npj | ocean sustainability

Article

Article in Press

https://doi.org/10.1038/s44183-026-00238-6

Linking blue economy sectors to ecosystem services and socio-economic priorities: a framework for integrated maritime spatial planning

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This study advances the integration of ecosystem services (ES) into maritime spatial planning and management by developing a structured framework that links blue economy sectors with their associated pressures and potential impacts on ecosystem services and socio-economic values. By doing so, it addresses a key gap in current practice: the fragmented treatment of ecological, sectoral and social priorities in isolation. The framework was built by adapting the DAPSI(W)R(M) approach—Drivers, Activities, Pressures, State changes, Impacts (on human Welfare) and Responses (as management Measures)—and integrating insights from ecosystem services literature, sector-specific analysis and socio-economic criteria. It was then applied qualitatively to two case-study sectors (fisheries and offshore renewable energy) to identify key interactions, assess potential trade-offs and illustrate management responses. While not intended as a site-specific or quantitative impact assessment, the framework shows how trade-offs between ecosystem health and socio-economic needs can be more clearly visualised and discussed.

Technological advances and growing demand for ocean-based resources have intensified and diversified the use of marine spaces, contributing to the expansion of ocean-based economic activities[1,2] This expansion is characterised by the growth of diverse sectors, including fisheries, offshore renewable energy, aquaculture, marine mineral extraction and tourism, which now span a much broader range of the ocean, increasing competition for spatial and ecological resources[3] Consequently, the Blue Economy has emerged as a central pillar of national and international agendas, aiming to reconcile economic growth with sustainability[4] However, this expansion has also led to widespread ecological degradation[5]

Human activities have triggered direct and indirect pressures on the marine environment, resulting in biodiversity loss, disruption of ecosystem functions and threat ecosystem services (ES) defined as the benefits people derive from ecosystems[6,7] that link ecological processes to human well-being[8,9] as well as altering the synergies and relationships among those services[10]

This situation highlights the need to integrate the effects of multiple anthropogenic drivers when assessing impacts on coastal and marine ecosystems. In response, several international projects, such as the MSP4BIO, Blue4All, BlueConnect, OceanCitizen and Protect Baltic, are developing tools to assess cumulative impacts, aiming to provide the evidence needed to reduce pressures and support more informed decision-making. Most of these efforts rely on linkage-based frameworks to support ecosystem-based management approaches[11,12]

Yet, even with these scientific advances, interventions can still lead to conflicting outcomes, or trade-offs, between environmental protection and economic use[13] These challenges are exacerbated by the fragmentation of coastal and marine governance, both horizontally (across sectors) and vertically (from local to international levels)[14] Addressing these complexities requires a shift towards integrative governance tools capable of managing multiple, often competing, uses and objectives to ensure long-term ocean health for future generations[15]

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This has given rise to the Ecosystem-based Approach (EBA), promoted by the Convention on Biological Diversity[16] to ensure the integrated and equitable management of ecosystems and the services they provide[17] Lately, the European Ocean Pact (COM/2025/281)[18] introduced a holistic governance vision by aligning the objectives of the Marine Strategy Framework Directive (MSFD; 2008/56/EC)[19] the Maritime Spatial Planning Directive (MSP Directive; 2014/89/EU)[20] and other related policies under a unified framework for protecting ocean health, enhancing sustainable competitiveness and ensuring coherent sea-basin governance.

ES are central to EBA as they translate ecological information into values meaningful to stakeholders and decision-makers, thereby supporting more inclusive and transparent marine planning[21,22] In participatory processes such as Maritime Spatial Planning (MSP)[20,23] this translation becomes particularly important for facilitating dialogue among sectors, supporting trade-off discussions and improving the interpretation of cumulative impacts. However, most ES-based assessments focus on individual sectors or single pressures and therefore often omit the cumulative and interactive effects of multiple anthropogenic impacts[24]

Although maritime activities are often assessed primarily through their pressures and negative impacts, some sectors can also contribute positively to ecosystem service flows when appropriately managed. For example, marine aquaculture can support food provision and other ES, while well-managed nature-based marine tourism may contribute to cultural ES by supporting recreation, environmental learning and conservation awareness. Recognising this dual role is important for frameworks that seek to assess how maritime activities affect ES and related societal priorities[25,26].

To address these complex interactions and conceptualise the underlying linkages, causal frameworks such as the DPSIR (*Driver-Pressure-State-Impact-Response*) model have been widely applied in environmental assessments to describe relationships between drivers, pressures, and ecosystem states[11,12] Despite its utility, traditional DPSIR often suffers from definitional confusion, particularly regarding the distinction between state changes and societal impacts[27].

Building on this foundation, the DAPSI(W)R(M) framework[28] further refines the model by distinguishing specific Activities (A), the human actions required to satisfy a driver, from the Pressures (P) they generate, which are the physical, chemical, or biological mechanisms through which an activity affects the environment. These pressures lead to changes in the State (S) of the environment, which represents the resulting abiotic and biotic condition of the ecosystem. Crucially, the framework then isolates how these altered states result in Impacts on Welfare (I(W)), specifically affecting the flow of ES capturing the consequences for human well-being and socioeconomic value[29–32].

Building on the results of the MSP4BIO Project[33] which develops an integrated socio-ecological management framework for biodiversity protection across five reference sectors—aquaculture, marine non-living resources, renewable energy, tourism and fisheries—this paper aims to operationalise a structured logic chain linking blue economy sectors, environmental pressures, ES and socio-economic criteria (SEC).

Following the conceptual foundation proposed by Solé Figueras et al.[34] the study applies this framework in a context-sensitive manner to identify tailored Good Management Practices (GMPs) that support evidence-based and adaptive marine governance. Specifically, the study extends previous approaches by incorporating pressures from diverse blue economy sectors and aligning them with a validated set of 20 SEC developed by Pegorelli et al[35] (Supplementary Table 1).

By linking sectoral pressures to both ES and SECs, the study helps identify key trade-offs and priority areas where GMPs can mitigate conflicts between ecological integrity and socioeconomic goals. In this context, SECs serve as a validated set of criteria, such as food security, local employment and cultural heritage, representing the human dimension and societal priorities of marine planning. While GMPs are defined as tested technical and administrative measures designed to mitigate specific sectoral pressures already present in an area.

The present study further advances this conceptual foundation by integrating the refinements proposed by Solé Figueras et al.[34] which better capture non-linear relationships between human activities and ecosystem responses. It is also informed by earlier linkage-based approaches, such as those developed by Knights et al.[11] and operationalized in the AQUACROSS Project[12] which established systematic connections between human activities, pressures and ecosystem components to support EBA.

While these previous studies focused primarily on identifying and clustering pressure pathways, our work extends this line of reasoning by explicitly linking ES and SEC to GMPs that can mitigate sectoral impacts. Because MSP is inherently participatory, the framework also incorporates a visual approach to translate complex socio-ecological relationships into more accessible formats, supporting stakeholder dialogue and the interpretation of cumulative impacts and trade-offs.

This study lies in integrating ES, SEC, cumulative pressures and management responses within a single operational framework for ecosystem-based MSP. By combining qualitative linkage analysis with Sankey-based visualisation, the approach supports a more transparent interpretation of socio-ecological trade-offs and cumulative impacts across marine sectors.

