Marine biodiversity indicators and online data knowledge systems

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Abstract

Coastal marine ecosystems and biodiversity are changing rapidly under climate forcing, resource use, pollution and habitat modification. Monitoring these changes, and tracking progress across policy targets, remain constrained by uneven data coverage, fragmented observing networks and inconsistent measurement practices. International policy frameworks, most prominently the Kunming-Montreal Global Biodiversity Framework, alongside Sustainable Development Goal 14 and Regional Seas Agreements, rely on structured indicators to track biodiversity state, pressures, change and management outcomes. However, how well existing indicators align with current monitoring needs, data readiness, analytical maturity and recurring assessment pipelines has not been evaluated systematically. This review compiled and synthesised 145 operational marine biodiversity indicators and examined 223 marine-relevant online knowledge systems that were active and accessible in December 2025. Indicators were classified by analytical role within a state, pressure, response, benefit model, and assessed against their data sources, calculation transparency, update frequency and assessment applicability across depth zones and regions. Indicators describing biodiversity state and spatial pressure composites dominate current reporting and assessment use, particularly for coastal habitats and species-population trends. Fisheries sustainability indicators are comparatively well represented, while indicators tracking responses and biodiversity-linked benefits remain less mature, less standardised across measurement pipelines and less developed for offshore and areas beyond national jurisdiction. The current indicator overview shows expanding analytical capacity, but routine indicator production pipelines and integration of measured biological responses into recurring assessments remain limited relative to pressure mapping and species-level status reporting. The next phase of marine monitoring will likely be defined by recurring analytical production of indicators, greater comparability of measurements and stronger integration of observed biological patterns into routine assessment and policy tracking. Further development of indicators that can support management of pressures at a sector-level to support environmental impact assessment and area-based management or zoning of human activities remains a key direction for future analytical progress.

1. Introduction

Marine life and biological diversity shift continually through chemical, physical and biotic (including human) interactions. Scientific and policy interest in predicting and interpreting these changes has intensified, driven by the growing understanding that marine biodiversity underpins economic and social benefits (Díaz et al., 2019; Fleming et al., 2023; Dajka et al., 2025). This review provides a broad, marine-focused evaluation of biodiversity metrics (including indicators, indices and spatial datasets) and online biodiversity knowledge systems that support monitoring, assessment and reporting across global and regional ocean governance regimes. Ocean monitoring enables detection of trends in species, habitats and ecosystem processes, interpretation of cumulative pressure responses, and alignment of conservation actions with societal outcomes. Indicators, and their measurement protocols, allow comparison of regional conditions, evaluation of management interventions, and tracking of policy progress (Pereira et al., 2013; IPBES, 2019). Planning economic outlooks, identifying emerging risks, and ensuring accountability for international commitments require transparent and interoperable indicator frameworks (von Schuckmann et al., 2025). Indicators serve as bridges between systematic marine observation and decision-making across multilateral agreements.

The terrestrial and marine biospheres differ fundamentally in structure, scale and observability, which directly shape what monitoring systems can realistically achieve. On land, the biosphere is comparatively two-dimensional, bounded by atmosphere and soil, allowing fixed plots, repeat surveys and persistent visual detection of organisms and habitats. In the ocean, biodiversity occupies a dynamic three-dimensional environment, structured vertically by light, oxygen, temperature and pressure gradients, creating stacked ecological provinces rather than a single surface plane, and complicating systematic sampling (Pereira & Cooper, 2006). Microorganisms constitute most of the marine biosphere, driving primary production, nutrient cycling and trophic transfer, yet remain difficult to monitor consistently due to their size, turnover rates and detection limits of conventional survey methods (Gagne et al., 2020). Unlike terrestrial systems, where static infrastructure commonly hosts long-term biodiversity sensors, marine observations increasingly incorporate fixed-location assets such as harbours, offshore energy and industrial platforms, aquaculture infrastructure, and sustained moorings or buoys, although these platforms have historically prioritized ocean physics over biological standardization and repeat survey continuity (Canonico et al., 2019; Deyoung et al., 2019; Martín Míguez et al., 2019). Complementary ocean observation pathways including satellite and animal telemetry, ships of opportunity and autonomous observing systems are rapidly expanding capacity to monitor ecosystem state and species movement (Benway et al., 2019; Mariani et al., 2021), but cross-platform harmonization, indicator automation, and standardized biodiversity pipelines remain uneven relative to terrestrial monitoring (Blowes et al., 2019). Large-scale syntheses show terrestrial metrics have achieved broader methodological alignment, indicator automation and policy uptake, while marine frameworks lag in cross-component compatibility and benefit tracking (Blowes et al. 2019; Burgess et al. 2024). Microbial dominance, vertical stratification, high dispersal connectivity and rapid compositional reorganisation in marine biomes explain why land-derived monitoring strategies, even when conceptually transferable, often fail to meet the logistical and analytical constraints of ocean systems (Steele & Brink, 2019).

Demand for marine biodiversity indicators translates into operational monitoring only when supported by structured, sustained observing systems. Indicators derive from surveys, monitoring programmes and observing networks, and reflect spatial and temporal sampling footprints across biodiversity levels (Miloslavich et al., 2018; Muller-Karger et al., 2018). Indicator development and analytical support differ markedly between realms. Terrestrial biodiversity metrics, models and indicator frameworks have advanced rapidly through systematic syntheses and standardisation (Burgess et al., 2024; Hughes et al., 2025). Marine indicator identification and development, by comparison, has been more fragmented, with development pathways often anthropocentric and shaped by sectoral or policy-specific drivers (Teixeira et al., 2016). Indicator maturity and recurring production pipelines are also influenced by governance mandates, which determine what is measured, reported and updated. International monitoring alignment efforts include essential variable frameworks. The Essential Ocean Variables (EOVs) defined under the Framework for Ocean Observing (IOC-UNESCO, 2012) outline sustained measurements required for globally coordinated, long-term ocean observation. The biology and ecosystems EOV (BioEco EOV) support standardised assessments of habitat extent, coral and seafloor community composition, and ecosystem condition and change (Miloslavich et al., 2018; Martin Miguez et al., in prep). The complementary Essential Biodiversity Variables (EBVs) are part of Bio-Eco EOV and provide a framework for indicators to support the Kunming-Montreal Global Biodiversity Framework (KMGBF) (Dajka et al., 2025) and other multilateral environmental agreements. The Global Climate Observing System (GCOS) coordinates Essential Climate Variables (ECVs), which also encompass some BioEco EOVs, emphasising long-term climate feedback on marine systems. Indicator production remains limited by spatial, temporal and depth-linked data coverage, analytical maturity and comparability across observing networks (Muller-Karger et al., 2018). The United Nations Sustainable Development Goals (SDGs), adopted in 2015 to guide sustainability progress to 2030, are tracked through a periodically refined global indicator framework. Seventeen Goals[1] are framed by specific targets and associated indicators that enable consistent measurement and reporting of progress across countries and sectors. Among them, SDG 14 (Life Below Water) aligns most directly with marine biodiversity by monitoring species status, habitat condition, ocean health and human pressures through globally standardised indicators.

Realm-wide imbalances in data coverage shape analytical and decision-support readiness. The ocean spans more than 70% of Earth's surface, but remains poorly observed e.g. only around 26% of the seabed bathymetry has been mapped accurately[2]. Similarly, systematic biological observations across

[1] https://sdgs.un.org/goals

[2] General Bathymetric Chart of the Oceans, www.gebco.net

the full water column, offshore and ABNJ environments remain sparse, with substantial data deficiencies in the bathyal, abyssal and hadal zones of the Atlantic, Indian and Pacific oceans (Webb et al., 2010; Bridges and Howell, 2025). These scientific gaps intersect with deep-ocean resource interest, including mining and fisheries, and align directly with monitoring expectations under the Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Agreement; UN Doc. A/CONF/232/2023/4). GBIF and OBIS continue to expose spatial and depth-linked data gradients that influence marine indicator maturity (Hughes et al., 2025). Policy tracking obligations across overlapping international and regional legal frameworks[3] that cover ocean uses generate further complexity. Legal frameworks guiding marine reporting include United Nations Convention on the Law of the Sea (UNCLOS, 1982), the BBNJ Agreement, Regional Seas Conventions, fisheries management organisations, the Convention on Migratory Species (CMS), the Convention on International Trade in Endangered Species (CITES), and Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), all of which rely on structured monitoring frameworks to track policy progress (Kemp et al., 2025; Hughes et al., 2025). Regional mandates (e.g. European Union Marine Strategy Framework Directive - EU MSFD contexts; Nicolaou et al., 2025), and national environmental reporting pipelines (e.g. Australia's State of the Environment Report[4] and Canada's Oceans Now report[5] continue to operate through diverse, and often fragmented, indicator production systems across spatial, sectoral and biological levels. Cross-governance indicator usability remains a shared ambition across regional policy communities (McOwen et al., 2025; Kemp et al., 2025).

For causal-chain alignment, Burgess et al. (2024) evaluated terrestrial indicators using the State-Pressure-Response-Benefit (SPRB) framework across genes, species-communities and ecosystems. Kemp et al. (2025) documented overlap, redundancy and decision-support gaps across online biodiversity knowledge systems. Equivalent synthesis for marine indicators, including recurring analytical pipelines and cross-realm comparability, remains less developed. This review therefore (i) compiles marine biodiversity metrics used in operational monitoring, assessment and reporting, (ii) evaluates their distribution across SPRB categories and biodiversity components, (iii) examines indicator support through transparent data sources and recurring analytical workflows, and (iv) analyses usability across online marine biodiversity knowledge systems. A total of 145 marine biodiversity indicators and 223 marine biodiversity-relevant global and regional online knowledge systems accessible in December 2025 form the indicator access environment for this evaluation. The review also examines how system structure, function and usability shape indicator delivery for recurring assessment and policy tracking.

2. Review methodology

Here indicators are defined as quantitative measurements derived from biodiversity observations collected over space and, or time. Indicators may describe biodiversity state directly (e.g. species abundance, biomass, demographic rates), or represent pressures, responses, or benefits through composite indices, or spatial data products. This interpretation is consistent with the indicator frameworks used under the Kunming-Montreal Global Biodiversity Framework and other regional, or national, policy reporting systems (CBD, 2022; Burgess et al., 2024).

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[3] Information on Multilateral Environmental Agreements: https://www.informea.org/en/mea-topic/biological-diversity
[4] https://soe.dcceew.gov.au/marine/environment/marine-ecosystem-processes
[5] https://www.dfo-mpo.gc.ca/oceans/publications/soto-rceo/2022/report-rapport-eng.html

Online biodiversity knowledge systems are web-accessible digital infrastructures that collate, serve, or enable interaction with biodiversity observations, derived indicators, curated datasets, or decision-support tools intended to support policy design, planning, conservation, reporting, or business applications (Kemp et al., 2025). System functionality varies, including: official data portals providing FAIR data ranging from a single resource to an integration of 1000s of quality controlled datasets; decision-support tools that generate tailored answers using predefined analytical pipelines; curated libraries, or catalogues, that index metadata and direct users to external sources; repositories storing deposited datasets for reuse; and data capture, or reporting, systems that collect structured inputs for policy tracking. Most systems are not the original source of observational data, and do not enable complex analyses beyond their intended interface. System endurance and analytical value are shaped by user focus, indicator transparency, update cadence, and trusted data governance (Kemp et al., 2025).

We used the State-Pressure-Response-Benefit (SPRB) framework to categorise both marine biodiversity indicators and online biodiversity knowledge systems by their analytical role (Table 1). Online system classification was applied to support transparent interpretation of system purpose, analytical role, overlap across SPRB roles, and indicator delivery readiness. Non-exclusive assignments were recorded explicitly for both indicators and online systems, preserving analytical overlaps. State category describes biodiversity condition, distribution, or temporal trends. Pressure category describes anthropogenic, or environmental drivers associated with biodiversity change. Response category describes institutional, regulatory, or management actions intended to reduce pressures, or support ecological recovery. Benefit category describes material, or non-material contributions from biodiversity that can be linked to human well-being, economic activity, or cultural outcomes. All assignments were retained as originally classified to enable clear interpretation of coverage, overlap and analytical maturity.

Table 1. Definition of SPRB framework in biodiversity measurement and three components of biodiversity.

SPRB Framework in biodiversity measurement	
State	Measure the condition, composition, or function of biodiversity (e.g., coral cover, seagrass extent, species presence, abundance or biomass).
Pressure	Describe environmental and direct human impacts on marine ecosystems (e.g., fishing intensity, pollution, habitat loss).
Response	Track conservation or management actions (e.g., marine-protected-area coverage, restoration extent).
Benefit	Assess ecosystem-service flows and other material or non-material benefits derived from biodiversity (e.g., sustainable seafood provision, tourism, blue-carbon sequestration).
Biodiversity Component	
Genes	Genetic attributes including effective population size, genetic connectivity, within-species diversity, and between-species diversity (phylogenetic diversity).
Species	Functional extinction risk, population abundance, changes in distribution and functional role. Includes communities as groups of two or more interacting populations within a habitat.
Ecosystems	Extent, density or percent cover, condition, regime shift, risk of collapse.

