doublecounting rule	Example qualitative scale
		code	name			
Accounting unit (group)	DPSIR element	Indicator	What it captures (brief)	Anti doublecounting rule	Example qualitative scale	Accounting unit (group)
ANCHORAGE (subset of coastal nodes)	Impact	A3	Cumulative anchoring disturbance	Degree of seabed alteration due to repeated anchoring.	Impact outcome; do not sum with A1.	Low/Medium/ High
ANCHORAGE (subset of coastal nodes)	Response	A4	Anchorage management regime	Existence and enforcement of regulated/planned anchorage practices.	Response metric; interpret with A1–A3.	Unregulated/ Basic/Planned/ Managed
COMPLIANCE (ship/port interface)	Pressure	D1	Dumping/discharge occurrence	Occurrence of illegal/accidental discharges at sea or near ports.	Attribute to one spatial unit (at-sea corridor vs port vicinity) based on evidence.	None/Rare/ Occasional/ Recurrent
COMPLIANCE (ship/port interface)	Response	D2	Monitoring & enforcement strength	Effectiveness of monitoring, inspections and enforcement (at-sea and port controls).	Response metric; avoid combining with D1 as a single score.	Weak/Moderate/ Strong
COMPLIANCE (ship/port interface)	State/Impact	D3	Contamination signals (sediments/biota)	Evidence of pollutants potentially linked to shipping activity.	Outcome layer; interpret alongside D1 and local sensitivity (P5/B1).	Background/ Elevated/High concern
COMPLIANCE (ship/port interface)	Impact	D4	Discharge risk–hotspot overlap	Overlap between discharge-risk areas and sensitive ecosystems.	Do not double count with SR2/P5; use as an interaction metric.	Low/Moderate/ High
BIODIVERSITY CONTEXT	State	B1	Biodiversity sensitivity class	Sensitivity classification of habitats/species (baseline ecological vulnerability).	Context layer; not to be summed with pressures.	Low/Medium/ High/Very high
BIODIVERSITY CONTEXT	Impact	B2	Biodiversity impact level	Observed or inferred effects attributable to shipping pressures.	Impact layer; do not sum with exposure indicators.	None/Emerging/ Documented
BIODIVERSITY CONTEXT	Response	B3	Strength of spatial protection	Effectiveness of spatial protection measures affecting exposure/pressures.	Response layer; interpret with overlap indicators.	Weak/Partial/ Strong

Note: Source: Authors' elaboration.

The resulting indicator set provided a coherent framework that can be applied immediately in qualitative assessments and later expanded through georeferenced, quantitative, or semi-quantitative approaches in geoportals. In this sense, Tables 3 and 4 worked jointly as a two-tiered framework: Table 3 delineates the structure of interactions between maritime transport and biodiversity, while Table 4 operationalises that structure into a consistent and scientifically traceable indicator system. This progression ensured transparency, reproducibility, and applicability of the results within marine environmental assessment and supports the development of future, geoportal-enabled tools for biodiversity-oriented maritime spatial planning in the Mediterranean.

5. Discussion

Our results of this study highlight the potential and limitations of existing data infrastructures for assessing the impacts of shipping on marine biodiversity in the Mediterranean. The geoportal analysis (Table 1) shows that substantial information is available for some components of the maritime system, particularly traffic density, vessel typologies, and emissions. By contrast, spatially explicit data on biodiversity state and impacts, as well as on certain pressures, such as underwater noise, anchoring disturbance, and ballast-water dynamics, remain incomplete or fragmented. This asymmetry shapes what can be monitored and modelled and partly explains why current tools emphasise emission-related variables rather than the full spectrum of shipping–biodiversity interactions.

Within this context, the DPSIR-based mapping presented in Table 3 provides a structured interpretation of how shipping activities influence marine ecosystems. By organising elements into drivers, pressures, states, impacts, and responses, the framework makes explicit the causal pathways linking maritime transport to biodiversity outcomes. It clarifies, for example, how route configuration and traffic intensity (drivers) translate into collision risk, noise, seabed disturbance, and species transfers (pressures), how these affect habitat condition, species composition, and contamination levels (state), and how they may result in biodiversity loss, habitat fragmentation, and the establishment of non-indigenous species (impacts). This conceptual articulation is essential for moving beyond generic references to “shipping impacts” and for identifying which processes should be prioritised in monitoring and management.

The stakeholder workshops and semi-structured interviews add a transdisciplinary dimension that cannot be captured by spatial data alone. Practitioners from shipping, port management, naval services, and environmental agencies broadly confirm the relevance of the DPSIR pathways, but also stress the constraints associated with safety requirements, fleet renewal cycles, port infrastructure, and the coexistence of international and European regulatory frameworks. These insights are reflected in the indicator framework through the inclusion of response-oriented indicators that account not only for the presence of measures but also for their technical and economic feasibility in the Mediterranean context.

The qualitative indicator set in Table 4 can be interpreted as the operational extension of the conceptual mapping in Table 3. It translates DPSIR relations into assessable elements that can be used to compare routes, ports, anchorage areas, fuel configurations, and dumping practices in terms of their likely relevance for biodiversity. The qualitative scales proposed for each indicator enable expert-based evaluation and preliminary spatial screening, while preserving compatibility with future quantitative calibration as more harmonised datasets become available. In this sense, the framework functions as a diagnostic tool under current data constraints and as a scaffold for future geoportal-enabled analyses.