The remainder of the paper is structured as follows. The 'Results' section first presents the cross-sectoral flow of pressures from blue economy activities to ES across five sectors, followed by a more detailed application of the framework to two selected sectors. The Discussion then examines the main findings and methodological limitations. The Conclusion summarises the study's main contributions. Finally, the 'Methods' section provides a detailed description of the analytical approach used in the study.

Results

Cross-sectoral pressure patterns

The following sections present the results of the logic chain application, which operationalises the DAPSI(W)R(M) framework for the selected sectors: aquaculture, marine mineral extraction, tourism, fisheries and offshore renewable energy. In this application, sectoral activities correspond to Activities (A), environmental pressures to Pressures (P), affected ES link changes in ecosystem State (S) to Impacts on Welfare (I(W)), SEC reflect the welfare dimension of these impacts and GMPs correspond to Management Responses (R(M)). The results are presented in three stages: (i) cross-sectoral pressure patterns; (ii) cumulative impacts on ES; and (iii) sector-specific pathways linking activities to management responses.

Analysis of the sector-specific logic chains reveals that while some pressures were relatively sector-specific (e.g. underwater noise from pile-driving in offshore wind energy), others, such as physical damage to the seabed, biodiversity loss and marine litter, were identified across multiple sectors. Fisheries and Marine non-living resources extraction were associated with the broadest range of ecosystem impacts, including physical destruction, bycatch-related biodiversity loss and sediment disruption. Tourism activities were mainly associated with localised impacts on sensitive ecosystems, including coral reefs and seagrass beds.

The detailed sector-specific categorisations are provided in Supplementary Tables 2–6, covering Fisheries, Marine Non-Living Resources, Renewable Energy, Aquaculture and Tourism, respectively. These tables show how sectoral activities generate pressures and affect marine ecosystems. Table 1 presents a synthesis of these tables, showing the pressures potentially exerted on the marine environment and the sectors and activities from which they originate.

Cumulative impacts on ecosystem services

Building on this cross-sectoral overview, the analysis further examines how these pressures translate into cumulative impacts on ES. The evaluation (scored -1 to $+1$) indicated that Fisheries had the highest number of negative ES linkages, followed by Aquaculture and Marine non-living resource extraction (Table 2). The detailed analysis of impacts for each activity and sector is provided in the Supplementary Material (Supplementary Tables 7–9).

Table 1 | Cross-sectoral linkages between MSFD pressures and blue economy activities by sector

Pressure (MSFD classification)	Activities (grouped by sector)
Physical loss	**Marine non-living resources:** Deep-sea mining; Offshore oil and gas extraction **Renewable energy:** Ocean energy—Tidal; Ocean energy—Wave; Wind farms **Aquaculture:** Aquaculture in coastal or intertidal zones
Physical damage	**Fishery:** Gillnetting; Longline; Trammel net; Trawling **Marine non-living resources:** Dredging; Offshore oil and gas extraction **Renewable energy:** Ocean energy—Tidal; Ocean energy—Wave; Wind farms **Aquaculture:** Aquaculture at sea **Tourism:** Cruise; Diving; Sport fishing; Yacht and motor boats/motor vessels
Biological disturbance	**Fishery:** Dredges; Drift netting; Gillnetting; Longline; Pots and traps; Push and stow net; Trawling **Marine non-living resources:** Deep-sea mining; Dredging; Offshore oil and gas extraction **Renewable energy:** Ocean energy—Tidal; Ocean energy—Wave; Wind farms **Aquaculture:** Aquaculture at sea (hatcheries, floating cages and rafts); Aquaculture in coastal or intertidal zones; Seaweed farming **Tourism:** Diving; Sailing vessels; Whale-watching
Contamination by hazardous substances	**Fishery:** Dredges; Drift netting; Gillnetting; Longline; Pots and traps; Purse seine (with FADs or not); Push and stow net; Trammel net; Trawling **Marine non-living resources:** Deep-sea mining; Dredging; Offshore oil and gas extraction **Aquaculture:** Aquaculture at sea (hatcheries, floating cages and rafts); Aquaculture in coastal or intertidal zones
Nutrient and organic matter enrichment	**Aquaculture:** Aquaculture at sea (hatcheries, floating cages and rafts); Aquaculture in coastal or intertidal zones
Other physical disturbance	**Marine non-living resources:** Deep-sea mining; Dredging; Offshore oil and gas extraction **Renewable energy:** Ocean energy—Tidal; Ocean energy—Wave; Wind farms

When examining the cumulative impacts on ES, the analysis reveals that Regulation and Maintenance Services were the most heavily compromised ES group. This degradation was led by 'Nursery and habitat maintenance', experiencing the highest cumulative negative impact (−68) in the study.

Provisioning services such as 'Genetic material' and 'Wild aquatic animals' followed closely, both with cumulative scores of −57. These services were mainly associated with extractive and production-oriented activities. Cultural services also showed negative cumulative scores, particularly 'Intellectual and representative interactions' and 'Environmental conservation for future generations' (both −34).

Notably, the framework also captured positive interactions (+1) where specific activities enhance service flows. For instance, Aquaculture provided the only positive cumulative score in Provisioning for 'Farmed animals' (+6). Furthermore, while 'Environmental conservation for future generations' showed an overall negative cumulative score due to extractive pressures, the analysis revealed that Tourism activities were associated with positive scores for this Cultural service (+4).

The three Sankey diagrams (Figs. 1–3) synthesise the main pathways linking sectoral activities, environmental pressures, ES and SEC. The sectoral overview (Fig. 1) shows Fisheries and Aquaculture as the main contributors to biological disturbance, while Tourism, Marine non-living resources and Renewables were primarily associated with physical damage and physical loss. ES such as 'Wild aquatic animals', 'Nursery and habitat maintenance' and 'Intellectual and representative interactions with the environment' showed the highest number of linkages within the logic chain and were connected to socio-economic priorities including human well-being, education and the blue economy.

Sector-specific pathways and responses

To illustrate how these relationships operate in practice, the framework was applied in detail to two sectors: fisheries and offshore renewable energy. The detailed logic chain for the Fisheries sector (Fig. 2) shows how specific activities generate distinct pressure profiles. For instance, while dredging and trawling are primarily associated with physical loss, longlining and drift netting emerge as major contributors to biological disturbance and bycatch.

These pressures induce changes in the ecological state, most notably impacting cultural ES. Within this group, 'Intellectual and representative interactions with the environment' emerges as the most impacted ES. These impacts were linked to SEC 8 (*Socio-cultural dependence on environmental quality*) and SEC 9 (Aesthetic and natural values).

Furthermore, SEC 18 (Importance for education and science) was associated with multiple ES categories. It represents a cumulative of impacts across multiple ES categories, including 'Intellectual and representative interactions' (Cultural ES), 'Wild aquatic animals' (Provisioning ES) and 'Nursery and habitat maintenance' (Regulation ES).

Table 3 presents examples of GMPs associated with the identified pressures and ES impacts. For trawling activities, identified GMPs included habitat mapping, bird-scaring lines, benthic protection zones and seasonal closures.

For the Renewable energy sector (Fig. 3), the framework distinguishes between wind farms, wave energy and tidal technologies. These activities exert significant pressures on the marine environment, most notably through physical loss and physical damage. These pressures induce changes in the ecological state, primarily affecting a broad range of ES including 'Wild aquatic plants/algae', 'Wild aquatic animals', 'Nursery and habitat maintenance' and 'Intellectual and representative interactions with the environment'. These ecological changes were associated with impacts on SEC 18 (Importance for education and science), SEC 8 (Socio-cultural dependence on environmental quality) and SEC 1 (Employment and income).