2.1. Marine indicators

A database of marine biodiversity indicators was compiled (Supplementary Table 1SupplTable1.xlsx) from the Biodiversity Indicators Partnership database (BIP, 2024), KMGBF monitoring documentation, SDG 14 indicator metadata, and established international observation and reporting programmes relevant to marine and coastal systems. Source systems included global initiatives, conventions and intergovernmental organisations (e.g. FAO, IOC-UNESCO, UNEP-WCMC, IUCN, CITES, CCAMLR, GEO BON, the Biodiversity Indicators Partnership - BIP, and regional ICES, and OSPAR Commission).

Indicators were retained in the database if they met three criteria: (i) quantifying a measurable attribute of marine biodiversity state, pressure, response, or benefit; (ii) being supported by an identifiable and transparent data source; and (iii) operational applicability at global or multi-regional scales, with evidence of repeated or ongoing updates. Indicators differing only in spatial resolution, or reporting format, but derived from the same underlying observation pipeline were merged into single representative entries. Composite indices maintained by a single programme, or organisation, were treated as single entries even when they served multiple reporting streams, ensuring analytical neutrality in system counts. Throughout the analysis, indicators are classified according to the analytical role they play within the SPRB framework (Table 1).

2.2. Online marine biodiversity knowledge systems

A structured inventory of global and regional online biodiversity knowledge systems was compiled from the datasets by Kemp et al. (2025). The marine subset was extracted from that global and regional inventory by retaining entries tagged as "marine & freshwater", "marine & terrestrial", "marine & coastal", and "coastal", capturing systems with explicit marine relevance as recorded in the original datasets (for global Supplementary Table 2 SupplTable2.xlsx and for regional Supplementary Table 2 SupplTable3.xlsx).

Discovering online biodiversity knowledge systems combined institutional inventories, expert-led verification batches, and targeted internet, or AI-assisted, searches across global and regional biodiversity communities, or ocean monitoring networks, including contributions from UNEP-WCMC, GEO BON, IUCN, FAO, IOC-UNESCO, GBIF and ICES. They were included in the inventory if they were web-accessible and operational at the time of review (December 2025). The typology of online marine biodiversity knowledge systems followed the functional classification of data systems, spanning from data portals to decision-support tools, and the main types of data included such as ecosystems, species data, and oceanographic layers (Table 2). They were further identified for the primary intended user groups (government, business, citizen or NGO, or scientist), based on stated purpose, documentation, interface design and example use cases. User-group classification was applied as non-exclusive when systems explicitly targeted multiple audiences, and all relevant user groups were recorded. The SPRB framework was then used as an analytical perspective to examine system coverage and identify shared gaps across global and regional online marine biodiversity knowledge systems.

Table 2. Typology of online marine biodiversity knowledge systems (modified from Kemp et al., 2025).

Category	Description
Main type of data systems	
Data source (portal)	Provides web-based access to one or a small number of biodiversity databases, enabling data discovery, download, and basic visualisation, with limited on-platform analysis.

Decision-support tool	Online systems designed to support specific policy, planning, or management questions by integrating data with predefined analytical workflows.
Libraries/catalogues	Curated collections of biodiversity datasets, indicators, reports, or metadata that guide users to external data sources rather than hosting data directly.
Repositories	Platforms primarily intended for long-term storage and access to biodiversity datasets, with minimal analytical functionality.
Others	Flexible analysis platform: Configurable platforms allowing users to combine datasets and apply custom analytical workflows. Data capture / reporting systems: Systems designed to collect biodiversity data or reports from users or institutions, often supporting monitoring or policy reporting. Initiative / organization: Websites coordinating biodiversity-related initiatives, commitments, or collaborations, without functioning as data or analysis platforms. Software: Standalone or web-enabled tools supporting biodiversity analysis or visualisation without hosting biodiversity data or indicators.
Main types of data included	
Earth observations	Satellite- and airborne sensor-derived datasets providing spatially explicit information on oceanographic, ecological, and environmental variables.
Ocean	Physical, chemical, and biological ocean data underpinning marine monitoring, modelling, and assessment activities.
Ecosystems	Data describing habitat extent, percent cover, condition, structure, functioning, and ecosystem dynamics across marine systems.
Species data	Data on species occurrence, abundance, biomass, distribution, population trends, and extinction risk across marine taxa.
Genetic	Information on genetic diversity, population structure, traits, or connectivity, including molecular and genomic datasets where available.
Natural capital and ecosystem service	Data quantifying ecosystem services, nature's contributions to people, and natural-capital attributes associated with marine biodiversity.
Business impacts and risks	Data describing biodiversity dependencies, pressures, and risks relevant to corporate activities, finance, and supply chains in marine and coastal contexts.
Area-based / land-use planning data	Spatial information supporting marine spatial planning, protected areas, zoning, and site-based management, including boundaries, designations, and planning layers.
Climate change and disaster risk	Information on environmental change, hazards, exposure, vulnerability, and adaptation relevant to marine and coastal ecosystems, including extreme events and long-term change.
Trade	Information describing extraction, harvest, trade, and use of marine biological resources, including fisheries and wildlife trade.

3. Results

3.1. Marine biodiversity indicators

A total of 145 marine biodiversity indicators were compiled and classified under the SPRB framework. These indicators encompass habitat extent (e.g. mangrove, seagrass and coral cover), ecological condition (e.g. live coral cover, reef-fish biomass, marine trophic index), human pressures (e.g. cumulative ocean impact, pollution indices, fishing effort), and management or socio-economic responses (e.g. protected-area coverage, certification schemes, fisheries contributions to national accounts).

State indicators formed the largest group (n = 34), followed by pressure (n = 25) and response (n = 21), while the benefit category comprised a single indicator (Figure 1a). Several indicators spanned more than one SPRB category. The most common overlap occurred between state and pressure (n = 27), with additional overlaps between state and response (n = 10) and between response and benefit (n = 4). Two indicators bridged three categories (pressure-state-response), but none linked all four.

Classification by biodiversity components (genes, species and ecosystems) showed broad distribution across components (Figure 1b). For remote reporting pipelines, including BBNJ, indicators are often produced at a unit larger than species and smaller than ecosystem, commonly documented as an assemblage. Assemblage-level products include seabed imaging in situ (diver cams, drop cams, ROVs, AUVs) and OTU-based outputs derived from box cores, dredges, sediment or water samples (Brasier et al., 2021). Indicator counts reveal strong analytical coupling between species- and ecosystem-level observations, with seventy-seven indicators shared between these components. Thirty-seven indicators described species-level attributes uniquely, twenty-four described ecosystem attributes specifically, and two linked species and ecosystems jointly. No indicator was retained exclusively for genetic components, underscoring limited operationalisation of genetic-level monitoring in the marine realm and the predominance of population- and habitat-based data structures (Supplementary Table 1SupplTable1.xlsx).

Weighted linkages between SPRB categories and biodiversity components (Figure 1c) showed that state indicators contributed the highest number of linkages across all of the components: 73 linkages to species, 58 to ecosystems and 44 to genes. Pressure indicators followed with 53, 44 and 37 linkages, respectively. Response indicators contributed 26 linkages to species, 28 to ecosystems and 16 to genes. Indicators classified under benefits were least represented across components (n = 12 for genes).

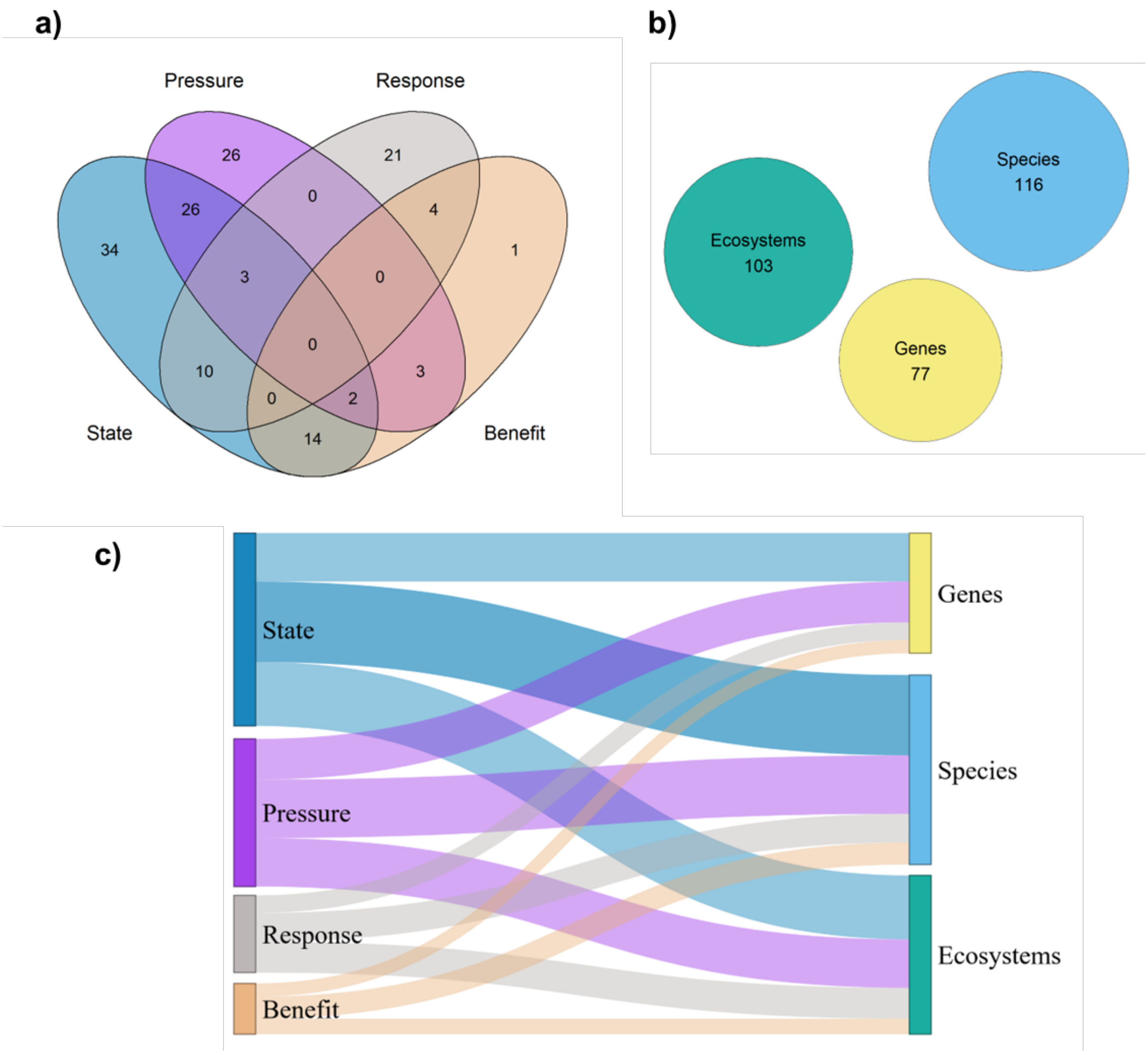

Figure 1. Overview of the 145 marine biodiversity indicators and their organisation into metrics (Supplementary Table 1). (a) Number of and overlap among indicators classified within the state-pressure-response-benefit framework. (b) Total counts (including overlaps) of biodiversity components (genes, species, and ecosystems). (c) Sankey diagram illustrating the distribution of twelve aggregated indicator flows from SPRB categories (left) to biodiversity components (right).

3.1.1 State of Biodiversity

Indicators classified under state (n = 36) describe the condition and spatial distribution of marine biodiversity, primarily at species and ecosystem levels (Supplementary Table 1SupplTable1.xlsx). Genetic diversity is not measured directly by any state indicator, a gap that reflects limited operational readiness for genetic-level monitoring. State indicators quantify habitat extent, habitat condition, population abundance, and spatial or temporal change across major marine systems, with strongest representation for coastal and shelf domains (Figure 3). Most state indicators draw on Earth-observation products, long-term ecological surveys, and harmonised spatial layers, enabling recurring production and multi-regional comparison. Carbon-focused indicators include spatial estimates of mangrove soil carbon at 30 m resolution (Global Mangrove Soil Carbon; Sanderman et al., 2018), and global model outputs for sediment carbon stocks (Global Patterns in Marine Sediment Carbon Stocks; Atwood et al., 2020). Habitat-climate linkages are captured by connectivity indicators integrating coral larval dispersal, thermal exposure and cyclone history (Coral Reef Connectivity; Beyer et al., 2019; Wood et al., 2014), and by characterising freshwater-marine migratory pathways (River Connectivity Status Index[6]). Marine bioregionalisation layers (e.g. Marine Biomes, MEOW-PPOW, Marine Realms and Pelagic Provinces) provide spatial context for species- and assemblage-level state interpretation (Spalding et al., 2007; 2012). Spatial prioritisation is represented by the Marine Priority Areas dataset, which integrates biodiversity state, food-provision potential and climate relevance (Sala et al., 2021).

