

REVIEW OPEN ACCESS

What Do We Know About the Environmental Status of European Seas?

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ABSTRACT

The European Union (EU) established the Marine Strategy Framework Directive (MSFD) to achieve good environmental status (GES) in European seas through an ecosystem-based approach to management. EU Member States implementing the MSFD must assess the environmental status of their marine waters, as well as the human pressures and impacts affecting them. The MSFD follows a 6-year cycle, with assessments made based on 11 descriptors linked to specific pressure, state and impact-related criteria. Member States assessments should determine the extent to which GES is achieved. However, for coherent management of EU seas, comparable assessments across Member States and EU-wide overview of the status and MSFD progress are essential. This study developed pressure, state, and impact indices, by integrating available MSFD data reported by EU Member States. For the first time, MSFD data across all descriptors have been integrated to produce a European regional assessment. Findings indicate that most European regions are far from demonstrating GES, suffering from intense pressures and impacts. Significant knowledge gaps were identified, particularly in the eastern Mediterranean. The findings highlight the urgent need for enhanced ecological monitoring and setting environmental targets to improve the dire state of European seas, advocating for stronger regional cooperation and standardized methodologies.

Introduction

Marine biodiversity in European regional seas has experienced a notable decline in recent decades (European Commission 2020; Bevilacqua et al. 2021; McQuatters-Gollop et al. 2022) due to cumulative human pressures and global environmental change (Gissi et al. 2021). This trend arises from the intensification of human activities and associated pressures, driven by the pursuit of sustaining livelihoods and fostering economic growth (Borja, Elliott, et al. 2024). These pressures exert detrimental impacts on marine ecosystem structure and functioning (Pusceddu et al.

2014; Korpinen et al. 2021). The effects of this degradation include a significant reduction in the flow of ecosystem services, which are essential for human well-being (Cardinale et al. 2012).

This concerning trend has emphasized the urgency for policy-makers to pivot toward sustainable ocean use while preserving marine ecosystem health (Ryabinin et al. 2019). In response, holistic environmental approaches and principles, such as the ecosystem-based approach to management (EBM) (Long et al. 2015), marine spatial planning (Katsanevakis et al. 2011), Risk-based Cumulative Effects Assessments (Stelzenmüller et al. 2018;

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Stelzenmüller et al. 2020), adaptive management (Rilov et al. 2020), and integrated ocean management (Borja et al. 2016; Winther et al. 2020) have gained prominence. These strategies advocate a whole-system approach, thus ensuring the consideration of the complexity of marine ecosystems (Dreujou et al. 2020). Holistic environmental approaches have become instrumental in biodiversity protection legislation on global, regional, and national scales, particularly after the adoption of the Aichi Biodiversity Targets, in 2010 (Dreujou et al. 2020).

Recognizing the importance of regional management and coordination for successful environmental protection and sustainable use of natural resources (IPCC 2022), the Marine Strategy Framework Directive (MSFD; Directive 2008/56/EC) was implemented by the European Union (EU) to ensure good environmental status (GES) in the European seas, under an EBM (European Union 2008). The GES under Article 3(5) of the MSFD refers to marine waters that maintain their inherent qualities of ecological diversity and dynamism, ensuring ocean health and productivity, while their use remains sustainable for present and future generations. To this end, EU Member States are required to assess the status of their marine waters based on 11 specific qualitative descriptors including marine biodiversity (D1); non-indigenous species (D2); commercially exploited fish and shellfish (D3); food webs (D4); eutrophication (D5); sea-floor integrity (D6); hydrographical conditions (D7); contaminants in the environment (D8); contaminants in seafood (D9); marine litter (D10); and introduction of energy, including underwater noise (D11) (further analyzed through specific descriptor related criteria, in 6-year cycles) and establish environmental targets and associated indicators to monitor the achievement of GES.

The initial assessment cycle (2012–2015) revealed that the knowledge base across Europe was inconsistent, marked by variations in reported indicators, methodological diversity, and data gaps (European Commission 2020). The concept of GES is intricate, encompassing various definitions and characteristics that must be collectively agreed upon. This includes the GES definition, standardized methods for determining reference and desired conditions, approaches for quantifying threshold values, strategies for integrating indicators, criteria, and descriptors, consideration of temporal variations of ecosystem components and human pressures, and ways for geographical upscaling from reporting units to ecoregion-scale assessments (Borja et al. 2013).

In 2017, the EU issued Commission Decision 2017/848 (hereafter “GES Decision”; European Commission 2017), establishing criteria and methodological standards to harmonize environmental status assessments and facilitate comparisons across the EU. Each descriptor is accompanied by relevant criteria that characterize the associated pressures, state, or impacts. Criteria elements (see Table 1 for description) should be assessed under their relevant criteria using threshold values for specific indicators. At a higher level, using integration rules, features (e.g., group of elements such as species groups or chemical substance groups; see Table 1 for description) that are linked to specific descriptors are assessed, allowing an overview of the extent to which GES is achieved. The “GES Decision” mandates that Member States establish threshold values for GES, enhancing coherence across marine regions and facilitating a comprehensive EU-wide evaluation of GES attainment in European seas (European Commission 2022).

The MSFD follows an EBM aligned with the Drivers-Pressure-State-Impact-Response (DPSIR) framework. This framework links natural and social systems in a way that facilitates management and protection, helping to maintain ecosystem services that provide societal goods and benefits (Elliott et al. 2017). Under the MSFD, the DPSIR was modified to Drivers-Activities-Pressures-State-Ecosystem Services: Management, Measures, and Monitoring (DAPSES-MMM) (CSWD 2020). This revision aimed to address the vagueness of the terms “driver” and “impact” while incorporating the concept of ecosystem services (CSWD 2020).

More specifically, Article 8(1)(c) of the MSFD requires an economic and social analysis of the use of EU Member States’ marine waters and the costs of marine environmental degradation (related to drivers and impacts on ecosystem services). In addition, it mandates an assessment of pressures and impacts (Article 8(1)(b)) and the current environmental status (Article 8(1)(a)). Furthermore, regarding the response aspect, under Article 10, based on the assessments in Article 8(1), Member States must establish a set of environmental targets. In accordance with Article 13, a Programme of Measures (PoM) should be developed to achieve these targets as part of the roadmap to achieving or maintaining GES.

The European Commission aims to achieve comparable assessments among Member States, ensuring coherence within marine regions, to provide a basis for effective EU-wide marine management. Under Articles 20(1) and (3)(a) of the MSFD, an EU-scale report reviewing the progress of the MSFD and the status of EU marine waters must be conducted. This will foster coherent communication of the status of marine waters to both managers and the public (European Commission 2022).