An important implication of our results is that improving biodiversity-oriented assessments will depend not only on generating new data, but also on reorganising existing information according to coherent analytical structures. Many of the datasets identified in the geoportal screening, such as AIS-derived traffic layers, port statistics, emissions inventories, and some habitat and species distributions, can support several indicators in Table 4 if they are accompanied by adequate metadata and interoperable formats. Other elements, notably underwater noise, anchoring disturbance, and fine-scale biodiversity state indicators, will require targeted monitoring efforts and stronger data-sharing arrangements. The indicator framework makes these gaps explicit and offers a reference for prioritising future data collection and integration.

From a governance perspective, the DPSIR-based indicator system offers a way to better align scientific assessment with instruments such as the MSFD and the MSPD. By explicitly linking drivers and pressures to states, impacts, and responses, the framework can help environmental authorities and planners trace how specific management options, i.e., route reconfiguration, speed reductions, designation of sensitive areas, stricter port environmental standards, or fuel-related measures, may affect biodiversity-relevant variables. Furthermore, stakeholder feedback underscores that ecologically desirable measures must be evaluated against operational feasibility and socio-economic constraints. The qualitative nature of the indicators enables these trade-offs to be captured and discussed transparently, rather than being concealed within composite indices.

Although we focus on the Mediterranean, several of the structural patterns identified, such as the overlap between dense traffic corridors and biodiversity hotspots, the concentration of pressures around ports and anchorages, and the fragmented nature of environmental information, are likely to occur in other heavily used sea regions. The framework developed here can therefore be adapted to different geographical contexts, such as other inner seas, if it is calibrated with local data and expert knowledge. In this sense, the present work should be viewed as a conceptually robust starting point for building integrated, geoportal-ready tools to support biodiversity-oriented maritime spatial planning.

6. Conclusions

In this study, we developed a qualitative, DPSIR-based framework to analyse the relationships between maritime transport and marine biodiversity in the Mediterranean and to support the design of indicators that can be implemented in marine geoportals. Starting from an interdisciplinary literature review and combining geoportal assessments and the elaboration of a DPSIR with stakeholder workshops and semi-structured interviews, we translated a complex set of shipping–biodiversity interactions into a structured system of drivers, pressures, state variables, impacts, responses, and qualitative indicators. The resulting framework is summarised conceptually in Table 3 and operationalised through a set of qualitative indicators in Table 4.

Three major conclusions emerge from our results. First, existing geoportals provide substantial information on certain drivers and pressures, particularly traffic density, vessel characteristics, and emissions, but offer limited and heterogeneous coverage of biodiversity state and impact variables. This imbalance strongly constrains the possibilities for comprehensive biodiversity-oriented assessments of shipping. Second, the DPSIR structure proves useful not only as a conceptual tool, but also as a practical guide for indicator design: it helps identify the aspects of maritime activity that are most relevant for biodiversity, the mechanisms that are visible in available data, and where the most critical gaps lie. Third, the transdisciplinary engagement with stakeholders is essential for ensuring that proposed indicators reflect realistic technological, regulatory, and economic conditions, rather than purely theoretical priorities.

The qualitative indicator set proposed here does not aim to provide a definitive or exhaustive solution. Rather, it offers a coherent and transparent basis for future work in three directions: the progressive integration of indicators into marine geoportals, starting from those for which data are available; the development of targeted monitoring efforts and data-sharing agreements to fill the most critical gaps, especially for underwater noise, anchoring disturbance, and biodiversity state; and the gradual calibration of indicators through quantitative or semi-quantitative methods, once harmonised datasets and stakeholder-validated weighting schemes become accessible.

From a policy perspective, the framework can support the implementation of the Marine Strategy Framework Directive and the Maritime Spatial Planning Directive by providing a structured way to relate shipping-related drivers and pressures to biodiversity outcomes and management responses. It can assist environmental authorities, planners, and port managers in identifying critical areas, evaluating alternative mitigation options, and prioritising interventions under conditions of data uncertainty. Although tailored to the Mediterranean, the approach is sufficiently general to be adapted to other regional seas, provided that local ecological characteristics, traffic patterns, and governance settings are considered.

This work should be regarded as a step towards integrated, indicator-based assessments of shipping impacts on marine biodiversity. By combining DPSIR conceptualisation, geoportal analysis and stakeholder knowledge, we establish a diagnostic lens on current data and governance configurations and a roadmap for future operational developments in biodiversity-oriented maritime spatial planning.

Authors contributions

Clara Di Fazio: Data curation; Formal analysis; Investigation; Visualization; Roles/Writing-original draft; and Writing. Stefania Palmentieri: Data curation; Formal analysis; Investigation; Methodology; Visualization; Roles/Writing-original draft; and Writing-review & editing. Maria Paradiso: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Roles/Writing-original draft; and Writing-review & editing.

For Italian Evaluation Purposes: Clara Di Fazio has written Paragraph 3.2—Geoportal assessment; Paragraph 3.3—Workshop; Stefania Palmentieri has written Paragraph 2—Shipping Evolution and its impact on marine biodiversity; Paragraph 3.4—Semi-structured interviews; Paragraph 4—Results; Maria Paradiso has written Paragraph 1—Introduction: Rationale and purpose; Paragraph 3—Materials and Method; Paragraph 3.1—Background research and adoption of DPSIR framework; Paragraph 5—Discussion; Paragraph 6- Conclusions.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare that they have no conflict of interest.

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