The corresponding GMPs focus on mitigating these specific pressure-state links. For offshore wind, GMPs include strategic turbine layouts designed to avoid bird migration routes, thereby reducing biological disturbance and protect regulatory and cultural ES[36] or retaining infrastructure on post-decommissioning, maintaining benthic biodiversity and related services[37] Additionally, tools like sensitivity mapping and multi-use zoning are identified as essential measures to enhance compatibility between renewable energy expansion and other maritime stakeholder values[38,39]

Discussion

By linking sectoral activities, environmental pressures, ES and SEC, this study operationalises the EBA within a marine planning context.

The validated SECs offer a consistent way to align ecological goals with regional priorities, helping connect ecological changes with relevant socio-economic priorities. GMP are presented as adaptive and context-sensitive options that can be tailored to local conditions and specific pressures. The link between ES and SECs follows the 'supply–demand' conceptual logic of the Butterfly Model[40], which emphasises the two-way feedback between ecosystems and society.

In this view, ES represent the ecological supply of benefits, while SECs capture the social-economic demand side, reflecting human dependence on

Table 2 | Pressure–ecosystem services matrix by sector

Serviço ecossistêmico	Fisheries	Marine non-living resources	Renewables	Aquaculture	Tourism	Total
Regulation and maintenance						
Nursery and habitat maintenance	−24	−14	−4	−13	−13	−68
Mediation of anthropogenic nuisances	−7	−10	−4	−2	−5	−28
Mediation of wastes	−14	−1	−2	−8	−2	−27
Regulation of soil quality	−6	−6	−6	−9	0	−27
Maintenance of physical, chemical, abiotic conditions	−1	−10	−6	−1	−8	−26
Pest and disease control	−11	−1	0	−10	−2	−24
Water conditions	−2	−4	0	−12	−2	−20
Atmospheric composition and conditions	0	−1	0	−1	−1	−3
Regulation of baseline flows and extreme events	−1	−3	0	**4**	0	0
Other type of regulation and maintenance service by abiotic/biotic processes	0	0	0	0	0	0
Provisioning						
Genetic material	−18	−11	−7	−15	−6	−57
Wild aquatic animals	−17	−15	−4	−12	−9	−57
Wild aquatic plants/algae	−13	−11	−7	−11	−6	−48
Mineral substances used for nutrition, materials or energy (N, M, EN)	−2	−6	−2	−8	0	−18
Farmed animals	−7	−2	−6	**6**	−5	−14
Water used for N, M, EN	0	0	0	−4	0	−4
Non-mineral substances or ecosystem properties used for N, M, EN	0	0	0	0	0	0
Other mineral/non-mineral subst. or ecosyst. properties used for N, M, EN	0	0	0	0	0	0
Cultivated aquatic plants for N, M, EN	0	0	0	**1**	0	1
Cultural						
Intellectual and representative interactions with environment	−21	−5	−2	−7	1	−34
Environmental conservation for future generations	−15	−11	1	−13	4	−34
Physical and experiential interactions with the environment	−21	0	0	−8	0	−29
Spiritual, symbolic and other interactions with natural environment	−3	0	0	−5	0	−8

ES section indicates ES groups in bold: Provisioning, Regulation and Maintenance and Cultural. Cell values reflect the magnitude of the impact: more negative values indicate a stronger negative impact and positive values indicate a positive impact of each sector on each ES. Bold and underlined numbers indicate ES that experience a positive impact from sectoral activities. N, M, EN stand for nutrition, materials or energy.

ecosystem conditions and the ways societal demands may influence them. This connection helps clarify how ecological changes may propagate into socio-economic consequences through altered ecosystem-service flows.

As the framework considers both negative and positive effects on ecosystem-service flows, positive linkages were included in the scoring matrix but not represented in the Sankey diagrams, which focus on the most negatively affected services. These positive linkages should therefore be interpreted as context-dependent, relying on appropriate management, territorial suitability and operational practices aligned with local ecological and socio-economic conditions[25,26].

The Sankey diagrams synthesise the causal pathways linking sectoral activities, environmental pressures, ES and SEC. By showing how pressures propagate through the logic chain, they help identify which sectoral activities are associated with the most affected ES, following similar applications in complementary cumulative-impact assessments[41].

It is important to note that the logic chain was developed in a general context, rather than for a specific ecosystem or case study. Therefore, the Sankey diagrams should not be interpreted as site-specific assessments, but as a communication and learning tool to support the understanding of how sectoral activities may generate pressures, affect ES and relate to SEC within the DAPSI(W)R(M) logic. Similar visual tools have been shown to support learning and stakeholder engagement in MSP by making complex socio-ecological relationships easier to interpret across different perspectives[42].

The general diagram (Fig. 1) offers an overarching view of the interactions across the five blue economy sectors—Fisheries, Marine Non-Living Resources, Renewable Energy, Aquaculture and Tourism—while the sector-specific diagrams (Figs. 2 and 3) provide deeper insights into the logic chains for Fisheries and Renewable Energy, respectively. Together, these diagrams illustrate how ecological pressures may propagate across ES and SEC under different sectoral activities.

In particular, the strong cumulative impact identified for 'Nursery and habitat maintenance' suggests that this service functions as a critical ecological bottleneck within the logic chain, as its degradation was associated with overlapping pressures from Fisheries, Aquaculture and Marine non-living resources. Because this ecosystem service supports multiple ecological functions and service flows, its decline may propagate across both provisioning and cultural dimensions. At the sector-specific level, the results highlight distinct trade-offs associated with fisheries and renewable energy. Figure 2 illustrated how ecological pressures cascaded into broader socio-economic effects in the fishery sector. It showed that impacts on Human Wellbeing, Education & Science and Culture were more pronounced than those directly linked to economic criteria, revealing uneven trade-offs among ES. These outcomes reflected how unsustainable fishing practices could erode food security, livelihoods and cultural identity, ultimately diminishing community wellbeing. This pattern mirrored Principle 2 of Roberts et al. (2024)[43], which stressed that fisheries should enhance the