3.1.1.1 Species

State indicators for species (n = 8) describe population abundance, temporal trends and spatial distributions across plankton, marine vertebrates, assessed fish stocks and reef-associated taxa. Long-baseline plankton biomass records support regional assessments using time series spanning the 1950s to 2023 (Plymouth University, HBDSEG programme; OSPAR[7]). Vertebrate trends are represented through Living Planet Index products, including the Marine Living Planet Index[8] and biennially updated products for migratory freshwater and diadromous species[9]. Regionally scaled species-state surrogates include Baltic seal abundance (by The Baltic Marine Environment Protection Commission - HELCOM) and population layers for selected marine mammals, seabirds and reptiles (by The Mediterranean Action Plan UNEP-MAP[10]). Fish-stock sustainability state is tracked through the FAO indicator on the proportion of fish stocks within biologically sustainable levels (since 1974, biennial updates as SDG 14.4.1 indicator (FAO, 2024). Reef species state is complemented by developing population-status composites coordinated by the Global Coral Reef Monitoring Network[11] under The International Coral Reef Initiative.

3.1.1.2 Ecosystems

Ecosystem-state indicators (n = 17) describe the extent and condition of habitats underpinning marine biodiversity observation and reporting. These include multi-decadal Earth-observation products for mangrove extent (Bunting et al., 2018; Hamilton and Casey, 2016), global compilations for saltmarsh and coastal wetlands (McOwen et al., 2017). Shelf-scale ecosystem state is supported by long-baseline seagrass bioregional layers[12], coral-reef extent composites[13], and higher-resolution reef products including Allen Coral Atlas (Lyons et al., 2022). Structural proxies for ecosystem condition, such as kelp-canopy extent from repeated photographic and satellite records (1980s onward by Environmental Data Initiative[14]), and seagrass-cover assemblage composites support recurring state interpretation for temperate and shelf habitats. Benthic structural-complexity indicators remain under development, and are therefore retained as state proxies with partial operational readiness.

3.1.2 Pressures on Biodiversity

[6] hydrolab.io/ffr
[7] https://oap.ospar.org/en/versions/1756-en-1-0-0-bb11-plankton-biomass-andor-abundance/
[8] livingplanetindex.org/projects
[9] https://www.livingplanetindex.org/migratory_lpi
[10] https://www.unep.org/unepmap/
[11] https://github.com/GCRMN/global_2024
[12] https://www.seagrassnet.org/map
[13] https://habitats.oceanplus.org/
[14] edirepository.org

Indicators on pressure upon biodiversity (n = 26) capture environmental and anthropogenic drivers affecting marine biodiversity across biological levels (Supplementary Table 1SupplTable1.xlsx). They encompass cumulative human impacts, pollutant inputs, nutrient enrichment, acidification, invasive-species trends and fishing effort. Species-level pressure indicators are currently regional in scope and supported by EU monitoring and reporting pipelines, including those coordinated under the EU MSFD (Descriptor 8 in Directive 2008/56/EC, 2008). Cumulative anthropogenic pressures on marine ecosystems are estimated through integrated global analyses combining climate stress, pollution and fishing activity (Halpern et al., 2015). Additional pressure components, such as inorganic pollution, nutrient plumes, pesticide inputs and ocean-based pollution, are available through associated global model outputs. Fishing pressure is quantified using global estimates of fishing effort derived from satellite-based vessel monitoring (Kroodsma et al., 2018). Ocean acidity (pH) is quantified annually (in relation with SDG 14.3.1 indicator), while coastal eutrophication and marine-debris are measured through metrics of nutrient enrichment and plastic accumulation (in relation with SDG 14.1.1a indicator). Regional pressure datasets complement global layers, for example nutrient and chlorophyll-a concentrations for the Mediterranean and nutrient loads, or hazardous substances and pollution trends for the Baltic Sea. Biological invasions are represented by trends in invasive alien species introduction events derived from global occurrence records. No indicators in the dataset directly quantify pressures on genetic diversity.

3.1.2.1 Pressures on species

A limited set of indicators (n = 3) quantify pressures resolved at species or taxon level, focusing on biological impairment, incidental mortality, or direct extraction. Most pressure indicators in the broader inventory describe environmental or human drivers at habitat or jurisdiction scale, but only three meet criteria for species-specific recurring monitoring and reporting. Contaminant pressure on gastropod reproduction is assessed using long-term records of imposex incidence, a condition where females develop male sexual characteristics following exposure to tributyltin (TBT), a legacy antifouling-paint contaminant. This indicator is operational under the The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) hazardous substances monitoring pipeline, and supports multi-decadal pressure interpretation across European marine regions (OSPAR, 2017). Incidental mortality of marine mammals and waterbirds in fishing gear is documented through regional bycatch assessments for the Baltic Sea (HELCOM, 2018). Global records on extraction pressures on cetaceans are represented by annual catch statistics reported by International Whaling Commission, providing a continuous record since the mid-1980s[15].

3.1.2.2. Pressures on ecosystems

Pressures on ecosystems (n = 1) are represented through global analyses of cumulative human impacts on marine habitats, integrating multiple stressor layers including climate change, pollution, habitat modification and fishing pressure (Halpern et al., 2015). These datasets provide globally consistent spatial and temporal estimates of anthropogenic pressure and can be resolved at national scales[16].

[15] iwc.int/total-catches

[16] nceas.ucsb.edu/globalmarine

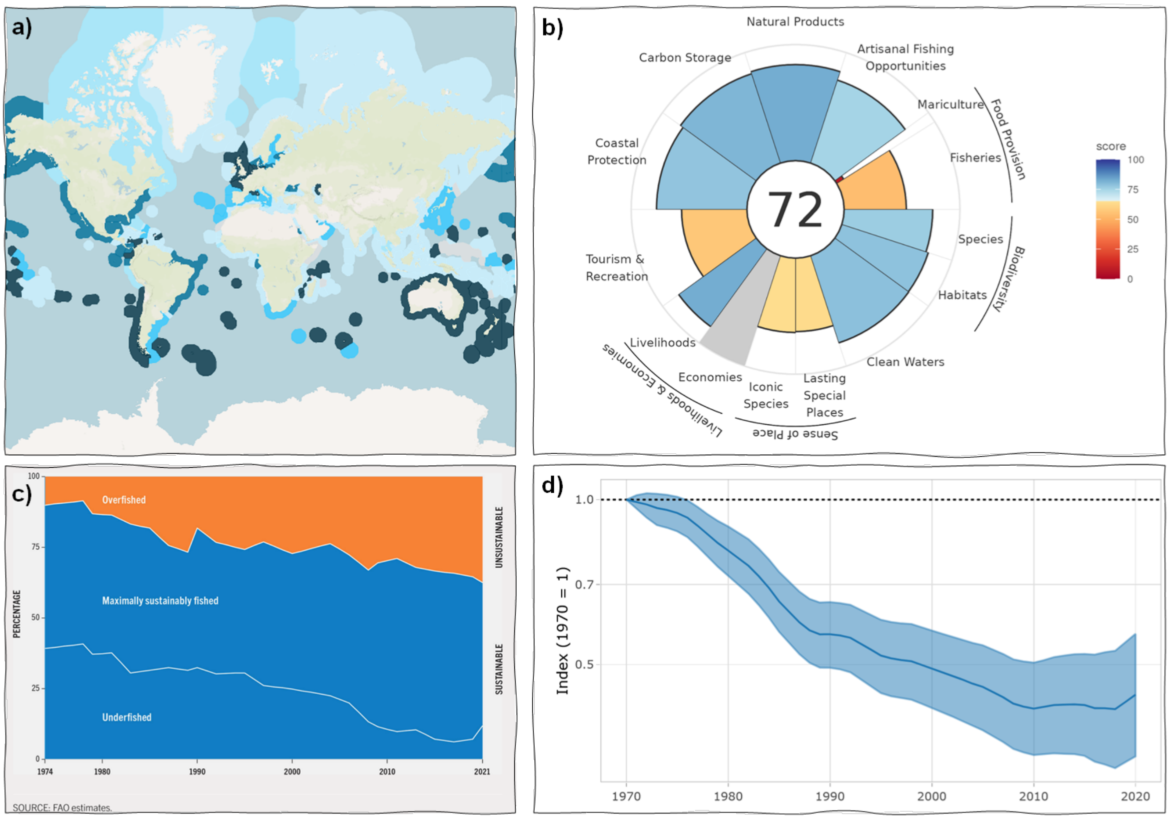

Figure 2. Examples of marine indicators. a) State-response indicator: Percent coverage of countries by protected areas and other effective area-based conservation measures (OECMs) for the marine realm as of August 2024; Source: UNEP-WCMC and IUCN 2024. b) State-pressure indicator: The Ocean Health Index 2025, global assessment includes scores from 2012 to 2025 for 220 coastal countries and territories. The global average 2025 Index score was 72 out of 100 (Ocean Health Index, 2025: https://oceanhealthindex.org/global-scores). c) State indicator: Global trends in the state of the world's marine fishery stocks, 1974–2021 (FAO, 2024); d) State indicator: The Living Planet Index for Marine populations between 1970 to 2020. The bold line shows the index values and the shaded areas represent the statistical certainty surrounding the trend (95%). The index represents 16,909 populations of 1,816 species (CC BY 4.0).

3.1.3 Policy and Management Responses

Indicators for policy and management responses (n = 21) capture institutional, policy and management actions implemented at national, regional and global scales (Supplementary Table 1SupplTable1.xlsx). They encompass protected-area coverage, restoration, regulatory frameworks, research capacity, marine spatial planning, statistical support and international cooperation. Many are formally linked to SDG indicators and therefore form part of national reporting processes.

Forest-restoration potential relevant to coral-reef conservation identifies terrestrial actions with direct implications for coastal and reef systems (Suárez-Castro et al., 2021). Marine science capacity is quantified through indicators (in relation to SDG 14.a.1) coordinated under the Global Ocean Science Report, including ocean-science researchers per million population, research-vessel days, national inventories of marine stations, the proportion of Exclusive Economic Zones (EEZs) covered by marine spatial plans, and the proportion of national research budgets allocated to marine technology (IOC-UNESCO, 2020). Change in water-use efficiency supports (in relation to SDG 6.4.1), national progress on integrated water-resources management[17] (in relation to SDG 6.5.1), and financial and technical support to biodiversity-relevant governance (in relation to SDG 17.9.1) are quantified[18]. Fisheries-related responses include reporting on the proportion of fish stocks under sustainable-management certification (in relation to SDG 14.4.1), and implementation of international instruments against Illegal, Unreported and Unregulated (IUU) fishing is addressed by Red List Index for impacts of fisheries[19]. Ecosystem restoration and protection responses include global records of mangrove restoration[20], quantifying spatial extent and restoration outcomes (Worthington and Spalding, 2018), and indicators reporting the proportion of coral reefs within effectively managed marine protected areas (MPAs) and other effective area-based conservation measures[21] [22] [23]. Contextual governance information is provided by response indicators beyond biological components. Maritime jurisdiction is delineated through the global EEZs dataset[24]. Climate-policy responses (in relation to SDG 13.b.1) are captured through national submissions of determined contributions, adaptation plans and long-term strategies compiled under the UNFCCC[25].

3.1.4 Benefits from Biodiversity

Only one indicator is classified exclusively under benefits (Figure 1a; Supplementary Table 1SupplTable1.xlsx). It quantifies tourism and recreation through modelled estimates of total visitation value of coral reefs at the global scale (Spalding et al., 2017 and Ocean Wealth).

3.1.5. Multidimensional indicators under overlapping metrics

Some indicators are multidimensional in that they present information on biodiversity state together with pressures and, in some cases, responses or benefits (Figure 1a; Supplementary Table 1SupplTable1.xlsx).