Despite the availability of comprehensive assessments for the European seas (Borja et al. 2019; McQuatters-Gollop et al. 2022), a unified approach that integrates all recent MSFD data reported by Member States into overarching indices of pressure, state, and impacts is lacking. The main objective of this study was to develop such indices by spatially scaling up from marine reporting units (MRUs)—assessment areas defined by EU Member States (see Table 1)—to the ecoregion level and integrating the available official MSFD data reported by Member States. This is the first time that all available MSFD assessment data across all descriptors have been integrated to provide an ecoregion-scale overview of the state of the marine environment and the pressures and impacts affecting European seas. The proposed methodology includes a weighted geographic upscaling scheme (based on assessment area and data quantity) to achieve a regional-level assessment and offer a holistic approach to assessing the pressure, state, and impacts of EU waters, as well as the overall MSFD progress. By mapping the state of marine biodiversity, pressures, and impacts, in alignment with the MSFD framework, this study also aimed to identify areas of concern, highlight achievements or shortcomings, and provide insights for achieving and maintaining GES.

Methodology

GES assessments for MSFD features across the 11 descriptors were obtained from the Marine Water Information System for Europe

TABLE 1 | Description of Marine Strategy Framework Directive (MSFD) terms and abbreviations.

Definition	Description	Abbreviation
Marine Strategy Framework Directive	Is a legal act of the European Union (EU), adopted in 2008, that establishes a common European approach for the protection and management of the marine environment. The MSFD requires EU Member States to achieve and maintain good environmental status (GES) in their marine waters.	MSFD
Good environmental status	Is defined in Article 3(5) of the MSFD “ <i>the environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive within their intrinsic conditions, and the use of the marine environment is at a level that is sustainable, thus safeguarding the potential for uses and activities by current and future generations.</i> ”	GES
Descriptors	Are 11 marine-related descriptors that should be taken into consideration by the EU Member States when assessing the environmental status of their marine waters.	D (followed by its number, e.g. D1)
Criteria	Are distinctive technical features that are used for determining good environmental status for each of the descriptors.	C (usually denoting criteria number for each descriptor, e.g. D1C2)
Features	The term “feature” is used in different ways under the MSFD framework (see CSWD 2020). In the context of this study, we adopt its definition as used for GES reporting purposes. The extent to which GES is achieved at a high level of integration is reported at feature level, as seen in the data structure of WISE in Table 2. For example, in D1, features correspond to species groups.	—
Elements	These are elements of the marine ecosystem, particularly biological ones, such as species and habitats, or aspects of pressures on the marine environment (biological, physical, chemical substances, litter and energy), which are assessed based on their related criteria.	—
Marine reporting units	These represent the spatial scale of the Member States’ assessments for environmental status. These are designated by Member States and can be merged depending on the descriptors and criteria assessments.	MRU

(WISE-Marine) Portal (<https://water.europa.eu/marine/data-maps-and-tools/msfd-reporting-information-products>), specifically from the “overall status assessments dataset” (the dataset structure is shown in Table 2). The categorization of criteria into pressure, state, and impacts follows the European Commission MSFD Guidance (European Commission 2022), ensuring consistency with the MSFD framework. These assessments are based on MRUs as reported by each Member State—areas defined for assessing specific features, elements, or descriptors.

Because the assessments in the “overall status assessment dataset” from WISE-Marine varied across integration level—with some features assessed at the criterion level (e.g. criteria

for D10 and D11) and others at the descriptor level (e.g. D5 Eutrophication)—the “criteria status assessments dataset,” a more detailed dataset extending down to the element level, was also used in combination. Assessments at the criterion element level for all D3 (commercial fish and shellfish) and D5 (eutrophication) criteria, as well as for D6 (sea-floor integrity) criteria D6C3 (spatial extent of each habitat type which is adversely affected), D6C4 (the extent of loss of the habitat type), and D6C5 (the extent of adverse effects from anthropogenic pressures on the condition of the habitat type), were not available in the “overall status assessments dataset.” For example, D3 includes D3C1 (fishing mortality rate), categorized as an impact criterion, and D3C2 (spawning stock biomass) and D3C3 (the age and size distribution of individuals in populations), categorized as state

TABLE 2 | Marine Water Information System for Europe (WISE-Marine) overall status assessments dataset structure.

Overall status dataset	
Descriptor	Integration level for Good Environmental Status assessment (features)
D1 Biodiversity	Species groups
D2 Non-indigenous species	Newly introduced non-indigenous species (NIS) Established NIS Adverse effects of NIS on species or habitats
D3 Commercial fish and shellfish	Commercial fish and shellfish
D4 Food webs	Ecosystem type (coastal, shelf, oceanic/deep)
D5 Eutrophication	Eutrophication
D6 Seafloor integrity and benthic habitats	Benthic broad habitats Other benthic habitats Physical loss of the seabed Physical disturbance to the seabed
D7 Hydrographical changes	Hydrographical changes Adverse effects of hydrographical changes on species or habitats
D8 Contaminants in waters and sediments	Contaminants categorized in UPBT (ubiquitous, persistent, bioaccumulative, and toxic) substances and non-UPBT substances Adverse effects of contaminants on species or habitats Acute pollution events Adverse effects of acute pollution events on species or habitats
D9 Contaminants in seafood	Contaminants in seafood
D10 Marine litter	Litter in the environment Micro-litter in the environment Litter and micro-litter in species Adverse effects of marine litter on species or habitats
D11 Noise	Impulsive sound in water Continuous low frequency sound

criteria (European Commission 2022). Similarly, Descriptor 5 has one pressure criterion D5C1 (nutrient concentrations), while all others are listed as impact criteria. For D6, D6C1 (spatial extent and distribution of physical loss) and D6C2 (spatial extent and distribution of physical disturbance pressures) are categorized as pressure criteria, D6C4 and D6C5 as state criteria, and D6C3 as an impact criterion. Assessments for the elements of these criteria (e.g., species) were accessible through the “criteria status assessments dataset” in the WISE-Marine portal. However, due to the lack of element-level integration at the criterion level within each MRU in the WISE-Marine database, a conditional integration approach was employed (Borja et al. 2014). Specifically, at least 75% of all assessed elements had to achieve GES for a criterion to be considered as meeting good status (Dierschke et al. 2021) (detailed methodologies in [Supporting Information](#)). To also account for the state of pelagic habitats, this approach

was also applied to D1C6 (pelagic habitats), a state criterion, as well as D1C1 (by-catch), an impact criterion. The final structure of criteria, species groups, and ecosystem types used in developing the indices is presented in Figure 1. This structure was designed to cover the state of the MSFD species groups and ecosystem types, as well as the pressures and impacts exerted on the marine environment, utilizing the available MSFD data.

In addition, recent assessments from Regional Sea Conventions were incorporated into the analysis. Data made available in 2023 were specifically retrieved from the Oslo and Paris Convention (OSPAR), which covers the North-East Atlantic (and more specifically the ecoregions of Greater North Sea, Celtic Seas, South European Atlantic Shelf) and Helsinki Convention (HELCOM) which covers the Baltic Sea. Updated data and corresponding references are listed in [Supporting Information](#).