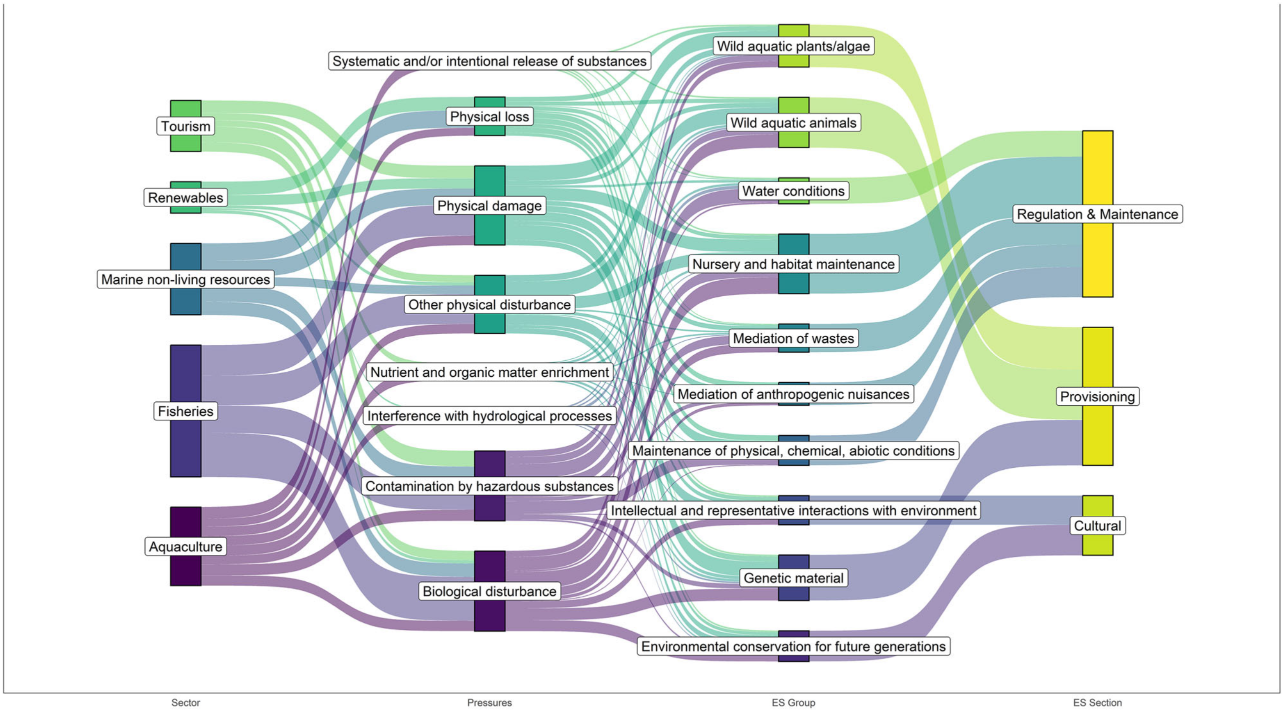

Fig. 1 | Sectoral pressures and their linkages to ecosystem services and societal benefit categories. Sankey Diagram: This diagram illustrates how selected marine and coastal sectors (left) generate specific environmental pressures (left-middle), which in turn affect different ecosystem services (right-middle) and ultimately impact broader societal benefit categories (right), such as human well-being, education and the blue economy.

resilience and welfare of people and communities rather than maximise industrial gains.

As the authors noted, these social and cultural dimensions remain undervalued in dominant management frameworks. These findings highlight how ecosystem-service impacts may extend beyond ecological degradation and generate broader socio-cultural vulnerabilities. In particular, the decline in 'Intellectual and representative interactions' and 'Environmental conservation for future generations' suggests that pressures on marine ecosystems may affect communities whose identity, cultural values and knowledge systems depend on environmental quality. The degradation of cultural ES associated with fisheries activities was linked to SEC 8 and SEC 9, reinforcing how ecological degradation can directly affect socially and culturally valued dimensions of marine environments.

Similarly, the renewable energy pathways showed that SEC 18 (Education and Science), SEC 8 (Socio-cultural dependence on environmental quality) and SEC 1 (Employment and income) were connected to impacts propagating across provisioning, regulation and maintenance and cultural ES. This highlights how pressures associated with offshore renewable energy may simultaneously affect multiple socio-economic dimensions within marine planning contexts.

From a management perspective, these findings can be translated into potential responses through GMPs. The GMPs presented are not exhaustive, but serve as concrete examples of practices that can help mitigate pressures and protect ES. When used alongside visual tools such as the Sankey diagram, they help show which services are most affected, where interventions may be most effective and which shared environmental concerns may benefit from cross-sectoral management responses. Additional examples are provided in Pegorelli et al.[44], which presents more than 90 GMPs across five sectors (renewable energy, aquaculture, fisheries, tourism and marine non-living resources), although these are not explicitly linked to ES or SEC.

To illustrate how GMP can mitigate specific pressures from sectoral activities, Table 3 presents a subset of GMPs applied to trawling and offshore wind farms. By aligning GMPs with specific ES, the framework helps illustrate how management actions may address pressures affecting different services and support more targeted responses that integrate ecological and socio-economic dimensions[45,46] For example, measures such as habitat mapping, bird-scaring lines, benthic protection zones and seasonal closures were associated with pressures linked to regulation and maintenance, provisioning and cultural services, illustrating how management responses may contribute to reducing cumulative impacts across multiple ecosystem-service categories.

In addition to sector-specific GMPs, recent literature highlights the potential of ocean multi-use as a complementary strategy to reduce spatial conflicts, enhance synergies and support biodiversity conservation. The concept of multi-use promotes the co-location of diverse maritime activities—such as aquaculture, renewable energy, ecotourism and conservation—within shared marine spaces[47] For instance, the co-location of aquaculture facilities and MPAs can support both habitat protection and sustainable seafood production[48,49] Similarly, offshore wind farms can serve as de facto refuges for marine life, contributing to local biodiversity[50] These examples suggest that multi-use strategies may complement GMP frameworks in marine planning.

It is important to note, however, that this analysis does not account for the relative intensity or spatial extent of each pressure. The width of each flow in the Sankey diagram reflects the number of distinct pressure-impact connections rather than the magnitude of environmental degradation, which should be considered when interpreting results for planning and prioritisation.

Despite these contributions, some methodological limitations were identified and should be considered when interpreting the results. For instance, the framework relies on literature-based and expert-derived linkages, which may introduce some subjectivity in how pressures and ES are scored. The comparatively smaller number of linkages identified for offshore renewable energy should not be interpreted as evidence of limited impacts, but rather as an indication of current evidence gaps. Recent reviews show that, despite the rapid expansion of offshore wind energy, knowledge of its environmental and socio-economic implications remains incomplete.

Renner (2025)[51] highlights that evidence on the physical marine environment, nutrient dynamics, phytoplankton, primary production and