Several indicators combine information on habitat extent or species state with exposure to environmental change or human activities (Figure 3). Long-term time series provide coastal and wetland extent and loss, surface-water dynamics and habitat modification (e.g. Global Mangrove Watch; World Mangrove Atlas; Ramsar Sites Information Service; Global Surface Water dataset) (Bunting et al., 2018; Thomas et al., 2017; Spalding et al., 1997; Pekel et al., 2016). Comparable spatial[26] baselines are available for seagrass, warm-water coral and cold-water coral systems, where updates over time reflect degradation or recovery (e.g. seagrass, coral reef and cold-water coral; Short, 2020; Freiwald et al., 2017). Composite indices merge state information with multiple stressors to generate national or global scores such as Ocean Health Index[27], as well as cumulative human-impact layers quantifying aggregated

[17] iwrmdataportal.unepdhi.org
[18] https://www.paris21.org/
[19] https://dart.informea.org/taxonomy/term/3865
[20] maps.oceanwealth.org/mangrove-restoration
[21] oceanconference.un.org/commitments/?id=15692
[22] iyor2018.org
[23] aires-marines.com
[24] https://www.vliz.be/en/imis?dasid=5465&doiid=312
[25] unfccc.int
[26] https://habitats.oceanplus.org/
[27] ohi-science.org/ohi-global

anthropogenic pressures across marine systems (Halpern et al., 2015). Species-based metrics similarly integrate population state with exposure to exploitation, climate stress or habitat loss. These include indicators tracking changes in trophic structure, abundance and size composition, thermal sensitivity and extinction risk (e.g. Marine Trophic Index[28], Living Planet Index[29] and its variants, Reef Fish Thermal Index[30], Red List Index[31] and its different products).

Linking biodiversity state directly to spatial protection or management measures represents another multidimensional approach. These include global and regional site-based designations recording both ecological importance and protection status such as Ecologically or Biologically Significant Marine Areas[32] (CBD, 2022) and Ramsar Wetlands[33]. Regional datasets further describe the representation of habitats, depth zones and ecoregions within MPAs, including key Mediterranean habitats and cetacean critical areas (UNEP/MAP[34], SPA/RAC[35] and MedPAN datasets[36]).

Spatial prioritisation frameworks identifying areas where maintaining ecosystem state supports food provision and climate relevance, and ecosystem-service models quantifying coastal protection, flood-risk reduction and tourism value (e.g. Marine Priority Areas for Food Security, Mapping Ocean Wealth) connect biodiversity state with benefits derived from biodiversity (Jones et al., 2018; Sala et al., 2021; Tellman et al., 2021).

Some indicators link pressures directly to benefits by illustrating how environmental stressors influence human well-being such as water availability under variable pressure regimes (eg. Freshwater Provisioning Index for Humans) and fisheries certification metrics connecting extraction pressure to sustainability outcomes by Marine Stewardship Council[37].

A smaller number of indicators integrate state, pressure and response within a single framework such as indices combining watershed state, fishing pressure and governance information (Sustainable Watershed and Inland Fisheries Index). Economic indicators can link fisheries performance to stock state and management (sustainable fisheries as a percentage of GDP), and carbonate-budget assessments combining reef state, erosion pressure and management signals (Supplementary Table 1SupplTable1.xlsx).

3.2. Online Marine Biodiversity Knowledge Systems

A total of 223 online marine biodiversity knowledge systems (systems hereafter) were identified, comprising 141 global and 82 regional entries (for global Supplementary Table 2 SupplTable2.xlsx and for regional Supplementary Table 2 SupplTable3.xlsx). The analysis follows a common typology and an SPRB lens, together with a user grouping and a main-data grouping.

[28] https://www.seaaroundus.org/data/#/marine-trophic-index
[29] https://www.livingplanetindex.org
[30] https://dart.informea.org/taxonomy/term/3878
[31] https://www.iucnredlist.org/assessment/red-list-index
[32] https://gobi.org/ebsas/
[33] https://www.ramsar.org/
[34] https://www.unep.org/unepmap/
[35] https://www.rac-spa.org/node/2047
[36] https://medpan.org/en/resource-center/status-marine-protected-areas-mediterranean-sea-2020-edition
[37] https://www.msc.org/for-business/fisheries

At the global scale (Figure 3a, c, e), systems categorized for showing state and pressure account for the largest number of systems (Supplementary Table 2 SupplTable2.xlsx), with state being the most frequently represented SPRB component, followed by pressure. Response and benefit are represented by substantially fewer systems. Across global, the main data groupings are dominated by ocean-related variables, species-level data, and ecosystem-level information, whereas genetic data and earth-observation-only categories are comparatively limited. Overlap among SPRB categories is common at the global scale (Figure 3c). The largest intersection occurs between state and pressure, followed by overlaps that include response. Systems related to benefits are few and typically appear in combination with other SPRB components. A small part spans three components simultaneously, while representation across all four SPRB categories is rare. None is classified solely as benefits but in combination with other categories.

At the regional scale (Figure 3b, d, f), the overall distribution across SPRB categories follows a similar pattern, with state related systems remaining the most frequently represented component (Supplementary Table 3 SupplTable3.xlsx). However, pressure classifications are less numerous than at the global scale, while response and benefit account for a relatively higher proportion of platforms. Regional systems are most often classified as data source portals and decision-support tools, with fewer entries falling under repositories or libraries compared to the global set. SPRB overlap at the regional scale (Figure 2d) is less extensive than at the global scale. Intersections most commonly involve state, pressure, and response, while benefit remains weakly represented and is rarely combined with other components.

Across both global and regional systems, species-level data constitute the most frequently represented biodiversity component, followed by ecosystem-level information. Genetic data are marginal in both cases. Global systems more often include ecosystem-related data within multidimensional SPRB classifications, particularly those combining state and pressure. In contrast, regional systems show a stronger concentration on species-level data, consistent with inventories, monitoring programmes, and assessment-focused initiatives. Ocean-related variables and earth-observation data are strongly associated with pressure classifications at both scales, with a higher concentration in global platforms. Regional systems more frequently combine physical and environmental variables with spatially explicit layers relevant to area-based planning and ecosystem assessments. User-group classifications differ between scales (Figure 3e, f). Global systems are most frequently associated with scientific users, followed by platforms with no clearly specified primary user group. Government, business, and NGO user groups represent smaller shares. In contrast, regional systems show a more even distribution between scientific and government users, with generic users also forming a substantial proportion.

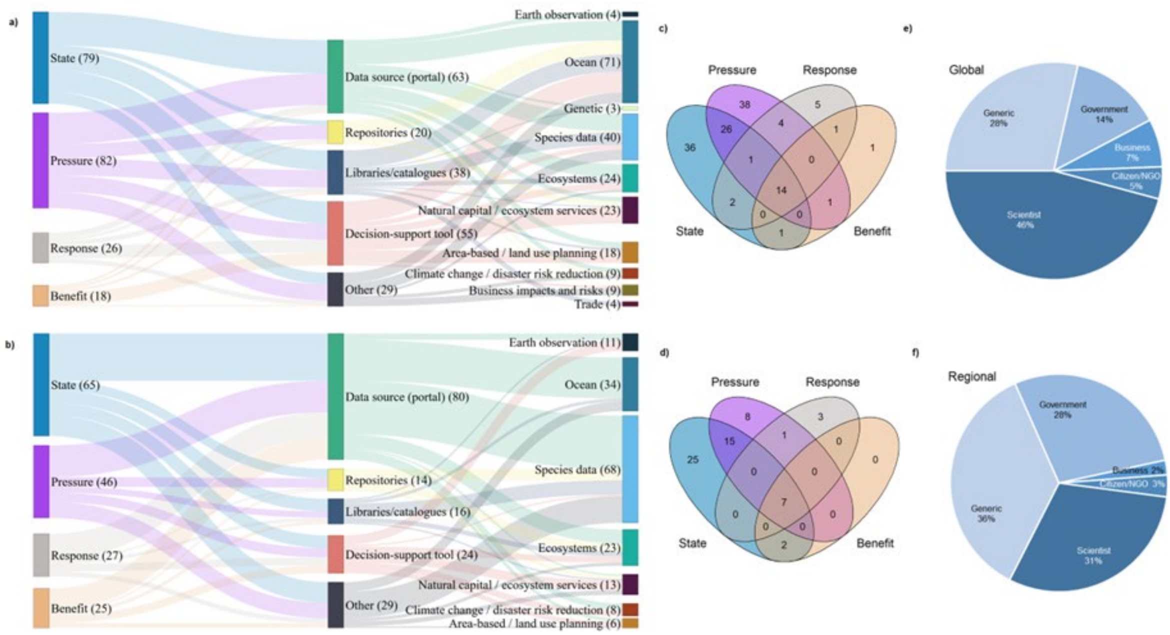

Figure 3. Structure and use of global-regional online marine biodiversity knowledge systems. (a-b) Sankey diagrams showing linkages between SPRB categories, type of data system, and main type of data included for global and regional systems, respectively. (c-d) Number of and overlap within the SPRB framework. (e-f) Distribution of primary user groups for global and regional systems.

3.2.1. Global Scale

State-related online systems (n = 36) provide baseline information on the distribution, status and temporal dynamics of marine biodiversity, without explicitly incorporating pressures, management actions or benefit-oriented valuation (Supplementary Table 2 SupplTable2.xlsx). They primarily deliver species occurrence data, taxonomic backbones, habitat extent and ecological state layers and are most commonly implemented as open-access data portals or map-based exploration tools supporting biodiversity assessment, research and reporting. Use is dominated by scientific users, with substantial uptake by government agencies. Update frequencies depend on the underlying monitoring programmes. Data source portals represent the dominant system type. Global species and taxonomic infrastructures provide access to occurrence and classification data (e.g. OBIS[38], World Register of Marine Species WoRMS[39], Blue Corridors[40], Seabird Tracking Database[41]) while ecosystem observation platforms provide standardised monitoring products (e.g. CoralNet[42], Reef Life Survey[43]). These are typically updated regularly and are widely used by scientists. Decision-support tools translate biodiversity observations into spatial products relevant for conservation planning and prioritisation (e.g. Important Marine Mammal Areas IMMA[44]; Important Shark and Ray Areas ISRA[45], AquaMaps[46], Happywhale[47]). Libraries and catalogues provide curated reference datasets rather than dynamic

[38] https://obis.org/
[39] https://www.marinespecies.org/
[40] https://bluecorridors.org/
[41] https://data.seabirdtracking.org/
[42] https://coralnet.ucsd.edu/about
[43] https://portal.aodn.org.au/search
[44] https://www.marinemammalhabitat.org/immas/
[45] https://sharkrayareas.org/
[46] aquamaps.org
[47] https://happywhale.com

monitoring outputs, including taxonomic and biological catalogues (e.g. Eschmeyer's Catalog of Fishes[48], FishBase[49], SeaLifeBase[50], Interim Register of Marine and Nonmarine Genera IRMNG[51]) and microbial or genetic reference systems (International Census of Marine Microbes ICoMM[52], Metazoogene[53]). A smaller number of platforms operate as repositories, initiatives or specialised software systems (e.g. MEOP[54]; eOceans[55]; Global Coral Reef Monitoring Network; Zostera Experimental Network[56]).

Pressures-related systems (n = 38) support detection and monitoring of physical, chemical and climatic stressors and are dominated by oceanographic, biogeochemical and Earth-observation data (Supplementary Table 2 SupplTable2.xlsx). Common data types include sea-surface temperature, sea ice, winds, radiative fluxes, sea level, ocean circulation, carbon chemistry, oxygen concentration, and nutrient enrichment. These platforms are closely embedded within global observing and climate-monitoring infrastructures. Data source portals and repositories dominate this category, providing access to continuous or near–real-time observational streams. Major global systems include satellite-derived products (EUMETSAT OSI SAF[57]), autonomous in situ observing networks (Argo; Biogeochemical Argo[58]), sea-level observing systems (GLOSS[59]), and integrated ocean data services (Copernicus Marine Data Store[60], NOAA CoastWatch[61]). Climate-change and disaster-risk-related pressure data are further delivered through tsunami-monitoring systems and coastal risk frameworks (Coastal Hazard Wheel[62]). Libraries and catalogues provide curated, quality-controlled reference datasets underpinning pressure analyses (ICOADS; SOCAT; GLODAP; Global Surface pCO_2 database). Repositories archive long-term or mission-based datasets supporting assessment of physical and biogeochemical pressures over decadal scales (GO-SHIP; OceanGliders; SOCAT; SWOT). These systems are updated less frequently and primarily serve expert scientific users. Decision-support tools and thematic initiatives form a smaller subset. The Ocean Health Index integrates multiple pressure layers alongside state information to support comparative assessments. Observing initiatives such as GO2NE and VOS/SOT coordinate measurements related to oxygen decline and shipping-based observations. Only one pressure platform explicitly incorporates natural-capital or ecosystem-service information, the ASFIS List of Species for Fishery Statistics Purposes maintained by FAO, which links species classifications to fisheries statistics and economic use.