Descriptors	State species groups/criteria	Pressure criteria	Impact criteria
D1 Biodiversity	Benthic-feeding birds	D2 Newly-introduced NIS (D2C1)	D1 By-catch (D1C1)
D2 Non-indigenous species.	Grazing birds	Established NIS (D2C2)	D2 Adverse effects on species or habitats (D2C3)
D3 Commercial fish and shellfish	Pelagic feeding birds	D5 Nutrient concentrations (D5C1)	D3 Fishing mortality rate (D3C1)
D4 Food webs	Surface-feeding birds	D6 Physical loss of the seabed (D6C1)	Chlorophyll a concentration (D5C2)
D5 Eutrophication	Wading birds	Physical disturbance to seabed (D6C2)	Harmful algal blooms (D5C3)
D6 Seafloor integrity and benthic habitats	Small toothed cetaceans	D7 Hydrographical changes (D7C1)	Photic limit (D5C4)
D7 Hydrographical changes	Deep-diving toothed cetaceans	D8 Contaminants (D8C1)	D5 Dissolved oxygen concentrations (D5C5)
D8 Contaminants in waters and sediments	Baleen whales	Acute pollution events (D8C3)	Opportunistic macroalgae of benthic habitats (D5C6)
D9 Contaminants in seafood	Seals	D9 Contaminants – in seafood (D9C1)	Macrophyte communities of benthic habitats (D5C7)
D10 Marine litter	Turtles	Litter in the environment (D10C1)	Macrofaunal communities of benthic habitats (D5C8)
D11 Noise	Coastal fish	D10 Micro-litter in the environment (D10C2)	D6 Adverse effects from physical disturbance (D6C3)
	Pelagic shelf fish	Litter and micro-litter in species (D10C3)	D7 Adverse effects on species or habitats (D7C2)
	Demersal shelf fish	D11 Impulsive sound in water (D11C1)	Adverse effects on species or habitats (D8C2)
	Deep-sea fish	Continuous low frequency sound (D11C2)	D8 Adverse effects of acute pollution events on species or habitats (D8C4)
	Coastal/shelf cephalopods		D10 Adverse effects on species or habitats (D10C4)
	Deep-sea cephalopods		
	Pelagic habitats (D1C6)		
	D3 Spawning stock biomass (D3C2)		
	Population age/size distribution (D3C3)		
	D4/D1 Coastal ecosystem		
	Shelf ecosystem		
	Oceanic/deep-sea ecosystem		
	D6/D1 Benthic habitat extent (D6C4)		
	Benthic habitat condition (D6C5)		

FIGURE 1 | Marine Strategy Framework Directive descriptors (D) categorized into state, pressure, and impact criteria (categorization is based on European Commission 2022). This grouping forms the foundational basis for the development of the corresponding three indices, each reflecting a different aspect of marine environmental assessment. Criteria of D1 and D4 are not present as these criteria are under the assessments of species groups and ecosystem type.

To upscale the assessments from MRU to ecoregion scale (as defined by Spalding et al. 2007; Figure 2), a weighted average scoring approach was applied to integrate GES assessments (see Figure 3 for a workflow diagram of the methodology). Scores of 1 or −1.5 were allocated for GES and non-GES, respectively, with the latter elevated (in absolute terms) score adhering to a precautionary approach. Weighting of the MRU scores was based on the size of the area and the number of reported elements per criterion (Borja et al. 2014, 2016), underpinning the assumption that assessments encompassing a broader array of elements in larger MRUs are deemed more significant. The area of each MRU was retrieved from WISE-Marine and Eionet Central Data Repository (CDR; <https://cdr.eionet.europa.eu/>). The formula below represents the weighted average calculation for deriving an overall score for each criterion (j) across all MRUs in an ecoregion (k) (Equation 1):

$$\bar{X}_{jk} = \sum_{i=1}^m w_{jki} X_{jki} \quad (1)$$

where X_{jki} denotes the score assigned to feature/criterion j in the i -th MRU of ecoregion k (either 1 or −1.5 for GES and non-GES respectively), and w_{jki} represents the corresponding weight. The estimated weights were estimated as shown in Equation (2)

$$w_{jki} = \left(\frac{s_{ji}}{\sum_{i=1}^m s_{ji}} \cdot \frac{1}{2} \right) + \left(\frac{n_{ji}}{\sum_{i=1}^m n_{ji}} \cdot \frac{1}{2} \right) \quad (2)$$

where s_{ji} is the size of the i -th MRU for feature/criterion j assessment and n_{ji} is the number of elements for the respective

assessed criterion in the i -th MRU. Because the weights are standardized, their sum equals one.

A positive value for \bar{X}_{jk} indicates GES for the respective criterion/ecoregion, while a negative or zero value signifies non-GES.

Through spatial upscaling, ecoregions were classified as GES, non-GES, or not assessed for each criterion (see Supporting Information), with corresponding scores of 1, −1, and −0.5, respectively (the latter to penalize the lack of assessments, under a precautionary approach). Three indices (pressure, state, and impact) were developed using a cumulative scoring approach, which involved summing the scores of all related features/criteria for each index (sensu Figure 1) and normalizing the total score to range between 0 and 1, using min–max scaling (Equation 3):

$$I'_{ks} = \frac{I_{ks} - I_{ks \min}}{I_{ks \max} - I_{ks \min}} \quad (3)$$

where I_{ks} is the summed score for a specific index (s) in an ecoregion (k), $I_{ks \min}$ and $I_{ks \max}$ are the minimum and maximum possible scores in each ecoregion, and I'_{ks} is the normalized score. According to the scoring method, the optimal score (= 1) is achieved when all relevant criteria are in GES, while a score of zero, the lowest possible, indicates non-GES for all criteria. The state index for each ecoregion was estimated using only the relevant species groups and biodiversity elements as per Palialexis et al. (2018), supplemented by an examination of key species ranges from the International Union for the Conservation of Nature (IUCN) Red List database (<https://www.iucnredlist.org/>).