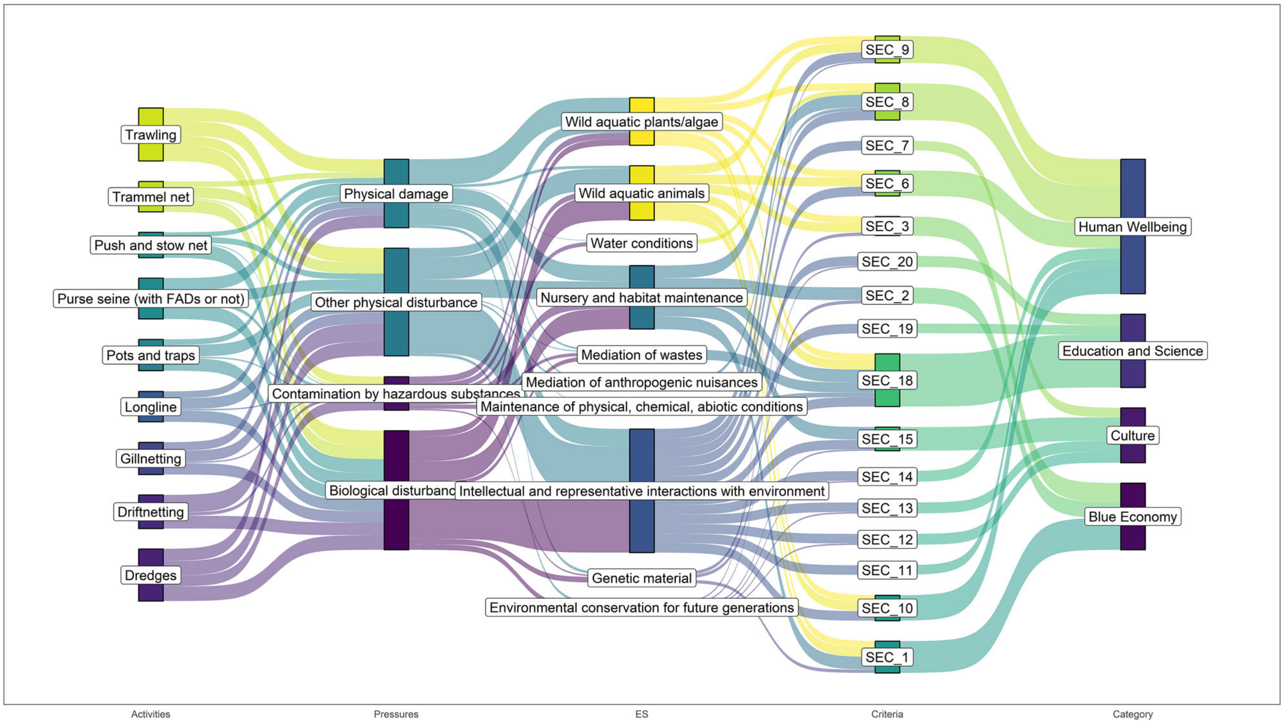

Fig. 2 | The Sankey diagram illustrates the linkages among fishery activities, associated pressures, impacted ecosystem services (ES) and their contributions to specific Socio-Economic Criteria (SEC), organised into broader categories. Where SEC_1—Employment and income from non-traditional activities; SEC_2—Importance for fishery activity; SEC_3—Blue economy development; SEC_6—Locally-caught seafood; SEC_7—Scenic/aesthetic value; SEC_8—Socio-cultural dependence on environmental quality; SEC_9—Traditional land/sea use; SEC_10—Cultural/traditional food security; SEC_11—Recreation and leisure; SEC_12—Cultural symbolic value; SEC_13—Historical/cultural structures; SEC_14—Health of residents/users; SEC_15—Iconic species/habitats; SEC_18—Demonstration/scientific management; SEC_19—Educational interest; SEC_20—Scientific interest.

Table 3 | Good management practices examples in marine sectors-fishing trawling and offshore wind sectors: addressing pressures and supporting ecosystem services through sector-specific measures

Sector	Good management practice	Mediation of impact	Ecosystem services
Fishing trawling	Mapping habitats: for identification of sensitive habitats and fauna, for a more sustainable and profitability of the fishery activity[62].	Physical damage	Regulation and maintenance, Provision[63]
	For bird bycatch reduction, Bird-scaring lines or Tori lines can be introduced as a requirement of the license[64].	Biological disturbance	Regulation and maintenance, Cultural[65]
	,Establishment of benthic protection areas with transferable quotes, observers and electronic net monitoring. Seasonal closures for ETP species[66,67]	Biological disturbance/ Physical damage	Provisioning[68].
	Additional MPA management measures to protect endangered species[67].	Biological disturbance/ Physical damage	Regulation and maintenance, Cultural[69].
Renewable Energy—Offshore Wind	Turbine layouts to avoid migration barrier effects for birds[36].	Biological Disturbance (Migration barrier for birds).	Regulation and maintenance, Cultural[65].
	Leave infrastructure in place during decommissioning if ecological community has developed[37].	Physical Loss (Loss of benthic and seabed habitats)	Cultural, Regulation and Maintenance, Provision[52]
	Use of sensitivity maps in MSP process to inform suitable sites.[38].	Biological Disturbance and Physical Loss	Regulation and maintenance, Provision[63]
	Define zones to allow co-existence with fisheries, tourism, habitat protection, etc[39].	Restriction of other activities	Cultural and Provision services[52].

floating wind technologies is still limited, with a strong reliance on modelling and a scarcity of in situ observations. Similarly, Watson et al.[52] found that more than 86% of possible relationships between offshore wind farm impacts, biodiversity groups and ES remain unknown, with particularly limited evidence on decommissioning, deeper-water floating structures and regulating services. Therefore, the renewable energy Sankey diagram should be interpreted not as a definitive representation of lower impact, but as a tool that also reveals where evidence is still scarce and where further assessment is needed.

Moreover, the linkages are established directly between human activities and ES, without explicitly accounting for the intermediary ecosystem components—such as habitats, benthic communities, or specific biodiversity types—that mediate these interactions. Consequently, the magnitude and nature of impacts may vary depending on the local ecological context, for example in coral reef, seagrass, or soft-bottom systems. In this context, future applications or case studies could further illustrate the applicability of the framework and help refine these linkages under specific ecological and management contexts.

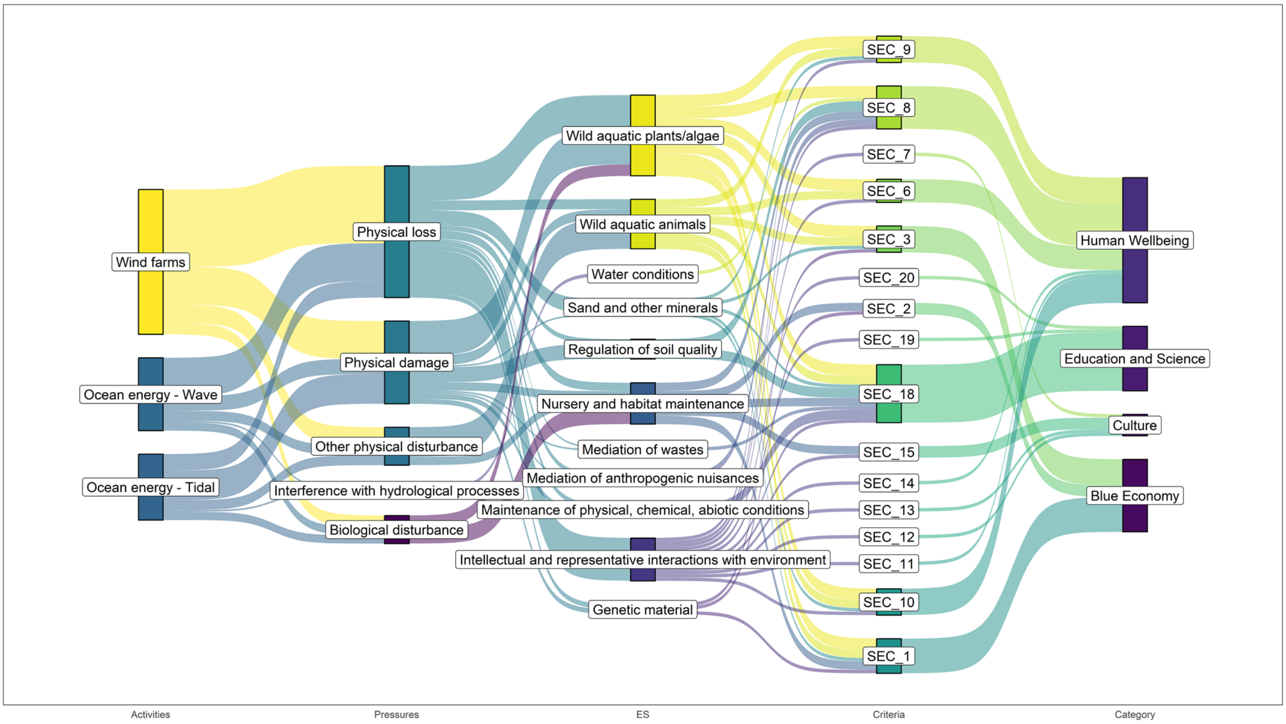

Fig. 3 | The Sankey diagram illustrates the linkages among marine renewable energy activities, associated pressures, impacted ecosystem services (ES) and their contributions to specific Socio-Economic Criteria (SEC), organised into broader categories. Where SEC_1—Employment and income from non-traditional activities; SEC_2—Importance for fishery activity; SEC_3—Blue economy development; SEC_6—Locally-caught seafood; SEC_7—Scenic/aesthetic value; SEC_8—Socio-cultural dependence on environmental quality; SEC_9—Traditional land/sea use; SEC_10—Cultural/traditional food security; SEC_11—Recreation and leisure; SEC_12—Cultural symbolic value; SEC_13—Historical/cultural structures; SEC_14—Health of residents/users; SEC_15—Iconic species/habitats; SEC_18—Demonstration/scientific management; SEC_19—Educational interest; SEC_20—Scientific interest.