Response-related systems (n = 5) document policy, management and governance actions implemented to reduce pressures, support recovery or improve sustainability outcomes (Supplementary Table 2 SupplTable2.xlsx). They compile information on spatial protection, financing mechanisms,

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[48] https://www.calacademy.org/scientists/projects/eschmeyers-catalog-of-fishes
[49] https://www.fishbase.se/
[50] https://www.sealifebase.se
[51] https://www.irmng.org
[52] http://www.coml.org/international-census-marine-microbes-icomm/
[53] https://metazoogene.org/database/
[54] https://meop.net/
[55] https://eoceans.co/
[56] https://serc.si.edu/research/projects/zostera-experimental-network-zen
[57] https://osi-saf.eumetsat.int/
[58] https://biogeochemical-argo.org/
[59] https://psmsl.org/
[60] https://data.marine.copernicus.eu/
[61] https://coastwatch.noaa.gov/
[62] https://chw-app.coastalhazardwheel.org/

management initiatives and business-oriented sustainability actions, rather than ecological state or environmental drivers. Information is typically structured around projects, commitments or management instruments and updated according to reporting cycles or institutional review processes. Spatial protection and planning are represented through global inventories of MPAs, and for example, Marine Protected Area Atlas[63] and ProtectedSeas Navigator[64], provides information on the expected effectiveness through the MPA Guide. Conservation finance and investment mechanisms are compiled through thematic platforms (e.g. Coral Reef Funding Landscape[65]). Fisheries-related responses are tracked through decision-support systems linking governance actions to structured progress indicators (FisheryProgress[66]). Technical mitigation responses are compiled through catalogue-based platforms (Consortium for Wildlife Bycatch Reduction[67]). Business-oriented response information is organised through resource databases addressing sustainability commitments, sourcing practices and supply-chain risk (Conservation Alliance for Seafood Solutions[68]). Benefit-related one system explicitly addresses benefits derived from marine biodiversity. The Atlas of Ocean Wealth - Mapping Ocean Wealth, developed by The Nature Conservancy[69], operates as a decision-support platform focused on natural capital and ecosystem services. It provides spatially explicit estimates of economic and protective benefits derived from marine ecosystems, including coastal protection, fisheries production and tourism value.

Many global systems combine more than one component of the SPRB framework (n = 60) (Figure 2; Supplementary Table 2 SupplTable2.xlsx). State and pressure related ones describe ecosystem or species state together with exposure to environmental or anthropogenic drivers (e.g. Allen Coral Atlas, Global Mangrove Watch[70], EBSAs). Species-focused systems follow the same logic by combining distribution data with environmental conditions or exploitation pressure (Marine Megafauna Movement Analytical Program[71], TurtleNet[72], Global Marine Species Assessment[73]). Some links state and response by associating ecological importance with spatial protection or management status (Important Marine Mammal Areas). Comparable linkages are represented by decision-support systems connecting state information to management and planning contexts (Local Ecological Footprint Tool Marine[74]). A single platform links state and benefit by relating ecosystem vulnerability to fisheries sustainability considerations (Vulnerable Marine Ecosystems Database[75]) while another one links pressure and benefit by connecting fishing-pressure indicators to natural-capital considerations in seafood supply chains (FishSource[76]). Some combine pressure and response by situating environmental or anthropogenic drivers within management or monitoring frameworks (Harmful Algal Information

63 https://mpatlas.org/mpaguide/
64 https://map.navigatormap.org
65 https://coralfunders.com
66 https://fisheryprogress.org/
67 https://bycatch.org/
68 https://solutionsforseafood.org/
69 https://oceanwealth.org/resources/atlas-of-ocean-wealth/
70 https://www.globalmangrovewatch.org/
71 https://megamove.org/data-portal/
72 https://experience.arcgis.com/experience/0eda722f6cfa4ac89606df50d7e40468
73 https://sites.wp.odu.edu/GMSA/initiatives/gmsa/
74 https://www.marineleft.ox.ac.uk/
75 https://www.fao.org/fishery/geoserver/factsheets/vme.html
76 https://www.fishsource.org/

System[77], MarineGEO[78]) while the others with response and benefit focus on governance actions and sustainability outcomes, particularly in fisheries contexts (Fisheries and Resources Monitoring System[79]). A small number integrate all four SPRB components within a single framework, combining biodiversity state, pressures, responses and benefit-oriented information (Ocean+Habitats, Mapping Ocean Wealth, Global Fishing Watch[80], Indicators for the Seas[81], Sea Around Us, Bycatch Management Information System[82]).

3.2.2. Regional Scale

Regional state-related systems (n = 26) document the condition, distribution and temporal dynamics of marine species and ecosystems within defined ocean basins, regional seas or biogeographic contexts (Figure 4, Supplementary Table 3 SupplTable3.xlsx). They provide baseline regional-scale information, including species occurrence and abundance data, ecosystem distribution layers and long-term monitoring records linked to specific regions.

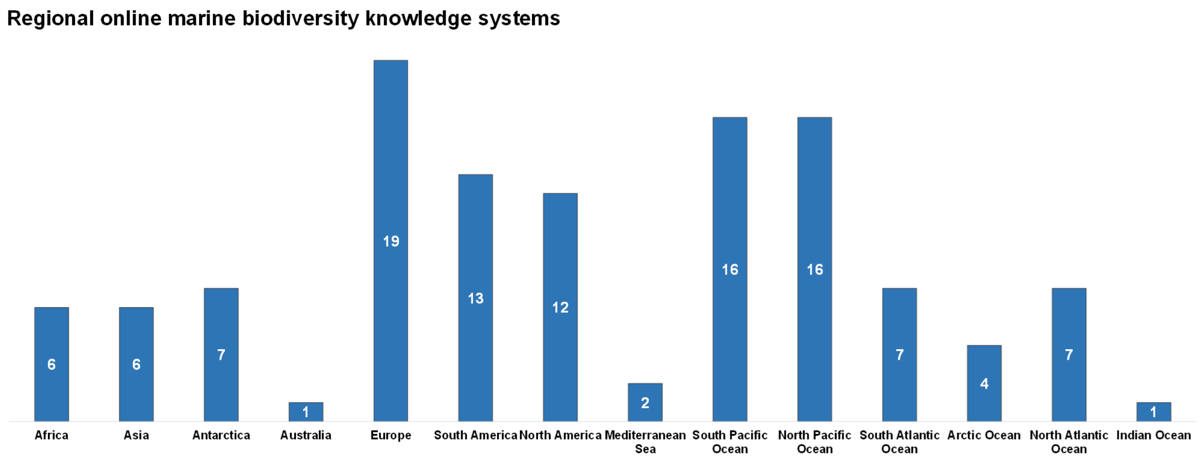

Figure 4. Distribution of regional online marine biodiversity knowledge systems.

Data source portals form the most common system type among regional state platforms. These provide access to observational and compiled datasets through map-based interfaces and basic visualisation tools (Critical Site Network[83], Sea Ice Aware[84], COSYNA[85]). Taxonomic and habitat-focused portals provide curated regional reference datasets used in biodiversity assessments (European Register of Marine Species[86], Deep Sea Corals and Sponges portal[87], Australian DNA Library[88]). Region-focused biodiversity systems provide access to species data within specific seas and regional conventions

[77] https://data.hais.ioc-unesco.org/
[78] https://marinegeo.si.edu/network
[79] https://firms.fao.org/firms/home/en
[80] https://globalfishingwatch.org/map/
[81] www.indiseas.org
[82] https://www.bmis-bycatch.org/
[83] https://criticalsites.wetlands.org/en
[84] https://livingatlas.arcgis.com/sea-ice/
[85] https://www.hereon.de/institutes/carbon_cycles/cosyna/data_management/index.php.en
[86] http://www.marbef.org/data/erms.php
[87] https://www.ncei.noaa.gov/maps/deep-sea-corals-portal
[88] https://nbdl.csiro.au/

(EurOBIS[89], HELCOM Biodiversity Database[90]). Ecosystem-oriented portals provide regionally scoped datasets on biogeochemical and ecosystem dynamics (Sustained Indian Ocean Biogeochemistry and Ecosystem Research portal[91], Micronesia Challenge Indicator Monitoring system[92]). Decision-support tools translate state observations into spatial products relevant for regional planning and ecosystem mapping (MarCNoWA Coastal Ecosystem Mapping[93], Sargassum Watch System[94]). Visualisation platforms provide interactive access to regional biodiversity-related datasets without operating as primary data repositories (FACT Network[95] visualisation platform). Libraries and catalogues provide curated datasets underpinning long-term regional biodiversity assessments (OSPAR Data and Information Management System[96], Joint Cetacean Data Programme[97], Intercet[98]). Long-term monitoring catalogues compile standardized biological time series used in regional and basin-scale assessments (SCAR Southern Ocean Continuous Plankton Recorder Survey[99], Continuous Plankton Recorder Survey[100]). A diverse set of regional initiatives and repositories complement these systems by aggregating species, habitat and monitoring data within specific geographic or governance contexts (DIPnet[101], CAFF[102], Asia-Pacific MBON[103], Southern Ocean Research Partnership portal[104], NOAA Whale and Dolphin Surveys in the Pacific Islands[105], Multi-agency Rocky Intertidal Network[106], SNO MEMO observing system[107]).

Pressure-related systems (n = 7) focus on environmental, anthropogenic and governance-related drivers affecting marine systems at basin, subregional or regional-seas scales (Supplementary Table 3 SupplTable3.xlsx). In contrast to global dominated by continuous physical and biogeochemical observations, regional ones emphasise region-specific threats, policy-relevant drivers and applied management contexts. They rely primarily on species data, interpreted Earth-observation products and policy-embedded indicators. Use is oriented towards governmental and intergovernmental users, with additional uptake by scientific communities involved in regional assessments. Update frequencies are typically annual or episodic, reflecting reporting cycles and coordinated surveys rather than continuous monitoring. Initiatives, repositories and catalogues represent the dominant system types within this category. Libraries and coordination platforms compile Earth-observation and in situ datasets relevant to pressure assessment within specific ocean basins (AtlantOS[108]). Repository-based ones provide

89 http://www.eurobis.org/about
90 https://maps.helcom.fi/website/biodiversity/
91 https://incois.gov.in/site/datainfo/jointportal.jsp
92 https://mcterrestrialmeasures.org/#/intro
93 https://acma.africanmarineatlas.org/catalogue/#/datasets
94 https://optics.marine.usf.edu/projects/saws.html
95 https://secoora.org/fact/data-visualization-tool/
96 https://odims.ospar.org
97 https://jncc.gov.uk/our-work/joint-cetacean-data-programme
98 https://www.intercet.it
99 https://data.aad.gov.au/aadc/cpr/index.cfm
100 https://www.cprsurvey.org/data/our-data/
101 http://diversityindopacific.net
102 https://www.caff.is
103 https://members.geobon.org/pages/ap-mbon.php
104 http://www.marinemammals.gov.au/sorp
105 https://www.fisheries.noaa.gov/pacific-islands
106 https://marine.ucsc.edu/explore-the-data
107 https://sextant.ifremer.fr
108 https://www.ocean-ops.org/board?t=atlantos

species-based indicators used as proxies for fishing pressure, ecosystem change or climate-driven redistribution (Western European Pelagic Acoustic Survey[109], Distributed Biological Observatory[110]). Thematic initiatives link environmental drivers to policy and management contexts. Earth-observation products are translated into coastal habitat assessment tools at the regional scale (IOC–WESTPAC Ocean Remote Sensing Project for Coastal Habitat Mapping[111]). Governance-oriented regional frameworks integrate pollution, habitat degradation and resource-use pressures within natural-capital and ecosystem-services perspectives (Northwest Pacific Action Plan[112]). Species-oriented pressure information links distributions to anthropogenic stressors such as bycatch, underwater noise and vessel traffic (ASCOBANS[113]). At the European scale, harmonised pressure and impact indicators support policy reporting and assessment under the Marine Strategy Framework Directive (WISE Marine[114]).

Response-related systems (n = 3) focus on policy implementation, management coordination and institutional action at the regional scale and are primarily implemented as data portals or decision-support systems (Supplementary Table 3 SupplTable3.xlsx). Fisheries governance platforms provide access to management measures, compliance information and stock-related policy instruments (Western and Central Pacific Fisheries Commission[115]). Species-focused response information is provided through harmonised datasets supporting conservation planning, monitoring obligations and regional reporting (Pacific Seabird Colonies Database[116]). Decision-support platforms translate policy commitments into spatial planning and management products for marine and coastal protected areas (Pacific Islands Protected Area Portal[117]).