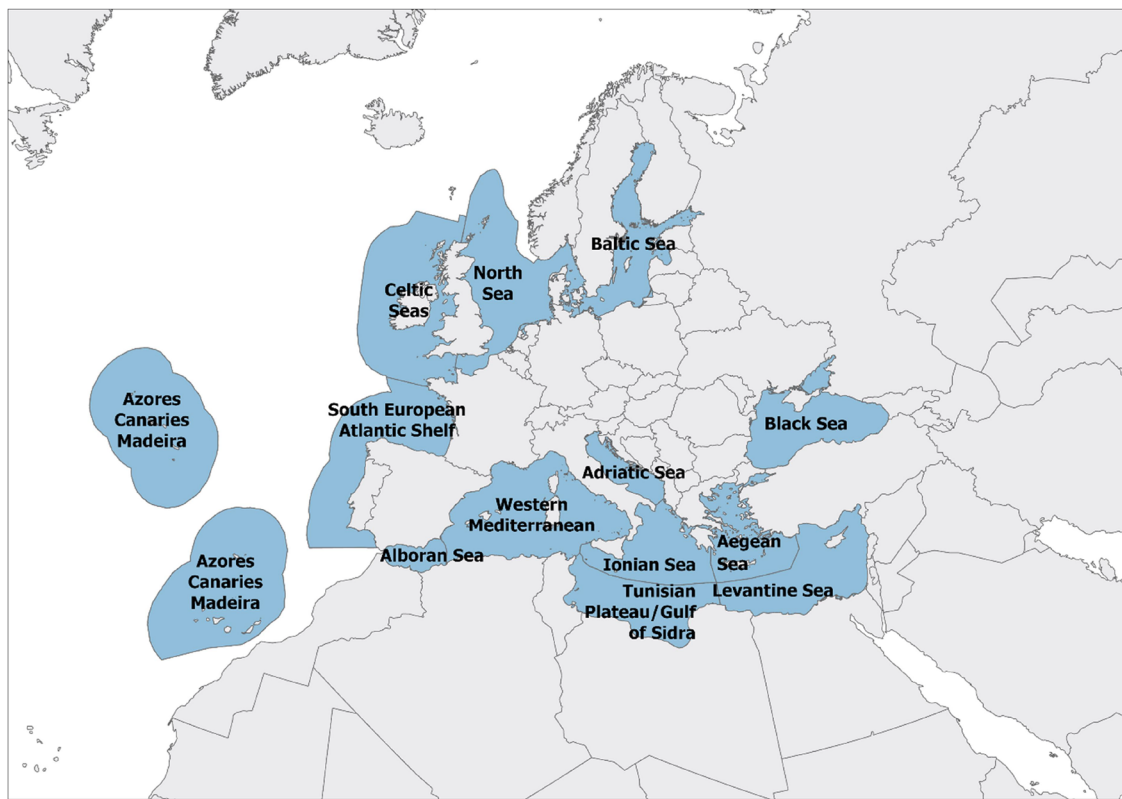


FIGURE 2 | Marine ecoregions of Europe according to Spalding et al. (2007).

The “GES Decision” distinguishes between primary and secondary criteria. Unlike primary criteria, the assessment of secondary criteria is not mandatory; they can be used complementarily to primary criteria or in cases where a specific secondary criterion is at risk of not achieving GES. However, if Member States choose to assess secondary criteria, they must be treated as required by the GES Decision. In line with these principles, only assessed secondary criteria were considered when estimating the relevant index. If a secondary criterion was not assessed in an ecoregion, it was not taken into consideration, and no penalty was applied when calculating the summed score.

To assess the correlation between pressure-state, pressure-impact, and impact-state relationships, Spearman’s rank correlation coefficients were estimated using R Studio (R Core Team 2024). Confidence intervals (95%) for Spearman’s rank correlation coefficients were estimated via bootstrapping (10,000 repetitions) using the `spearman.ci` function from the `RVAideMemoire` package (Hervé 2023). In addition, linear regression models were fitted to visualize the trend of each relationship.

Results

For the pressure index, the Azores-Canaries-Madeira ecoregion scored the highest (0.67), indicating the least anthropogenic pressure, followed by the Celtic Seas (0.65), and descending through other ecoregions to the lowest score in the Alboran Sea (0.15) and Western Mediterranean (0.18) (Figure 4 and Table S1). The Baltic Sea (92% of relevant criteria assessed), North Sea (86%), western Mediterranean (86%), Adriatic (85%), and Ionian Sea

(85%) had the most comprehensive assessments (Figure 4 and Table S2). The Alboran Sea and Black Sea had the least pressure criteria assessed (42% and 45%, respectively).

The analysis revealed a generally deteriorated state across all assessed European ecoregions, with low variation in the state index scores. The Levantine Sea exhibited the highest state index score (0.33), followed by the Adriatic (0.32) and the Azores-Canaries-Madeira ecoregion (0.26), while the lowest scores were estimated for the western Mediterranean (0.11) and the Baltic Sea (0.12). The Baltic Sea led in the number of assessed features and state criteria, with a full assessment of all relevant features/criteria, followed by the North Sea (75%), with the Azores-Canaries-Madeira ecoregion having assessed the least (only 3 out of 24 features/criteria), followed by the Alboran and Levantine ecoregions having assessed 4 out of 24 features/criteria.

The impact index was highest (indicating least impact) in the Azores-Canaries-Madeira ecoregion (0.90), and lowest in the Baltic (0.23). The impact index is primarily composed of secondary criteria (10 out of 15), with the five primary criteria being assessed across nearly all ecoregions. However, the highest number of assessed criteria, including secondary criteria, was assessed in the Baltic (13 criteria in total), followed by the North Sea (12), the Black Sea (11), and Azores-Canaries-Madeira (10).

The results for pressure criteria across European seas were mixed (Figure 5a). Criteria such as newly introduced non-Indigenous Species (D2C1), contaminants in seawater (D8C1), and litter in the environment (D10C1) predominantly failed to achieve GES,