It is also important to note that the assessment focused primarily on direct interactions between sectoral activities, pressures and ES. Therefore, some indirect or secondary impacts, such as oil spills, lost fishing gear and ghost fishing, or coastal and onshore infrastructure supporting maritime activities, were not explicitly represented in the current framework. The contribution of the framework is not to replace existing assessment approaches, but to bring activity–pressure, ecosystem-service, socio-economic and management-response linkages into a single structured workflow for supporting trade-off discussions in marine planning.

As already mentioned, the framework presented in this study was not applied to a specific case study. Rather, it provides a structured analytical basis to support the discussion of trade-offs and inspire locally relevant applications[53] Similarly, the GMPs explored are not intended as prescriptive or one-size-fits-all solutions, but as illustrative examples that can inform stakeholder dialogue and be adapted to specific ecological, social and management contexts.

The findings underscore the potential value of integrating ecosystem service assessments with socio-economic priorities represented by a previously validated set of criteria[35] to support marine planning that is both ecologically grounded and socially legitimate[54,55] Furthermore, this approach offers a step toward operationalizing more adaptive and inclusive governance frameworks, capable of addressing the complexity of cumulative impacts in marine environments.

Future work should aim to quantify the intensity of sectoral pressures, incorporate spatial heterogeneity in ecosystem vulnerability and strengthen stakeholder participation in scenario-based planning. Applying the framework in a test site would also be relevant to gather feedback from stakeholders and policymakers, helping to identify its practical limitations, usability and potential for supporting decision-making in real planning contexts. These developments would strengthen the applicability of the framework for ecosystem-based marine planning.

Conclusion

This study shows that the proposed framework can support a more integrated understanding of how blue economy sectors generate pressures, affect ES and influence socio-economic priorities. By linking activities, pressures, ES and SEC, the framework helps make cumulative impacts and trade-offs more visible and easier to discuss among scientists, planners and stakeholders. In this sense, it contributes to the practical implementation of integrated ocean management and governance, as encouraged by the European Ocean Pact[19].

The Sankey diagrams strengthen this contribution by showing how pressures move through the logic chain and how impacts on ES may also affect other activities and societal priorities. This is particularly useful in marine environments where multiple sectors operate simultaneously and pressures overlap.

By comparing Fisheries and offshore renewable energy, the study shows that the framework can be applied to sectors with different characteristics and levels of available evidence. Fisheries presented broader and better-documented impact pathways, while offshore renewable energy showed fewer identified linkages. This should be interpreted as a reflection of current knowledge gaps rather than evidence of lower environmental impact.

However, the approach should not be interpreted as a final assessment. It focuses mainly on direct impacts and does not quantify the intensity, frequency, duration, or spatial extent of each impact. It also does not fully account for indirect effects or differences in ecosystem vulnerability. Future applications in real case studies would help test and refine the framework under specific ecological and management contexts.

Methods

Framework design and sector selection

This study operationalises the DAPSI(W)R(M) framework (*Drivers—Activities—Pressures—State of the environment—Impacts on Welfare—*

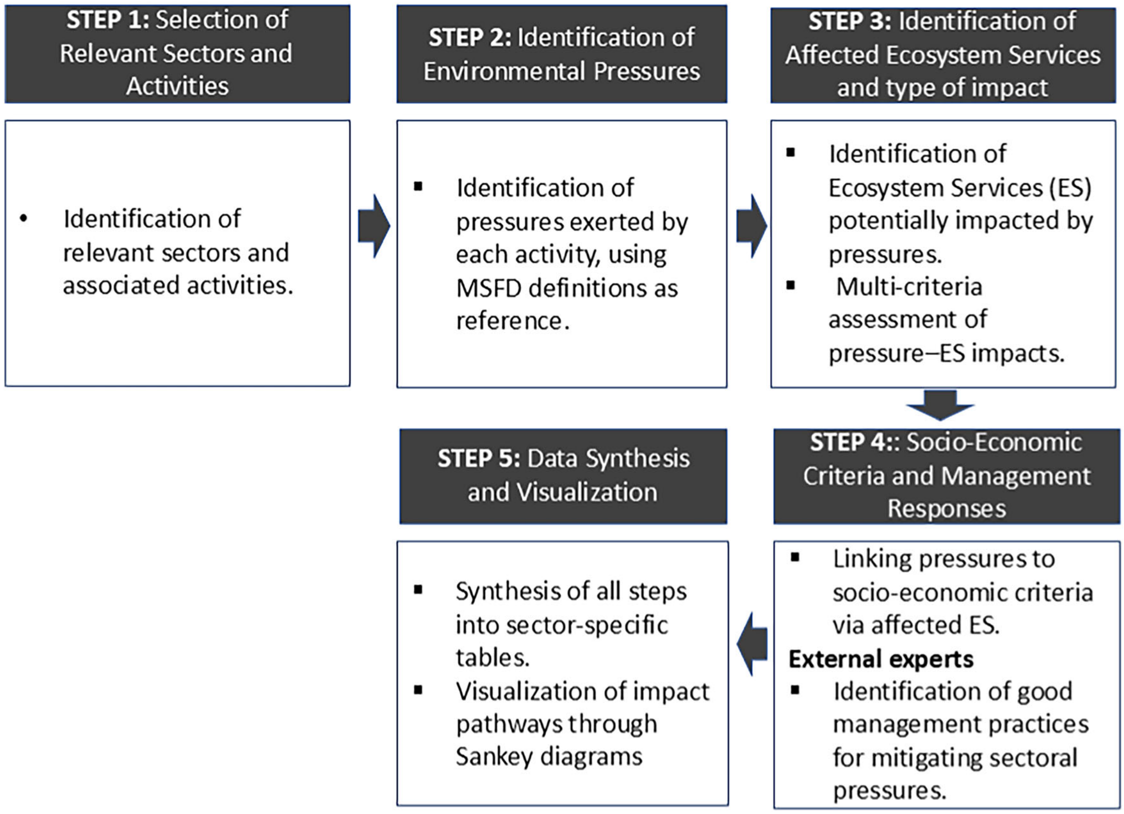

Fig. 4 | Methodological workflow used to operationalise the DAPSI(W)R(M) framework. Summary of the five-step process developed to link blue economy sectors, environmental pressures, ecosystem services, socio-economic criteria and management responses. Step 1 identifies the relevant sectors and associated activities. Step 2 classifies the environmental pressures generated by each activity using the MSFD pressure typology. Step 3 identifies potentially affected ecosystem services and assesses the direction of impacts resulting from pressure–ecosystem service interactions. Step 4 links affected ecosystem services to socio-economic criteria through a validated ecosystem service–socio-economic criterion framework and identifies GMPs as potential management responses, supported by expert review. Step 5 synthesises the resulting relationships into sector-specific matrices and visualises the pathways linking activities, pressures, ecosystem services, socio-economic criteria and management responses using Sankey diagrams.