A substantial part of regional systems are multidimensional, reflecting the integration of monitoring, assessment, management and reporting functions within regional governance and observing frameworks (Supplementary Table 3 SupplTable3.xlsx). State and pressure are mostly data-portals integrating biodiversity or ecosystem state with environmental or anthropogenic drivers (e.g. PacificMap[118], Coral Triangle Atlas, Ocean Networks Canada[119], Atlantic Meridional Transect[120]). Species-oriented platforms follow a similar structure by linking species distributions or movements to environmental variability or climate-related pressures (e.g. Censo Centroamericano de Aves Acuáticas[121], European Tracking Network[122], Humpback Whale Sentinel Program[123]). Connecting ecosystem condition or stock status directly to management and conservation action combines state and response (e.g. ICES data systems[124], Blue Forests platform[125]). Platforms combining pressure and

[109] https://www.marine.ie/site-area/areas-activity/fisheries-ecosystems/acoustic-surveys
[110] https://www.pmel.noaa.gov/dbo/cruise-data
[111] https://ioc-westpac.org/session/xv/marine%20biodiversity/Ocean%20Remote%20Sensing.pdf
[112] www.unenvironment.org/nowpap
[113] www.ascobans.org
[114] https://water.europa.eu/marine
[115] https://cmm.wcpfc.int/
[116] https://map.pacificdata.org
[117] https://pipap.sprep.org/
[118] https://map.pacificdata.org/
[119] https://data.oceannetworks.ca
[120] https://www.bodc.ac.uk/resources/inventories/edmed/report/207/
[121] https://whsrn.org/es
[122] https://europeantrackingnetwork.org
[123] https://www.southernoceansentinel.org
[124] https://data.ices.dk
[125] https://gefblueforests.org/

response translate environmental or anthropogenic drivers into management-relevant information without explicitly tracking biodiversity state (e.g. Sea Turtle Tag Inventory[126], CARICOOS[127]). Fisheries-oriented systems link fishing-pressure indicators to natural-capital and ecosystem-service considerations relevant for governance (e.g. Western and Central Pacific Fisheries Commission[128]). Some platforms combining response and benefit describe how management actions and governance arrangements generate sustainability or socio-economic outcomes (e.g. Fisheries and Resources Monitoring System[129], Bycatch Management Information System[130]). A limited number integrate all four SPRB components. These include large-scale observing and information infrastructures that combine ecological baselines, environmental drivers, management-relevant analytics and benefit-oriented outputs (e.g. Copernicus Marine Environment Monitoring Service[131], EMODnet[132], Mediterranean Ocean Observing System for the Environment[133], Pacific Islands Ocean Observing System[134], MACBIO[135], Baltic Sea Environment Database[136]).

4. Discussion

Our review and synthesis of marine biodiversity indicators and data systems helps to understand the information base available to evaluate KMGBF, the BBNJ agreement, and other marine-relevant policy processes. Marine biodiversity indicators are strongly weighted toward describing state and regional pressures, while response and benefit indicators are less common, especially for offshore, bathyal, and ABNJ regions (Hughes et al., 2025; Bridges and Howell, 2025), where biological sampling and indicator uptake remain less systematic despite alignment with formally recognised global frameworks, including EOVs and EBVs (Pereira et al., 2013; Miloslavich et al., 2018; Muller-Karger et al., 2018). Online marine biodiversity knowledge systems show a comparable geography of information: ecological records from deeper and distant waters exist, but are distributed across regional or institutional databases, move slowly into shared global infrastructures, and are seldom structured explicitly for indicator workflows or EBV classes. Strengthening harmonised data ingestion, automated quality control, and governance-aligned digital design would help ecological evidence transition more consistently into online knowledge systems, improving their capacity to support transparent, comparable, and policy-ready biodiversity reporting, including evaluation of regional management outcomes and global commitments.

4.1. What do we have, and what are the gaps

Across ocean monitoring programmes, the challenge is lack of cohesive data pathways that serve indicator workflows. Long-term reef surveys in frequently visited protected areas of Seychelles demonstrate that ecological signal detection is limited not by monitoring effort, but by rarity-weighted sampling noise, where nearly half of all recorded species were represented by fewer than three

[126] https://accstr.ufl.edu
[127] http://caricoos.org
[128] https://cmm.wcpfc.int/
[129] https://firms.fao.org
[130] https://www.bmis-bycatch.org/
[131] https://marine.copernicus.eu
[132] https://www.emodnet.eu
[133] https://www.moose-network.fr
[134] https://www.pacioos.hawaii.edu
[135] https://macbio-pacific.info
[136] https://metadata.helcom.fi

individuals, and species continued to accumulate despite sustained sampling (Barnes et al., 2011). This pervasive rarity explains why indicator confidence declines offshore and at depth, even in nominal data hotspots, and sets the context for understanding platform-level gaps.

Ships of opportunity have substantially expanded spatio-temporal coverage of upper-ocean physical, chemical, and selected biological measurements through the deployment of instruments on volunteer commercial and research vessels, and now constitute a core component of sustained observing networks, such as the Ship-of-Opportunity Programme (SOOP[137]) coordinated under GOOS. Complementing these vessel-based contributions, AniBOS[138], the GOOS tagged animal programme that tracks sensor-equipped marine fauna (Harcourt et al., 2019; McMahon et al., 2021; McMahon et al., 2025), demonstrates a growing and coordinated approach to observing animal movement, behaviour and in situ environmental conditions, strengthening biological EOV uptake across epipelagic and mesopelagic. Contributions from multiple national and regional institutions follow broadly shared methodological principles (e.g., NOAA[139], IMOS[140]), although practical implementation varies with fleet composition, sensor suites, and regional priorities. Sampling is inherently concentrated along established shipping routes and restricted largely to surface and upper-water layers, leaving deep pelagic waters and seafloor habitats outside the routine scope of observation. Biodiversity monitoring in these environments requires vessels to interrupt transit, deploy specialised sampling or imaging equipment, and allocate substantially greater operational time and effort, factors that sharply limit data acquisition relative to continuous, or underway, measurements. Alignment with physical and biogeochemical EOVs is therefore strong, whereas biological and ecological EOVs that depend on targeted sampling, imaging, or specimen-based observations remain weakly supported, contributing to the persistent under-representation of deep-sea systems relative to shelf and coastal waters across both indicators and the platforms that underpin them.

Recent large-scale mapping has enabled substantial improvements in baseline knowledge for some previously under-represented areas. Mapping of biodiversity, rare species, biomass, vulnerable marine ecosystems, and conservation priorities across the southern half of Greenland's continental shelf has filled a major Arctic data gap and provided a more resolved picture of ecosystem structure in a region that had long remained poorly characterised (Zwerschke et al., 2025). At the global scale, datasets describing deep-sea features, such as seamounts and hydrothermal vents, have expanded spatial coverage, but typically remain static and offer limited insight into ecological conditions, or change, through time (Bridges and Howell, 2025). More recent compilations of marine critical habitats extend spatial representation further by integrating seamounts and vent fields across the global ocean, improving understanding of the distribution of ecologically significant deep-sea environments, while remaining largely focused on habitat occurrence, rather than temporal dynamics, of ecosystem change (Dunnett et al., 2025).

Animal-borne telemetry has similarly become an important component of the ocean observing toolkit, providing in situ measurements across wide spatial and temporal scales, while linking physical variability to animal behaviour and performance (Fedak, 2004; Fedak, 2013; Harcourt et al., 2019; McMahon et al., 2021; McMahon et al., 2025). However, data generated by these approaches are not

[137] https://goosocean.org/who-we-are/observations-coordination-group/global-ocean-observing-networks/ship-of-opportunity-programme-soop/
[138] https://anibos.com/
[139] https://www.aoml.noaa.gov/ships-of-opportunity/
[140] https://imos.org.au/facility/ships-of-opportunity

yet consistently incorporated into indicators, or into platforms, designed for routine reporting, which constrains their contribution to repeated assessment, and comparative, decision-making.

Technological advances such as Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), drones or Remotely Piloted Aircraft Systems (RPAS) are very promising, especially when accompanied by powerful Artificial intelligence (AI). AI, and machine-learning approaches are reshaping marine biodiversity monitoring through improved processing of underwater imagery (Remmmers et al., 2025), and large environmental DNA (e-DNA) datasets. These methods increasingly support biological and ecological EOVs, including ecosystem structure, community composition, and species distributions, while enabling the derivation of corresponding EBVs at spatial scales that were previously impractical to observe consistently. Automated segmentation, and classification, of photogrammetric products now allow extraction of benthic community composition, colony-level metrics, and fine taxonomic information from large-area underwater image mosaics at speeds and spatial extents that exceed manual approaches by orders of magnitude (Remmers et al., 2025). Gains in detection capacity, and taxonomic resolution, have strengthened baselining, and monitoring, of vulnerable marine ecosystems and selected taxa (Bridges et al., 2023a; Gros et al., 2023). e-DNA workflows are also advancing rapidly, and emerging analytical environments increasingly support large-scale visualisation, and exploration, of molecular biodiversity signals across many samples, including datasets spanning surface to deep-ocean environments (e.g., OceanOmics eDNA Dashboard[141], UNESCO eDNA Expeditions Dashboard[142]). Sustained use of systems depends primarily on standardised metadata, stable data pipelines, robust quality control procedures, and long-term institutional support, rather than analytical capability alone.

Limitations in observation and data integration constrain the capacity to quantify ecosystem functions, and benefits derived from marine biodiversity. For example, marine organisms mediate a substantial share of the ocean's role in the global carbon cycle through the production, transformation, and vertical transport of organic carbon from surface waters to depth (Grigoratou et al., 2025). The efficiency of this biological transfer is shaped by ecosystem structure, trophic interactions, particle aggregation, and remineralisation processes, which together determine the proportion of carbon retained in the upper ocean, versus sequestered at depth, (Passow and Carlson, 2012). Recent global analyses have quantified, and valued, biologically mediated carbon sequestration (Morley et al., in press), revealing pronounced spatial structure across ocean basins, and substantial contributions, from areas beyond national jurisdiction, (Berzaghi et al., 2025), within the online marine biodiversity knowledge systems reviewed here, decision-support tools show a spatial bias similar to that observed for biodiversity indicators. Most of these observing networks are concentrated in coastal and shelf waters, where data availability is higher, jurisdictional boundaries are clearer, and management mandates are well established. Moving decision-support tools into offshore and open-ocean settings introduces additional challenges linked to three-dimensional ocean structure, moving water masses, shifting species distributions, and connectivity driven by currents. Although global bathymetric, and habitat, datasets now provide extensive spatial coverage, these products are typically static, and offer limited representation, of biological dynamics, or ecosystem change, through time.

Finally, online marine biodiversity knowledge systems addressing pressures tend to focus on stressors that are spatially explicit, and comparatively tractable, including pollution, eutrophication, bottom-contact fishing, seabed-associated infrastructure, and anthropogenic noise. These pressures are

[141] https://www.minderoo.org/media/uncovering-the-mysteries-of-the-sea-meet-the-groundbreaking-new-oceanomics-dashboard/

[142] https://dashboard.ednaexpeditions.org/

increasingly combined within cumulative-impact products that summarise multiple drivers to support broad-scale comparison (Halpern et al., 2015; O'Hara et al., 2021; 2024). While useful for identifying areas of elevated exposure, such products remain constrained by the resolution, and update frequency, of underlying datasets, particularly in offshore, and deep-sea, contexts, and provide limited insight into how exposure translates into ecological response. This limitation is especially evident for fishing pressure. Satellite-based vessel monitoring delivers unprecedented spatial coverage of global fishing pressure, but most pressure layers remain gear-implicit, preventing separation of fishing gears with very different benthic footprints, intensity, frequency, or ecological consequence. Bottom-contact fishing, especially trawling, can have disproportionate, and spatially extensive, effects on benthic habitats, and associated biodiversity, which remain inseparable within aggregated fishing-effort layers (Kroodsma et al., 2018). Emerging global syntheses targeting bottom fishing, and seabed disturbance, illustrate the scale, and corridor-level concentration, of impacts, but these data streams are not yet consistently integrated into routinely updated pressure-related biodiversity indicators[143] [144] [145].

4.2. Relevance to international policy agreements

This section interprets the policy relevance of the marine indicators and online marine biodiversity knowledge systems analysed in this study, drawing directly on the documented distribution of indicators across the SPRB framework and the functional characteristics of existing online systems. While many international agreements articulate clear monitoring ambitions for marine biodiversity, the current landscape shows that indicator availability and online system design remain uneven, with strong representation of state and pressure-related ones, comparatively limited coverage of response and benefit. The linkages between available marine indicators and the KMGBF and the SDGs show clear traction at the global policy level, alongside growing expectations that existing metrics and platforms can better inform global and regional decision-making. Monitoring ambitions across international instruments are well articulated, but translating marine observations into repeatable, governance-aligned indicators remains uneven because digital pipelines and sampling designs have not co-evolved at the same pace.