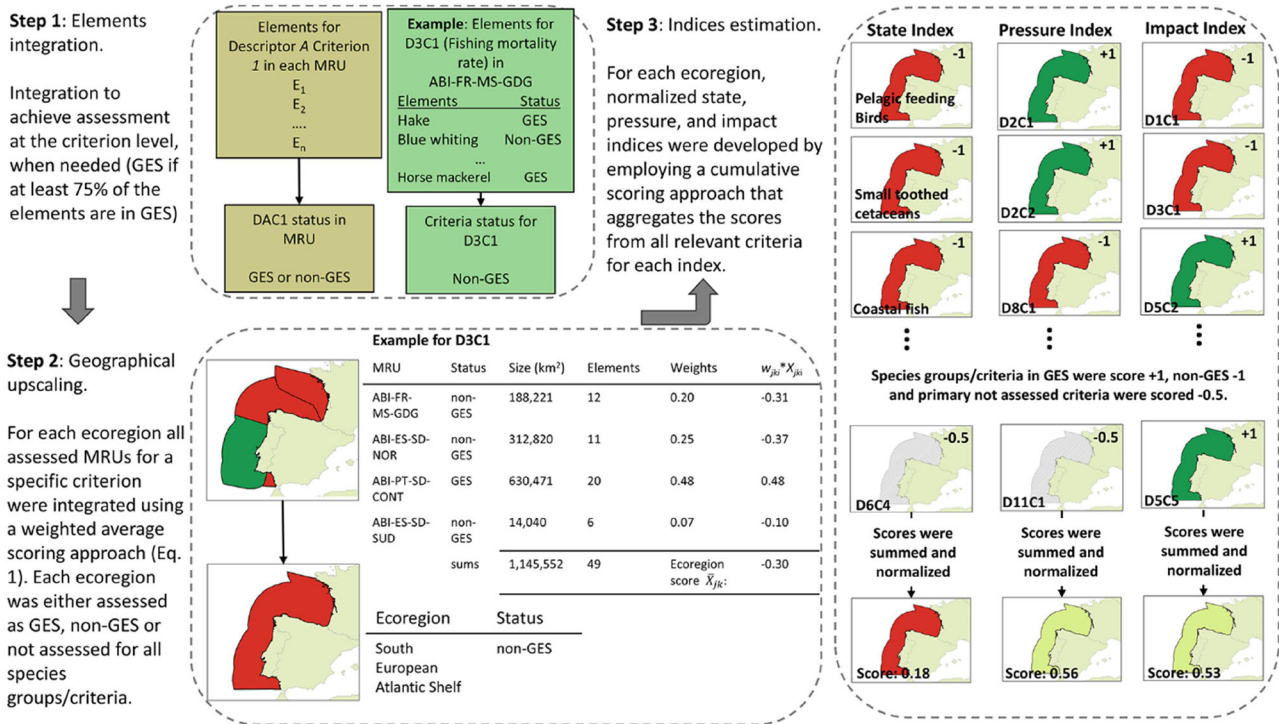


FIGURE 3 | Schematic workflow of the methodology with indicative examples. The examples provided in the schematic workflow represents the utilization of marine reporting units (MRUs) codes sourced from Member States reporting. In the color scheme, green designates good environmental status (GES), red denotes non-GES, and grey signifies areas not assessed. Specifically, in Step 1, the illustration focuses on elements integration, exemplifying Descriptor 3 (Commercial fish and shellfish) Criterion 1 (Fishing mortality rate). The selected elements for this step include some fish species/stocks such as the Hake (*Merluccius merluccius*), Blue whiting (*Micromesistius poulassou*), and Horse mackerel (*Trachurus trachurus*). The example provided for Step 2 illustrates the weighted average scoring approach (Equation 1) used for geographical upscaling. Each criterion for each MRU is scored (X_{jki}), with a score of either 1 or -1.5 for GES and non-GES respectively. The weights (w_{jki}) are calculated based on the size of the MRU and the number of elements used for the assessment. Finally, in Step 3, all criteria in each MRU were categorized as pressure, state, or impact criteria and assigned scores of +1 for GES, -1 for Non-GES, and -0.5 for primary criteria that were not assessed. The sum score for each index was then normalized to a 0–1 scale.

whereas hydrographical changes (D7C1) achieved GES in most ecoregions. A significant number of ecoregions were not assessed for criteria such as micro-litter in the environment (D10C2), litter and micro-litter in species (D10C3; a secondary criterion), impulsive sound in water (D11C1), and continuous low-frequency sound (D11C2).

The ecoregion scale results highlighted that most species groups and state criteria were not in GES (Figure 6). Notably, 11 out of 24 state features/criteria were not assessed in over half of the ecoregions. Particularly, the Oceanic/Deep-sea ecosystem under D4 (food webs) was not assessed in any ecoregion.

Similarly, most impact criteria were not assessed in a significant number of ecoregions; 7 out of 15 criteria were not assessed in over half of the ecoregions (Figure 5b). Probably this is because most impact criteria are secondary, thus their assessment is not mandatory. However, criteria such as chlorophyll-a concentrations (D5C2), dissolved oxygen concentrations (D5C5), adverse effects from hydrographical changes (D7C2), and adverse effects from contaminants (D8C2) achieved GES in most ecoregions. In contrast, criteria such as by-catch (D1C1), and fishing mortality rate (D3C1) were predominantly assessed as non-GES.

For the pressure-state, pressure-impact, and impact-state relationships, correlations were found positive (Table 3 and Figure 7; note that the higher pressure and impact score means more criteria in GES thus lower pressure and impacts). However, these correlations were not found statistically significant (Table 3) except for Spearman's rank coefficients for the impact-state combination (Spearman's $\rho = 0.60$, C.I.:0.071, 0.86; $p = 0.049$). Moreover, potential correlations between the number of assessed elements and the GES scores were tested, but no significant results were found.

Discussion

This study represents a pivotal effort to holistically evaluate the current knowledge regarding ecosystem status across European seas. Unlike previous foundational efforts that assessed specific regions or a subset of descriptors/criteria (Uusitalo et al. 2016; Borja et al. 2019; Fraschetti et al. 2022; McQuatters-Gollop et al. 2022), this study analyzed all officially reported assessments across Europe. It provides a comprehensive overview of the MSFD implementation, introducing intuitive indices for gauging progress toward achieving GES in the European seas. These indices, fully aligned to the MSFD, are easily communicated