Management Responses) through a stepwise, qualitative methodological workflow that translates its conceptual logic into an applied analysis linking blue economy sectors, sectoral activities, environmental pressures, affected ES, SECs and potential GMPs. The methodology is designed to apply the framework in a transparent and reproducible manner suitable for EB-MSP. Drivers were not assessed separately, as the analysis starts from Activities as the operational entry point for identifying Pressures, affected ES, SECs and management responses.

The methodological workflow is summarised in Fig. 4 and consists of five consecutive steps: (1) selection of relevant sectors and Activities (A); (2) identification of environmental Pressures (P); (3) identification and assessment of affected ES (State and Impacts on Welfare bridge); (4) linkage to SECs (Impacts of Welfare (I(W))) and GMPs (R(M)); and (5) data synthesis and visualisation. These steps are described sequentially below.

The analysis began by identifying key blue economy sectors relevant to biodiversity conservation and MSP, drawing on the MSP4BIO project's scope and objectives. These included fisheries, aquaculture, renewable energy, tourism and marine non-living resources. To compile an initial inventory of sectoral activities occurring in European marine waters, a multi-source review was conducted. Data sources were categorised into three primary groups to ensure reproducibility: (i) EU policy documents and technical reports (e.g. FAO, EU Blue Economy Report[56] EU Fish Market Report[57] Fishing Activity[58] classifications), (ii) peer-reviewed literature on sectoral impacts and (iii) technical review by three specialists with expertise in ES.

In this study, the term 'Activity' is used as an operational unit representing the primary mode of interaction between a sector and the marine environment. This includes fishing techniques, gear types, or infrastructure categories that directly generate environmental pressures. While some items listed (e.g. wind turbines or trawlers) refer to infrastructure or gear, they are treated here as the 'Activity' unit because they represent the functional source of the pressure. Lifecycle phases (e.g. construction or decommissioning) were not treated as separate analytical units. This exclusion maintains analytical coherence across sectors and focuses the assessment on the operational phase, providing a consistent temporal baseline for comparing long-term pressures across diverse blue economy activities.

While the framework was developed for all five sectors, fisheries and renewable energy were selected for more detailed analysis due to their contrasting operational characteristics, strong relevance for marine planning, and frequent spatial interaction with conservation objectives. The list of activities considered for these two sectors is presented in Table 4, with activities for the remaining sectors—marine non-living resources, aquaculture and tourism—provided in Supplementary Tables 3, 5 and 6, respectively.

Pressure classification

Environmental pressures associated with each sectoral activity were identified through a targeted literature review. To ensure methodological consistency across sectors, pressures were classified using the MSFD typology, which defines eight broad categories of physical, chemical and biological pressures, accompanied by illustrative examples of their impacts (Table 5). These categories served as a reference framework for classifying the diverse impacts identified in the literature.

Table 4 | List of activities selected for the fisheries and renewable energy sectors with short descriptions

Sector	Activity	Description
Fisheries	Trawling	Cone-shaped net towed along the seabed or midwater; low selectivity, high discards and benthic disturbance. Targets shrimp, prawns, flatfish and whitefish.
	Trammel net	Three-layer gillnet that traps fish when pushed through; poor selectivity and risk of ghost fishing. Targets sole, prawn and squid.
	Push and stow net	Fixed cone-shaped nets anchored in rows; frequent juvenile catch with negative impacts on stocks. Targets small fish and fry.
	Purse seine (with FADs or not)	Encircles pelagic schools near the surface; FADs increase bycatch and drift uncontrolled. Targets mackerel and herring.
	Pots and traps	Cages that attract and retain crustaceans; contribute to marine litter and ghost fishing. Targets lobsters, crabs, shrimps and octopus.
	Longline	Hooks set along a mainline in open water; low selectivity; bycatch of turtles, seabirds and sharks. Targets tuna and swordfish.
	Gillnetting	Stationary wall of netting that catches by gilling or entanglement; risk of ghost fishing. Targets hake, herring, mackerel and sardine.
	Drift gillnet	Free-floating gillnet that drifts with currents; high bycatch of sharks, cetaceans and turtles. Targets pelagic fish.
	Dredges	Towed cages scraping seabed to collect shellfish; alter substrate and harm benthic fauna. Targets scallops, clams, oysters and mussels.
Renewable energy	Wind farms	Offshore turbines and substations producing electricity; habitat loss and collision risks for seabirds and marine mammals.
	Ocean energy—Wave	Devices capturing motion of surface waves; may cause seabed alteration and collision risks.
	Ocean energy—Tidal	Turbines exploiting tidal flows between basins and open sea; potential seabed damage and collision risks.

Descriptions adapted from refs. 70,71 and ref. 72.

As MSFD pressure categories are commonly associated with negative impacts, they were applied here in a neutral, descriptive manner to identify both negative and positive interactions with ES. This interpretation enables a more comprehensive assessment of how normal sectoral operations may alter ES flows.

In some cases, experts highlighted additional impacts not explicitly mentioned in the literature but known to occur from their field experience. Examples included the contribution to ocean plastic by derelict FADs, underwater noise from vessels and dredging operations, antifouling substances and fuel spills from boats and ships, or the disturbance caused by bottom-set gillnets and pots dragging or breaking benthic habitats such as reefs and corals. When such cases arose, expert judgement was used to establish the most likely pressure–impact relationships, ensuring that the assessment remained comprehensive and consistent across sectors.

The assessment intentionally focused on primary pressures directly generated by the activities under consideration. Secondary or indirect impacts (e.g. land-based infrastructure, port operations, or downstream processing) were excluded to maintain a clear and manageable analytical scope. Similarly, general environmental impacts associated with mass tourism were not considered unless they could be directly attributed to a specific activity within the sector.

Moreover, the impact analysis for Aquaculture required methodological adaptation. Unlike other sectors, which provided clearer information on activities and their effects, aquaculture presented limited sector-specific data. To address this, a zonal approach was adopted based on available literature, categorising impacts into two operational contexts: (i) coastal or intertidal zones and (ii) aquaculture at sea (including hatcheries, floating cages and rafts).

Ecosystem services assessment

ES potentially affected by each activity-pressure were identified using the Common International Classification of Ecosystem Services (CICES) version 5.1. In this step, the ES act as the bridge between the ecological State (S) (the condition of the ecosystem components) and the resulting Impacts on Welfare (I(W)).