The agreements discussed here were selected to span global biodiversity governance, sectoral regulation, and emerging ocean governance, and to illustrate distinct ways in which marine biodiversity metrics and online platforms are expected to support monitoring, reporting, and evaluation across policy contexts. Rather than providing an exhaustive review of all marine-relevant multilateral environmental agreements, this section focuses on representative frameworks where the alignment, or misalignment, between policy-articulated data needs and the current landscape of marine metrics and platforms is most evident.

Convention on Biological Diversity: The monitoring framework of the KMGBF comprises 26 headline indicators, 58 component indicators and 230 complementary indicators adopted by Parties to track progress toward the Framework's goals and targets (CBD, 2022; CBD/COP/DEC/16/31). While the framework is not organised by ecological realm, a substantial subset of these indicators is directly applicable to marine and coastal systems, or explicitly designed to be disaggregated by ecosystem type or realm. Approximately one-third of headline indicators, a similar proportion of component indicators, and a smaller but still substantial subset of complementary indicators can be operationalised using

[143] https://www.seaaroundus.org/bottom-trawling-global-extent-impacts-and-solutions/
[144] https://obis.org/node/6f3223e3-50a6-4ba5-b02c-0037ae3863ce
[145] https://epi.yale.edu/measure/2024/BTO

marine biodiversity data, based on indicator scope and the disaggregation options defined in the monitoring framework. In practice, however, the marine-relevant indicators most commonly implemented correspond to biodiversity state and pressure dimensions, while response- and benefit-oriented indicators remain comparatively under-represented in marine reporting.

These marine-relevant indicators are concentrated primarily on well-established coastal ecosystems such as coral reefs, saltmarshes, seagrass beds, and mangroves, while other ecologically and carbon-significant marine habitats, including macro-algal forests, fjords, and seamounts, remain comparatively weakly represented in both biodiversity and climate-related monitoring frameworks. Despite their prominence in monitoring and reporting, nearshore and coastal protected areas are also subject to substantial erosion of protection through legal changes. Global analyses of marine Protected Area Downgrading, Downsizing, & Degazettement (PADDD[146]) document at least 43 enacted PADDD events across six countries, affecting more than 1,1 million km² of marine protected area, with most events associated with industrial-scale resource use and commercial fishing (Albrecht et al., 2021). Recent assessments further indicate that the designation of new protected areas has not consistently offset losses arising from PADDD, particularly in coastal systems where governance pressures and competing uses are highest, undermining assumptions of stable protection embedded in biodiversity indicators (Turner et al., 2024).

This distribution closely mirrors the patterns identified in our online systems analysis, where indicators aligned with GBF reporting are predominantly supported by data portals and repositories, rather than by integrated ones capable of linking biodiversity state to management actions and societal benefits. Although indices such as the Red List Index and Living Planet Index include marine species and can be disaggregated by realm, they remain uneven in their coverage of deep-sea and polar biota, despite evidence of rapid environmental change and heightened sensitivity in these systems (Rogers et al., 2020). As Parties move toward repeated global reviews of GBF implementation, these structural imbalances risk constraining the interpretability of reported progress in marine and offshore contexts. This gap between policy ambition and operational data supply is consistent with broader assessments of international biodiversity monitoring needs, which identify response-oriented and outcome-focused indicators as persistently under-supported within existing marine data infrastructures (McOwen et al., 2025). Table 4 summarises all GBF headline indicators with clear marine relevance alongside prominent component and complementary indicators, and maps them to the marine metrics and platform capacities identified in this study.

Table 4. Alignment between GBF headline, component and complementary indicators with marine relevance and the marine metrics and platforms identified in this study.

Indicator type	GBF indicator (COP-16)	Marine relevance	Dominant SPRB	Marine indicators	Platform support
Headline	Extent of natural ecosystems	Explicitly includes coastal and marine ecosystems	State	Coral reef, mangrove, seagrass, saltmarsh extent	Strong
Headline	Red List of Ecosystems	Disaggregable by realm, includes marine ecosystems	State	Risk of collapse, ecosystem condition indices	Moderate
Headline	Red List Index	Includes marine taxa, realm-disaggregable	State	Marine RLI, threatened marine species indices	Moderate

[146] https://www.padddtracker.org/

Headline	Proportion of fish stocks within biologically sustainable levels	Explicitly marine	State / Pressure	Stock status, exploitation indicators	Strong
Headline	Coverage of protected areas and OECMs	Explicit reference to marine areas	Response	MPA and OECM coverage	Strong
Headline	Percentage of land and sea area covered by biodiversity-inclusive spatial plans	Explicit reference to sea area	Response	Marine spatial planning coverage	Moderate
Headline	Area under restoration	Applicable to coastal and marine restoration	Response	Mangrove, seagrass, reef restoration extent	Weak/Moderate
Headline	Rate of invasive alien species establishment	Includes marine invasive species	Pressure	Marine IAS occurrence trends	Weak
Headline	Services provided by ecosystems	Includes marine ecosystem services	Benefit	Blue carbon, fisheries, coastal protection proxies	Weak
Headline	Nature's contributions to people	Includes marine contributions	Benefit	Fisheries yield, tourism proxies	Weak
Component	Sustainable fisheries	Core marine target	Pressure / State	Fishing effort, bycatch, stock exploitation	Strong
Component	Pollution and eutrophication	Coastal and marine impacts	Pressure	Nutrient loading, pollution indices	Moderate
Component	Climate change impacts on biodiversity	Strong marine relevance	Pressure	Warming, acidification proxies	Moderate
Component	Spatial management effectiveness	Marine relevance via MPAs	Response	Management coverage and designation metrics	Moderate
Complementary	Cumulative human pressures	Widely applied to marine systems	Pressure	Cumulative impact indices	Strong
Complementary	Ecosystem services and benefits	Marine benefits under-represented	Benefit	Blue carbon, tourism value	Weak
Complementary	Genetic diversity	Applicable but rarely operationalised	State	Population structure proxies	Very weak

Convention on Migratory Species (CMS): CMS was established to facilitate global cooperation to improve the conservation status of species that regularly cross international boundaries, including wide-ranging marine taxa such as seabirds, cetaceans, pinnipeds, marine turtles, and sharks and rays. In line with approaches adopted under the Convention on Biological Diversity, the development of the CMS monitoring framework emphasises the use of existing indicators supported by scientifically robust, peer-reviewed methodologies. For marine migratory species, additional metrics are needed to underpin indicators relevant to the Samarkand Strategic Plan, particularly to address recognised gaps in tracking functional connectivity, key pressures such as bycatch and marine pollution, disease (Leguia et al., 2023), and management responses including the integration of migratory species into marine spatial planning and the effectiveness of multilateral cooperation.

Given its mandate, CMS requires indicators that capture ecological processes central to migration. While many global biodiversity metrics are broadly relevant to the marine realm, few can be readily disaggregated or interpreted in ways that align directly with CMS-listed species and migratory processes. This creates a need to bridge the gap between global-scale marine metrics, which often describe broad ecosystem or pressure trends, and more granular, species-specific information that reflects movement, connectivity, and exposure to threats along migratory pathways. Open-data platforms and atlases providing information on species at-sea distributions and movements, including OBIS, Movebank, MiCO, and the emerging Move BON initiative, offer important opportunities to support this integration by linking species-level data with other spatially explicit datasets. This reliance on species-level distribution and movement data reflects a broader pattern identified in our analysis, whereby connectivity-related indicators remain weakly represented (Metaxas et al., 2024) among operational marine indicators and are rarely embedded within platforms that also integrate pressures and management responses. As a result, CMS monitoring risks remaining data-rich but analytically fragmented, particularly in its capacity to evaluate progress against response-oriented elements of the Samarkand Strategic Plan.

Convention on International Trade in Endangered Species (CITES): CITES regulates international trade in a substantial number of marine taxa, including tropical corals and marine fishes traded for the aquarium and ornamental markets. Of the approximately 6500 animal species included in the CITES Appendices, around 2400 are marine taxa, including all cetaceans, all marine turtles, many sharks and rays, and coral species (Pavitt et al., 2021). Trade in ornamental fish remains a gap. At present, around 35 ornamental fish are listed in CITES, but there are more than 1000 species in trade (CITES Secretariat and UNEP-WCMC, 2022). Under CITES, the primary metric used to characterise trade is the number of individuals, or parts of individuals, recorded in international trade, supported by dedicated online systems that facilitate access to trade statistics and non-detriment findings. While effective for tracking regulated international trade volumes, this reliance on trade quantities provides limited insight into how trade pressure relates to population status, extinction risk, or cumulative impacts alongside other drivers of biodiversity change. Some of these insights can be gleaned by linking CITES appendices to the IUCN Red List database, but this is not without challenges (Challender et al. 2023). Large numbers of traded marine species are not listed in the CITES appendices and are therefore not captured within CITES trade databases, limiting the capacity of existing trade metrics to be interpreted in relation to broader patterns of marine biodiversity status and cumulative pressure (Murray et al., 2025; Hughes et al., in prep). Broader-scale datasets for commercially harvested and widely distributed marine species, including those maintained by FAO and represented within macroeconomic databases such as OECD, GTAP[147], and UN Comtrade Database[148], similarly prioritise extraction or economic value over ecological status because they record aggregate commodity flows by product codes rather than species-level ecological detail. The marine extension of the Species Threat Abatement and Restoration metric (Marine STAR) integrates species distributions, IUCN Red List extinction risk, and threat information to quantify where reducing pressures such as unsustainable fishing would deliver the greatest reductions in marine species extinction risk (Turner et al., 2024). In parallel, variants of the Living Planet Index explicitly track population trends of exploited species, providing a direct means of relating harvest and trade pressures to observed biodiversity change over time. This separation reinforces a broader pattern identified in our analysis, whereby pressure-related indicators are comparatively well developed but rarely embedded within shared analytical environments capable of evaluating whether trade regulation under CITES is contributing to measurable conservation outcomes in marine systems.

Regional Seas Management Agreements (RSMOs)**:** RSMOs provide an important regional-scale governance framework for marine biodiversity, typically relying on periodic integrated assessments to synthesise information on ecosystem condition, pressures, and management actions across contracting parties. Our analysis suggests that most online marine biodiversity knowledge systems supporting RSMO reporting emphasise biodiversity state and selected pressures, with limited capacity to

[147] https://www.gtap.agecon.purdue.edu/

[148] https://comtradeplus.un.org/

systematically track coordinated management responses, implementation progress or outcomes across countries. As a result, these knowledge systems tend to support descriptive regional overviews rather than enabling consistent evaluation of policy effectiveness, comparability among parties or assessment of change through indicators.

RSMOs increasingly recognise the need to connect pressure observations with ecological consequences, but most existing monitoring frameworks still prioritise spatial presence over dynamic attributes such as intensity, frequency or duration, limiting inference on cumulative effects and temporal change. Pressures mediated by discrete or interrupted sampling, unlike continuous underway measurements, remain harder to implement systematically across contracting parties (McOwen et al., 2025). Large areas of the global ocean are weakly represented in open-access online marine biodiversity knowledge systems, especially deep-sea environments and ABNJ (Hughes et al., 2025; Bridges and Howell, 2025). This reinforces a persistent imbalance in how indicators describing ecological response and benefit can be derived, updated and compared through time across multinational reporting cycles. Observation fragmentation, rather than ecological absence, remains a defining constraint of current RSMO digital support, many online marine biodiversity knowledge systems ingest overlapping datasets from a small set of shared sources, reinforcing geographic and taxonomic bias toward well-monitored coastal or surface-accessible demersal species, while deep-sea ecological dynamics, genetic signals and indicator uptake remain inconsistently incorporated into routinely updated indicators (McOwen et al., 2025). Improving structured, automated ingestion and quality control pipelines within online marine biodiversity knowledge systems would strengthen the ability of RSMOs to track coordinated multinational outcomes, resolve ecological confidence in deep-sea environments and support more comparable, repeatable and routinely updated indicators for future integrated regional assessments.

Biodiversity Beyond National Jurisdiction: The Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Agreement; UN Doc. A/CONF/232/2023/4) establishes obligations for implementation, review, and adaptive management that are explicitly grounded in the use of the best available scientific information, including biodiversity data from areas beyond national jurisdiction. Recent syntheses of international biodiversity policy requirements indicate that the operationalisation of the BBNJ agreement will depend on the development of a monitoring and review framework supported by appropriate metrics and indicators, and on the availability, representativeness, and continuity of biodiversity data from ABNJ (McOwen et al., 2025). Within this context, assessing monitoring readiness, rather than defining new indicator concepts, emerges as a priority for early implementation.