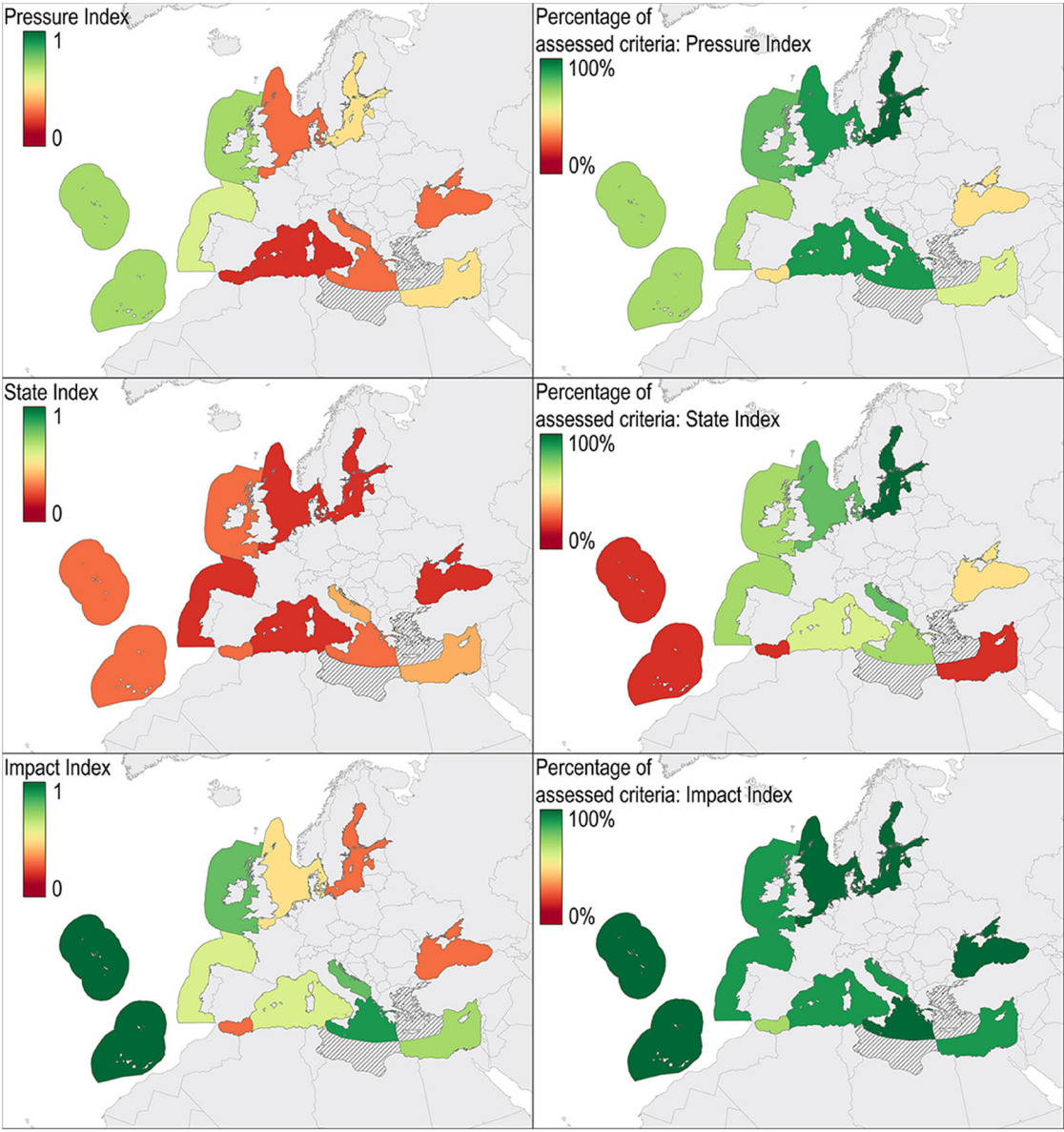


FIGURE 4 | The left panel depicts the three indices (pressure, state, and impact) across European ecoregions (sensu Spalding et al. 2007). The right panel illustrates the percentage of relevant criteria/features assessed for the three indices in each ecoregion. Ecoregions marked with black stripes indicate regions not assessed. Marine Strategy Framework Directive (MSFD) data for the Aegean Sea, regarding the 2012–2017 implementation cycle, were unavailable in the WISE Marine portal (January 2024), and the Tunisian plateau is not under the MSFD jurisdiction.

TABLE 3 | Results of correlation analysis for Spearman's rank coefficient for combinations of pressure, state, and impact.

Correlation parameters	Pressure-state	Pressure-impact	Impact-state
Correlation coefficient	0.33	0.55	0.60
Confidence Intervals	−0.29, 0.82	−0.085, 0.93	0.071, 0.86
<i>p</i> value	0.32	0.081	0.049

to policymakers, thereby effectively bridging the gap between science and policy.

EBM is an adaptive, participatory, dynamic, and iterative process for taking measures to protect the sea and achieve healthy marine systems (Haugen et al. 2024). Systematically assessing the state of

biodiversity and its response to management measures is crucial for evaluating the effectiveness of policy measures and guiding necessary adjustments (Perino et al. 2022). Various assessments tools exist for conducting holistic ecosystem assessments (Borja, Berg, et al. 2024; Papadopoulou et al. 2025), at national, regional, or EU scale, including the overarching assessment tools NEAT

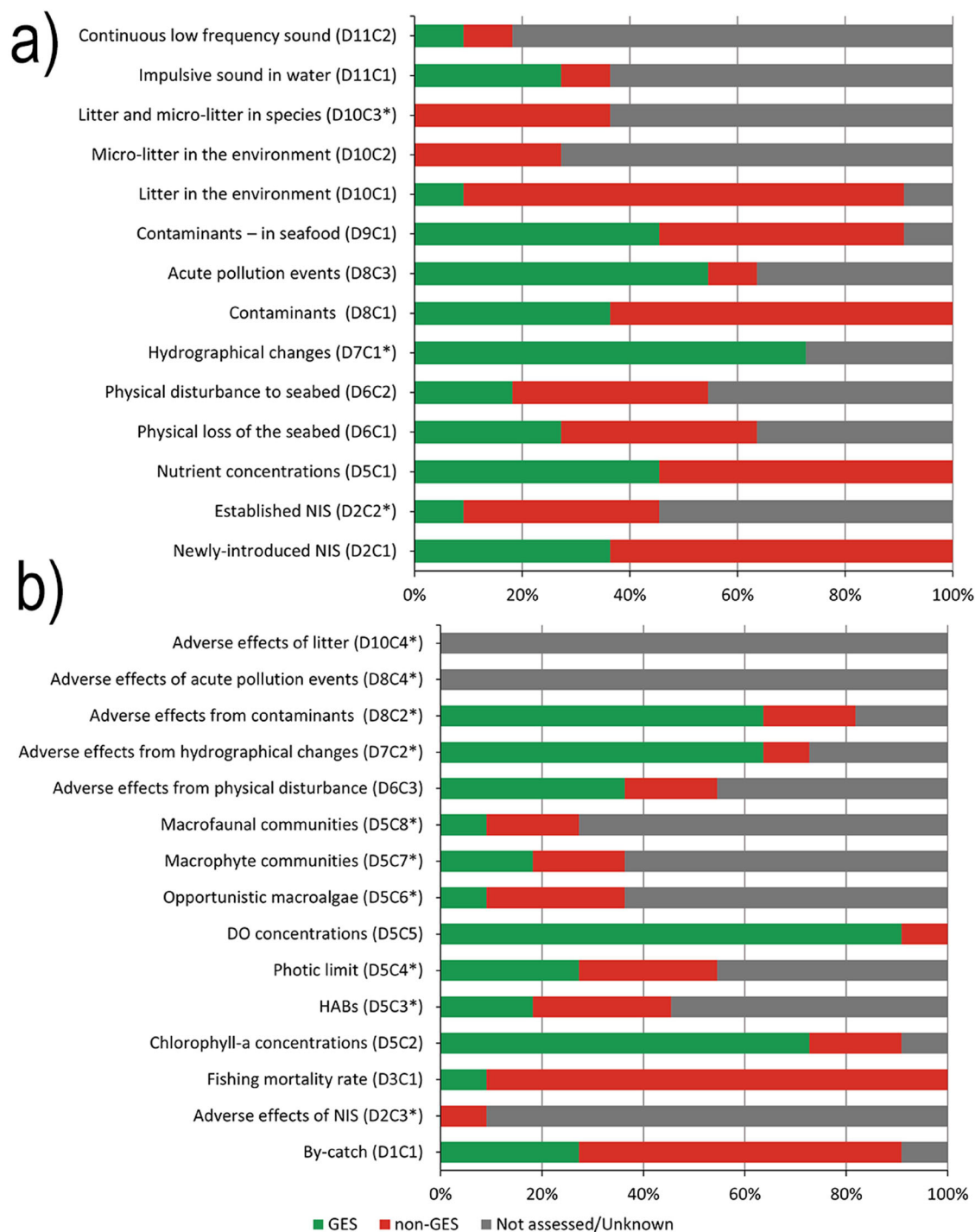


FIGURE 5 | The stacked bar chart depicts the proportion of assessed (a) pressure and (b) impact criteria in the European ecoregions relevant to the Marine Strategy Framework Directive, categorized as achieving Good Environmental Status (GES), not achieving GES, or remaining not assessed/unknown. Criteria with asterisk (*) are secondary criteria according to the “GES Decision.”