The identification of relevant ES was determined by evaluating how each physical, chemical, or biological pressure (Step 2) alters the abiotic or

Table 5 | Pressures and associated impacts according to the MSFD

Pressure type	Description and examples
Physical loss	• Loss of seabed due to structures or materials. • Smothering (e.g. dredge spoil disposal) • Sealing (e.g. permanent constructions)
Physical damage	• Alteration of seabed without complete loss. • Siltation changes (e.g. dredging, run-off) • Abrasion (e.g. fishing gear, anchoring) • Selective extraction (e.g. mining, trawling)
Other physical disturbance	• Disturbances not causing direct damage or loss. • Underwater noise (e.g. ships, sonar) • Marine litter
Hydrological changes	• Changes in water properties. • Thermal changes (e.g. power plant outfalls) • Salinity changes (e.g. dams, water abstraction)
Contamination by hazardous substances	• Input of harmful chemicals. • Synthetic (e.g. pesticides, pharmaceuticals) • Non-synthetic (e.g. heavy metals, oil) • Radio-nuclides
Intentional release of substances	• Release of other substances under legal frameworks. • Solids, liquids, gases intentionally released (e.g. via permitted discharges)
Nutrient and organic enrichment	• Excess input of nutrients or organic matter. • Fertilisers (e.g. from agriculture, aquaculture) • Organic matter (e.g. sewage, mariculture)
Biological disturbance	• Disruption by living organisms. • Microbial pathogens • Non-indigenous species/translocations • Selective extraction (e.g. fishing, bycatch)

Table 6 | New nomenclature for CICES Group Ecosystem Services

ES Section	ES Group CICES V5.1	Adapted ES Group nomenclature
Regulation and maintenance	Lifecycle maintenance, habitat and gene pool protection	Nursery and habitat maintenance
	Maintenance of physical, chemical, abiotic conditions	Maintenance of physical, chemical, abiotic conditions
	Mediation of wastes or toxic substances of anthropogenic origin by living processes	Mediation of wastes
	Water conditions	Water conditions
	Mediation of nuisances of anthropogenic origin	Mediation of anthropogenic nuisances
	Regulation of soil quality	Regulation of soil quality
Provisioning	Wild animals (terrestrial and aquatic) for nutrition, materials or energy	Wild aquatic animals
	Genetic material (from plants, algae or fungi, animals and other organisms)	Genetic material
	Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Wild aquatic plants/algae
	Mineral substances used for nutrition, materials or energy	Mineral substances used for nutrition, materials or energy
	Reared aquatic animals for nutrition, materials or energy	Farmed aquatic animals
Cultural	Intellectual and representative interactions with environment (abiotic and natural)	Intellectual and representative interactions with environment
	Other biotic characteristics that have a non-use value	Environmental conservation for future generations
	Physical and experiential interactions with the environment (abiotic e.g. caves. natural: whales)	Physical and experiential interactions with the environment

biotic State (S) of the ecosystem. By synthesising the nature of these impacts from the literature review (Step 2), we mapped these pressure-state interactions to specific CICES service flows. This process ensured that the identified ES represented a verified, evidence-based pathway between the activity's operational footprint (Step 1) and the resulting consequences for human well-being.

Technical expert review was used to validate the ES–pressure relationships. Three specialists were selected based on their expertise in ES independently reviewed the draft activity–pressure–ES matrices, drawing on the literature synthesis developed for each activity–pressure–impact pathway presented in Supplementary Tables 2–6. Discrepancies were jointly discussed and, where possible, resolved through additional literature checks.

To characterise the direction of these impacts on ES, a qualitative analysis was conducted by cross-referencing the sector–activity–pressure relationships with the affected ES. Impacts were scored as −1 when the normal operation of an activity reduced the capacity of ecosystems to supply a given service, +1 when the activity increased service supply, and 0 when no direct or significant effect on the service was identified. For example, fishing extraction was interpreted as reducing the ecosystem's capacity to provide wild aquatic animals, whereas aquaculture was interpreted as increasing the supply of farmed aquatic animals.

Only direct, significant, and clearly supported interactions were scored to avoid speculative or context-dependent assumptions, ensuring the framework remains robust and reproducible.

Socio-economic criteria and management responses

Connections between environmental pressures and SEC (representing Impacts on Welfare), were established indirectly, using the affected ES as intermediaries. The ES–SEC linkages were derived from the validated framework developed by Pegorelli et al.[35], which defines a set of 20 SECs representing societal priorities relevant to marine planning. These criteria were adopted for use in Step 4 of the present study; their identification and validation were not repeated here. This indirect linkage provides a transparent and conceptually consistent pathway from sectoral activities to socioeconomic relevance because it relies on a validated expert-based matrix that maps the specific dependencies of societal priorities on ecological service flows. By anchoring SECs in specific ES, the framework ensures that human welfare impacts are directly traceable to ecological changes, preventing the 'black box' assumptions often found in socio-economic assessments.

This approach was applied in detail for the fisheries and renewable energy sectors, to demonstrate the feasibility and flow of the methodology in practice.

Potential GMPs were then associated with specific pressures and ES impacts based on evidence from peer-reviewed literature and technical guidance documents. GMPs are presented as illustrative, context-dependent options rather than prescriptive measures, highlighting how management responses may mitigate pressures and support affected services. In the DAPSI(W)R(M) framework, these GMPs constitute the Management Responses (R(M)).

Data synthesis and visualisation

Finally, all identified relationships were compiled into sector-specific matrices that outline the complete logic chain among activities, pressures, affected ES, relevant SEC and corresponding GMPs. To support integrative spatial planning and facilitate stakeholder communication, Sankey diagrams were used to visualise the causal pathways across the logic chain[59–61]

The diagrams are structured to mirror the DAPSI(W)R(M) phases, moving from left to right to illustrate how specific activities trigger pressures that propagate through the ecosystem to affect human welfare and management options.

Diagram flow widths represent the number of identified links between components rather than the magnitude or spatial extent of the impacts. Given the high number of ES ($n = 22$), only the ten most affected services per sector were included in the diagrams (Table 2), based on cumulative impact scores. ES labels were further simplified (Table 6) to improve accessibility for non-specialist audiences and improve the results' utility for diverse stakeholder groups.

Data availability

The data supporting the findings of this study are available in the paper and its Supplementary Material. The processed dataset used to organise the linkages for the Sankey diagrams and related analyses is not publicly available because it was created as an intermediate file for data organisation and analysis, but is available from the corresponding author upon reasonable request.

Received: 29 July 2025; Accepted: 17 August 2026;
Published online: 08 September 2026

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Acknowledgements

The authors would like to thank the MSP4BIO project for its support and funding under the Horizon Europe Programme (Grant Agreement No. 101060707). We also thank all contributors whose input was essential to the development of this resource for Marine Protected Area managers and blue economy stakeholders. Special thanks go to Helena Calado, Martina Bocci, Frederick Bruce, Stefano Menegon, Debora Gutierrez, Margarita Stancheva, and Mauro Randone. We are also grateful to Gabriel Tedone for his support in developing the R code used to produce the Sankey diagrams presented in this paper.

Author contributions

C.P.: Conceptualisation, Data curation, Formal analysis, Methodology, Investigation, prepared figures, Writing—original draft, Writing—review and editing. I.S.: Writing—original draft, Writing—review and editing. M.D.A.: Formal analysis, Methodology, Supervision; J.G.-O. Formal analysis, Methodology, Supervision. S.R.L.: Conceptualisation, Data curation, Methodology, Investigation, Formal analysis Writing—original draft, Writing—review and editing. J.G.-S. Funding acquisition, Project administration, Writing—review and editing.

Competing interests

J.G.S. is Guest Editor of npj Ocean Sustainability Journal special collection dedicated to the 'Integration of Marine Protected Areas and Maritime Spatial Planning Processes'. J.G.S. was not involved in the journal's review of, or decisions related to, this manuscript. The other authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44183-026-00238-6.

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