Results from this study show that marine biodiversity information is predominantly delivered through data portals and repositories, with relatively few platforms designed to support sustained, standardised, and repeatable indicator production. This structural pattern is particularly consequential for ABNJ, which rely almost exclusively on global data infrastructures and lack complementary national monitoring systems. Consistent with broader assessments of monitoring capacity, biodiversity data collection has increased in polar regions, but this growth has been accompanied by increasing fragmentation across national, project-based, and institution-specific repositories, such that progress is not always visible when assessed through any single global platform, including OBIS or GBIF (McOwen et al., 2025). By contrast, biodiversity sampling in the mid-ocean, bathyal, abyssal, hadal, and sub-ice-shelf environments remains disproportionately sparse, reflecting the high logistical and financial costs associated with access and sustained observation.

At the same time, advances in acoustic instrumentation, seabed mapping, and analytical methods have improved the capacity to infer habitat extent and structure in data-poor regions using non-biological observations. Activities associated with seabed mineral exploration, subsea cable installation, and other offshore infrastructure developments have become important sources of multibeam sonar data, which, when combined with improved interpretation tools and ground-truthed reference data, offer opportunities to approximate habitat status and extent at broad spatial scales (Bridges et al., 2023b). However, our platform inventory indicates that data systems relevant to ABNJ currently operate primarily as project-based or discipline-specific repositories, rather than as sustained platforms designed for routine and repeatable indicator production. This misalignment creates a structural tension between the long-term monitoring ambitions articulated under the BBNJ agreement and the current organisation of marine biodiversity data infrastructures, particularly for deep-sea and mid-ocean ecosystems (McOwen et al., 2025).

4.3 Relevance to business needs

With growing awareness and understanding of the importance of biodiversity among businesses, an increasing number of businesses are taking steps to assess, manage and disclose their biodiversity impacts, dependencies, risks and opportunities (IPBES, 2026; TNFD, 2025a; CDP, 2025). This creates a clear need for biodiversity data for business use, including data on biodiversity in the marine realm. Leading frameworks and standards, such as the Taskforce on Nature-related Financial Disclosures (TNFD), GRI Standards or European Sustainability Reporting Standards (ESRS), cover marine biodiversity disclosures through cross-realm disclosure recommendations as well as topic- and sector-specific guidance (TNFD, 2023a; GRI, 2021; ESRS 2025). The Science Based Targets Network (SBTN) provides target setting guidance for business, including methods for several types of business targets in oceans (SBTN, 2025a). Limited availability of data for the marine realm is often cited as a challenge for business assessment, disclosure and target setting, and therefore seen as one of the key barriers to business action on marine biodiversity impacts and risks (TNFD, 2025b; UNEP FI, 2025). Although this study focused on marine biodiversity metrics applied as indicators in policy frameworks, several of them are relevant for use by business. For example, metrics measuring the change in the extent of marine and coastal ecosystems can be applied at the level of an individual firm or business operation site to reflect business impact on these ecosystems. Other metrics reviewed may not be applicable at sub-national or sub-regional levels, but information on performance against these metrics can inform business biodiversity assessments as high-level indicators on state of biodiversity in different countries and regions (e.g. Ocean Health Index, Marine Living Planet Index). Further research could explore overlap between the 145 marine biodiversity metrics reviewed here and metrics recommended for business disclosure, assessment and target setting (see for example business metrics recommended in TNFD, 2023a; SBTN, 2025b; WBCSD, 2025). This could complement ongoing efforts to build scientific consensus on marine biodiversity metrics for business (NPI, 2025; TNFD, 2025b).

From the online marine biodiversity knowledge systems (Annex1_Sept 2025.xlsx) reviewed in this study, 73 mention business among their main stated user groups. This includes 5 data sources (portals), 30 decision-support tools, 19 flexible analysis platforms, 4 libraries/catalogues, 2 repositories and 13 other resources or initiatives. Of the 73 marine biodiversity platforms that aim to support users from business, 10 platforms are specifically focused on marine and coastal data (e.g. Coastal Risk Index, FishSource, Global Fishing Watch, OBIS). The remaining 63 platforms cover the marine realm alongside terrestrial and/or freshwater realm (e.g. GIST Impact, Iceberg Data Lab, IBAT). Many cross-realm platforms have started with a narrower focus, with other realms being added at a later stage. For example, IBAT is planning improvements in its coverage of the marine realm with the incorporation of marine STAR (Turner et al., 2024). The global Critical Habitat screening layer, as another example, was initially calculated for the marine realm (Martin et al., 2015), was then expanded to the terrestrial realm (Brauneder et al., 2018) and has recently been updated as one cross-realm layer (Dunnett et al., 2025).

Business assessment and disclosure of biodiversity impacts, dependencies, risks and opportunities encompasses multiple use cases for marine biodiversity metrics and platforms. This includes prioritization of locations based on ecological sensitivity, evaluation of business impacts and dependencies, and assessment of risks and opportunities for the business (UNEP-WCMC, Capitals Coalition, Arcadis, ICF, WCMC Europe, 2022; TNFD, 2023b). Each of these use cases has its own metrics requirements and data specifications. For example, high-level screening of ecologically sensitive locations can be completed with coarser data than data needed to measure a change in the state of nature caused by the activities of a business in a specific location. Yet another example is prioritization of potential impacts based on biodiversity footprints, which uses secondary and modelled data on pressures and impacts of different economic activities and sectors (PBAF, 2022; TNFD, 2023c). Marine biodiversity indicators and online systems gaps for business therefore include necessary improvements in Earth observation and *in situ* data as well as further development of datasets, models and indices that transform this data for business applications.

4.4. Moving forwards

Biodiversity monitoring originates locally, where ecological signals are first detected, interpreted, and validated. Local observing nodes must align with shared principles, standardized protocols, metadata standards, and interoperable indicator workflows to support aggregation to regional and global scales. When harmonisation is inconsistent at the point of data generation, marine indicators inherit uneven comparability and reduced analytical maturity. GOOS plays a central role in coordinating the harmonisation of ocean observations by defining Essential Ocean Variables (EOVs) through standardised specification sheets[149] that align measurements, methods and data practices across global observing networks. Advancing beyond the gaps identified in this review requires a conceptual shift from incremental expansion of observations toward integrated, outcome-focused marine monitoring (O'Callaghan et al., 2025). Similar to the sustained development logic advocated within the GOOS, progress depends on co-designed partnerships, an inclusive and skilled workforce, long-term technological innovation, and durable operational models that prioritise system endurance over temporary, project-bound data generation (Miloslavich, 2025). Collectively, these enabling conditions define how marine biodiversity data evolve from disparate local observations into scientifically robust and policy-relevant indicators that can be interpreted with multi-regional consistency.

Marine biodiversity observation remains inherently more complex, costly, and logistically demanding than in terrestrial systems. Ship-based surveys, autonomous and remotely operated underwater vehicles, fixed and mobile acoustic platforms, and deep-water sampling methods such as box corers, multicorers, and drop cameras continue to underpin observation of offshore and deep-sea ecosystems. These approaches are time-, effort-, and capital-intensive, and in practice are often constrained less by sensor availability than by access to vessels and specialist taxonomic expertise. Opportunities for low-cost, mobile phone–based citizen science are therefore more limited, although surface-based initiatives have proved highly effective for whales, seals, seabirds, and coastal wetland species. At the same time, the use of ships of opportunity, including commercial and cruise vessels, for plankton sampling, plastics monitoring, and water collection demonstrates how observation coverage can be expanded when biodiversity monitoring is embedded within routine maritime activity.

Recent advances in artificial intelligence are beginning to alter the balance between data volume and analytical capacity, particularly for monitoring human pressures. AI applications applied to vessel monitoring systems, automatic identification systems, electronic monitoring, and related fisheries data streams are now widely used to classify fishing activity, estimate effort, and infer bycatch and discards, substantially strengthening global monitoring of fisheries pressure (Welch et al., 2024). These approaches have the potential to support near–real-time analysis of large volumes of vessel tracking

[149] https://goosocean.org/what-we-do/framework/essential-ocean-variables/

data and increasingly integrate multiple observation sources, including satellite imagery, radar, and on-board sensors, allowing detection of fishing activity even where vessels do not broadcast location data. Animal-borne telemetry systems, in addition, providing near-real-time biological data, such as AniBOS, strengthen spatial management readiness in regions where direct biological sampling is constrained, complementing pressure indicators including fishing activity[150]. Such developments illustrate how advances in analysis, rather than new observation platforms alone, can significantly enhance monitoring capacity.

Despite these advances, large areas of the ocean will remain inaccessible to routine biological observation, and much available data will continue to originate from infrequent, project-based scientific expeditions. In this context, improvements in high-resolution digital imaging, automated image analysis, and machine-learning classification are particularly significant for deep-sea monitoring. Automated processing of seabed imagery can reduce reliance on on-site taxonomic expertise and enable repeatable extraction of benthic community metrics at spatial scales previously impractical (Gros et al., 2023; Remmers et al., 2025). Parallel advances in molecular approaches further extend monitoring potential. As genetic reference databases expand, curation improves, and taxon-specific primers become more widely available, environmental DNA approaches offer relatively low-impact detection of species and communities in semi-remote and offshore environments, provided that metadata standards and analytical pipelines are robust and interoperable.

Technological capability alone, however, is insufficient. Progress toward effective marine biodiversity monitoring also depends on accelerating the translation of observations into actionable information. Real-time quality control, automated data ingestion, and standardised data flows across platforms are advancing, yet fragmentation and duplication continue to limit efficiency and comparability. Frameworks based on Essential Variables provide a coherent pathway for aligning observations, indicators, and policy needs, but uptake remains uneven across the science–policy interface and inconsistently reflected in monitoring frameworks. Moving faster will require clearer incentives for adoption, including explicit alignment of Essential Variables with reporting obligations under major international agreements and sustained support for platforms that operationalise them.

Tangible societal and economic benefits from marine observing systems help sustain the transition toward digital, automated monitoring. Near-real-time biodiversity and pressure data increasingly support adaptive operations that reduce ecological risks while strengthening management and industry use, including dynamic vessel routing or speed adjustment during marine mammal aggregations, migration-linked bycatch reduction windows for fisheries, and time-bounded offshore infrastructure activity that avoids disturbance in sensitive ecological periods. Norwegian fisher evaluations of automatic catch-registration technologies show that acceptance rises when monitoring systems remove manual reporting burden, support perceptions of legal fairness among skippers, and generate benefits that are directly relevant to daily operations, including improved detection of species migrations and catch-composition shifts which influence willingness to adopt digital monitoring and data-sharing systems across commercial fleets (Ahlquist et al., 2025). Automated segmentation and multi-view benthic image classification now enable extraction of colony- and community-level seabed biodiversity signals at spatial scales and processing speeds previously impractical using manual annotation, strengthening EOVs and EBVs confidence classes for benthic community composition, coral colony metrics, and habitat-linked species populations (Remmers et al., 2024).

Closing remaining gaps will require coordinated action across organisations operating at different points along the marine data landscape. Global coordination bodies such as GOOS and Ocean Decade initiatives provide the structural backbone for aligning observation priorities and supporting the uptake

[150] https://www.ocean-ops.org/goosreport/#oceanhealth-section

of Essential Variables. Major data infrastructures including OBIS and GBIF remain indispensable for aggregation, standardisation, and global accessibility of marine biodiversity observations, particularly by resolving spatial, depth-linked, and taxonomic gradients (Hughes et al., 2025). Policy advice and interventions (such as protection) should still significantly aid reducing nature loss (and climate mitigation, see Shin et al., 2022). Policy-facing organisations, including regional seas conventions and fisheries management bodies, currently provide the primary interfaces connecting monitoring outputs to international reporting obligations. However, this interface remains disproportionately centred on fisheries pressure reporting, and a broader thematic expansion of biodiversity monitoring outputs is now needed to support more balanced international assessments and governance decisions.

Moving beyond gap identification toward meaningful gap closure will require strategic prioritisation and systemic realignment. Expanding observations in underrepresented regions and depth zones, embedding biodiversity monitoring within routine maritime and industrial activities, and strengthening interoperability through Essential Variable frameworks will increase cross-realm comparability. A more holistic overview of marine biodiversity demands improved integration of non-fisheries biological indicators, particularly for ecosystems, species interactions, and genetic observations, so that monitoring outputs more equitably represent biodiversity state alongside fisheries pressures (Miloslavich, 2025). Together, these actions outline a realistic path toward a marine biodiversity monitoring system that is progressively more comprehensive, thematically balanced, scientifically traceable, and responsive to the needs of both global governance and advancing marine science.

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Supplementary Materials

Supplementary Table 1 SupplTable1.xlsx
Supplementary Table 2 SupplTable2.xlsx
Supplementary Table 3 SupplTable3.xlsx

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