(Nested Environmental status Assessment Tool; Borja et al. 2016) and OHI (Ocean Health Index; Halpern et al. 2012). Papadopoulou et al. (2025) highlighted that multiple assessment tools must be used in combination to comprehensively address all aspects of EBM. Therefore, these overarching tools should be complemented by other approaches, such as Cumulative Impact Mapping (Halpern et al. 2008), as well as descriptor-specific tools, such as the HELCOM Hazardous Substances Status Assessment Tool (CHASE; Andersen et al. 2016), the HELCOM Eutroph-

ication Assessment Tool (HEAT; Andersen et al. 2010), and the HELCOM Biodiversity Assessment Tool (BEAT; Andersen et al. 2014). This study enhances the assessment toolbox with an MSFD-oriented approach.

Given the constraints of limited data availability and substantial knowledge gaps (Palialexis et al. 2019; European Commission 2020), leveraging existing data is paramount. Borja et al. (2019) demonstrated that large scale assessments with existing MSFD

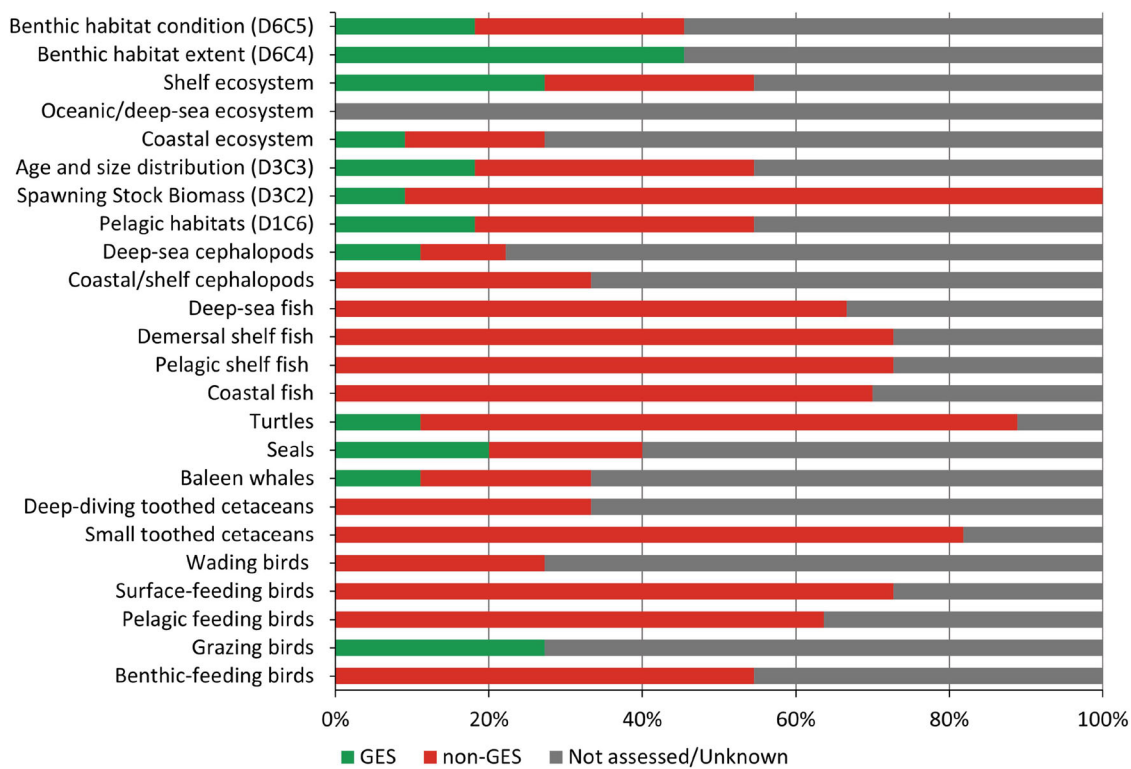


FIGURE 6 | The stacked bar chart depicts the proportion of state features/criteria in the European ecoregions relevant to the Marine Strategy Framework Directive, categorized as achieving Good Environmental Status (GES), not achieving GES, or remaining not assessed/unknown.

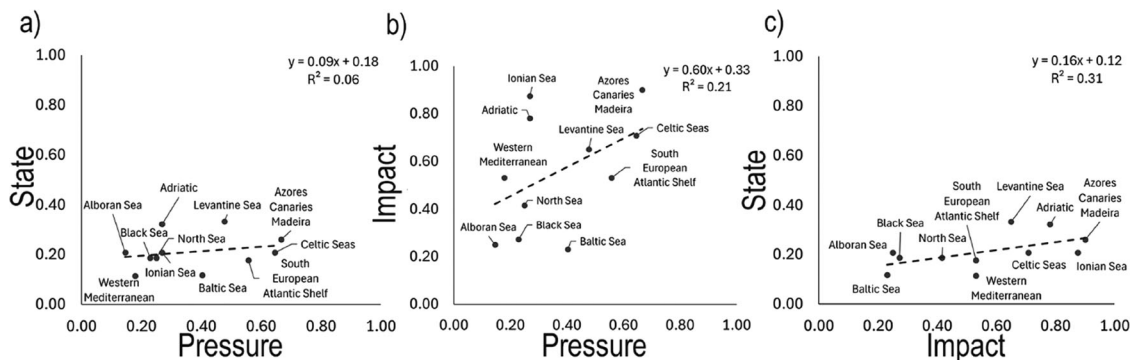


FIGURE 7 | Correlations between the scores of the indices (a) pressure-state, (b) pressure-impact, and (c) impact-state. Solid black lines depict linear regressions. Note that the highest scores for the pressure and impact index correspond to the least pressured and impacted area.

data is possible using the overarching assessment tool NEAT. In this study, the developed indices facilitate our understanding of marine ecosystem status across European regions, as well as the links between pressures, state, and impacts. However, the absence of assessments for multiple criteria in a region may render these indices less representative of the actual ecosystem health, potentially leading to misconceptions.

In addition, secondary criteria are not mandatory for Member States and were not considered in the indices estimation if they were not assessed in an ecoregion. Most secondary criteria are categorized as impact criteria (European Commission 2022), leading to an unequal distribution of primary and secondary criteria across pressure, state, and impact criteria. Specifically,

very few impact criteria are designated as primary, whereas pressure and state criteria are predominantly primary. To ensure a more balanced assessment, additional impact criteria could be reclassified as primary under the MSFD, capturing key impacts that should be assessed consistently across European seas.

Regions such as the Aegean, Levantine, and Alboran Seas, alongside several species' groups and ecosystems, such as deep-sea environments (Danovaro et al. 2020), are herein highlighted for their lack of comprehensive monitoring and assessment (but see Kazanidis et al. 2020). The findings of this study advocate for expanded ecological monitoring and regional cooperation, aligning with other expert recommendations (Palialexis et al. 2019; McQuatters-Gollop et al. 2022; Frascchetti et al. 2022).

The North Sea and Baltic Sea emerge as exemplars of thorough monitoring and assessment, given the coordinated efforts within OSPAR and HELCOM (McQuatters-Gollop et al. 2022; HELCOM 2023a). There is an urgent need for all European Regional Sea Conventions to advance their monitoring and assessment frameworks, potentially within a unified European framework to standardize and consolidate efforts in a harmonized way, as it has been done by the European Environment Agency (Reker et al. 2019). This would be particularly beneficial for knowledge-poor regions, such as the Aegean, the Levantine, and the Alboran Seas.

Our findings reveal an unsatisfactory state of biodiversity and significant knowledge gaps, echoing other large-scale holistic assessments in European Seas (Uusitalo et al. 2016; Reker et al. 2019; McQuatters-Gollop et al. 2022). Even in regions where intensive efforts have been made with detailed assessments and the implementation of EBM measures, such as in the Baltic, the overall state remains poor (HELCOM 2023a). In regions lacking in-depth understanding of ecological pressures, state, and impacts, as well as comprehensive EBM and environmental objectives, unprecedented ecological changes may be ongoing with unknown implications for ecosystem health, functioning, and supply of ecosystem services.

The inconsistencies in methodological approaches across European regions are problematic, as they can hinder comparability. The MSFD still lacks consistency, particularly regarding monitoring, assessment methods, and threshold values (Palialexis et al. 2021; Vasilakopoulos et al. 2022; Tornero Alvarez et al. 2023). For example, divergent threshold values for Non-Indigenous Species (NIS) introductions (D2C1) by OSPAR and HELCOM challenge achieving a harmonized GES assessment. HELCOM adopts a stringent threshold of zero new introductions, a standard that is difficult to achieve, resulting in a non-GES designation (HELCOM 2023b). In contrast, OSPAR follows a trend-based threshold, assessing areas as attaining GES, despite new NIS introductions (Stæhr et al. 2022).

The weak correlations observed in pressure-state, pressure-impact, and impact-state relationships, along with the limited variation in the state index across European ecoregions, despite substantial differences in pressures and impacts, highlight key ecological and methodological challenges in assessing GES. One major factor is the legacy of historical degradation in marine ecosystems, particularly in benthic habitats, where recovery from pressures such as trawling and eutrophication can take many years or decades, even after mitigation efforts (Williams et al. 2010; Lotze et al. 2011; Rooper et al. 2011; Carstensen et al. 2014; Murray et al. 2019; Hiddink et al. 2017). This is evident in regions like the Baltic Sea, where reductions in nutrient loads and fishing pressure have yet to yield significant improvements in state indicators due to persistent ecosystem inertia and internal feedback mechanisms (Carstensen et al. 2014; Murray et al. 2019; HELCOM 2023a).

Furthermore, the weak correlation between pressure and state, with minimal state improvement despite a wide range of pressures suggests that MSFD pressure assessments may not fully capture key drivers of degradation. In particular, fishing pressure and climate change are inadequately reflected in the set of pressure indicators. Aside from D6C2 (physical disturbance to

the seabed), which accounts for the pressure of trawling and bottom-contact fishing gear, there is no dedicated indicator for overfishing and unsustainable fishing practices, factors that may be primary drivers of ecosystem degradation in certain ecoregions (Jackson et al. 2001; Daskalov 2002; Coll et al. 2008). Climate change has already caused severe declines in native biodiversity in certain European ecoregions (Raybaud et al. 2013; Nikolaou and Katsanevakis 2023) but it is not considered as a pressure by MSFD. Such gaps challenge the coherence of assessments under the DPSIR or similar frameworks (Elliott et al. 2017). Addressing these challenges require standardized methodologies and advanced ecological modeling to refine pressure-state-impact relationships, particularly in the context of cumulative pressures and nonlinear ecosystem responses (Andersen et al. 2015; McQuatters-Gollop et al. 2022).

A key challenge in large-scale environmental assessments involves selecting integration methods, which may significantly affect outcomes (Borja et al. 2016). Changing integration rules alters the spatial upscaling results and index scores. For instance, the “One-Out, All-Out” principle can lead to non-GES classification for most criteria and regions (Borja et al. 2019), whereas lenient integration rules may lead to a broader achievement of GES. Despite the challenge, substantial progress has been made toward developing common integration rules across European regions (Dierschke et al. 2021; European Commission 2022).

Addressing criticisms common to large-scale studies, this study mitigates concerns over using broad datasets, such as those from open-access repositories, remote sensing, or models, without local expert input on local ecological characteristics (Wyborn and Evans 2021). By integrating each Member State’s assessments, which reflect regional specifics, it fosters a unified GES comprehension. Furthermore, despite data limitations, the methodology and maps developed here can lay groundwork for further research and support evidence-based conservation (Chaplin-Kramer et al. 2022).

Finally, we note the urgent need to embed climate change impacts within the MSFD framework. Despite increasing evidence of unprecedented impacts from climate change in the European seas (Nikolaou and Katsanevakis 2023) and the EU’s commitment to climate action (European Union (EU) 2021), the MSFD does not adequately address the rapid adaptations required to monitor and assess climate change effects on marine ecosystems, which can prevent achieving GES. Developing specific criteria for assessing climate change pressures and impacts, such as thermal vulnerability indices (Boyce et al. 2022) and the effects of ocean acidification (Vargas et al. 2022) is imperative for informed EBM and the preservation of biodiversity and ecosystem services.

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the grammar and syntax of the manuscript. All outputs were reviewed and edited accordingly by the authors.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All datasets used are available from the WISE Marine EU Portal from the GES Dashboard. Produced data are made available through the Supplementary Material.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting Table 1: Table with the estimated scores for the state, pressure, and impact index across European ecoregions. **Supporting Table 1:** Table with the proportion of assessed features/criteria relevant to each European ecoregion. **Supporting Information 1:** Supplementary material including decisions and steps made for integration of elements and information on the updated data retrieved from regional sea conventions. **Supporting Information 2:** Results of the geographical upscaling for each ecoregion and feature/criterion.