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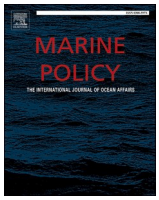

Is Maritime Spatial Planning a tool to mitigate the impacts of underwater noise? A review of adopted and upcoming maritime spatial plans in Europe

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ABSTRACT

Sound is essential for marine life and, as anthropogenic noise in the marine environment increases, the scientific community becomes more aware of its negative impacts on marine organisms. Noise travels long distances underwater, including across national boundaries and jurisdictions and impacts a variety of mobile species. Marine Spatial Planning (MSP) represents a useful methodology and policy framework to manage noise-producing human activities with an ecosystem-based approach. This paper provides a picture of the current situation regarding the role of MSP in addressing underwater noise across a sample of 11 countries in Europe. A thorough analysis of their marine plans and related materials is carried out and validated through interviews with the relevant MSP experts. A vision is proposed for the potential synergies between MSP and underwater noise, defining a two-way relationship between the noise community (e.g., scientists, engineers, consultants, operators, authorities) and marine planners. This type of analysis is timely both from an MSP and an underwater noise perspective. Most EU countries have now released their MSP plans following the 2021 deadline of the Maritime Spatial Planning Directive (2014) and a new phase of MSP is approaching, which will attempt to fill the gaps left by the current cycle and introduce substantial improvements. Moreover, thanks to the contributions from the Marine Strategy Framework Directive (MSFD) and its Technical Group on Underwater Noise (TG-Noise), quantitative rules to evaluate noise status and impacts are being defined, while a number of research projects continuously produces new and highly relevant knowledge.

1. Introduction

Underwater soundscapes, defined as "ambient sounds in terms of their spatial, temporal, and frequency attributes" [1], contain important information that marine organisms use to exploit their surroundings. Invertebrates, fish and cetaceans are known to use environmental sounds to orientate and migrate [2,3]. A large number of organisms intentionally produce sounds to communicate when defending their territory or during reproduction, but also generate sounds unintentionally while displaying predatory or anti-predatory behaviours [4]. However, human activities ensonify the underwater environment, too.

In the last century, anthropogenic underwater noise, whether deliberate or incidental, impulsive or continuous, has increased the underwater ambient noise levels [5–7], resulting in a growing threat to marine life [8]. Impulsive sounds are generally pulsed, transient, very loud sounds of low, medium, or high frequency characterized by a sudden onset; they are generated by human activities such as geophysical surveys to inspect the subsea, percussive pile driving for inshore and offshore constructions (i.e., windfarms), naval sonars and multi-beam echosounders, underwater explosions. Among all the impulsive sources, seismic surveys and explosives produce the highest levels of noise [9]. Continuous anthropogenic sounds are rather constant, fluctuating, or slowly varying over a long time interval, and are mainly generated by maritime transport or recreational boating. Offshore drilling and marine dredging also produce continuous noise in the range of small or medium sized vessels and contribute to the local ambient sound [10]. This dual classification (impulsive vs continuous noise) is range-dependent: for example, impulsive sounds dissipate with distance, becoming non-impulsive at some distance from the source; still, they influence the soundscape noise levels [11].

The scientific community has clearly demonstrated the significant negative impacts of anthropogenic noise on marine biota [12,13].

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Impulsive sounds have the potential to physically injure marine mammals, fish and invertebrates at shorter distances and to cause behavioural disturbance at longer distances [11,14,15]. Acute effects include permanent or temporary hearing loss and impairment [16–18]. The exposure to continuous anthropogenic noise can mask the detection of relevant sounds, as clearly demonstrated for cetaceans as well as certain fish species [19–21], negatively affecting animal behaviour at various levels, in particular foraging ability, predation avoidance, reproductive interactions, and navigation ability [13,22]. Displacement from noisy areas has also been reported in marine mammals [23–25]. Given such evidence, potential impacts of anthropogenic noise on populations and ecosystems are foreseen.

Underwater noise is able to travel long distances including across national boundaries and jurisdictions [26] and impacts highly mobile or migratory species such as cetaceans. However, cetacean species are not the only ones enduring noise-related impacts: affected taxa also include fish, reptiles and invertebrates such as crustaceans and plankton [18,27,28].

The aim of this study is to provide a representative picture of the current situation around the role of Maritime Spatial Planning (MSP) in addressing or providing solutions to underwater noise and, on that basis, identify the main needs and approaches to obtain "noise-proof" MSP plans in the medium term. This type of analysis is timely both from an MSP and an underwater noise perspective. A new cycle of MSP is approaching, which will attempt to fill the gaps left by the current cycle and better adhere to the European Green Deal, making it a good time to identify what is missing and try to bridge gaps. Moreover, thanks to the contributions of the MSFD and its Technical Group on Underwater Noise (TG-Noise), quantitative "rules" to evaluate noise have recently been defined (e.g., threshold values for impulsive and continuous noise) to be included in the next phase. The twin themes of underwater noise and MSP are set out in the following section (Section 2), while the methodology adopted for the structured analysis is described in Section 3. The study's outcomes are illustrated in Section 4, with regard to the three stages of MSP: i) assessment (Section 4.1), ii) planning (Sect. 4.2) and iii) monitoring and adaptation (Section 4.3). A vision is proposed for the potential synergies and exchanges between MSP and underwater noise in Section 5 defining a mutual relationship between the two: on one hand, ensuring that underwater noise and its sources are considered in the MSP process by defining how marine planners can adapt and improve their plans through the inclusion of noise; on the other, using MSP tools to reduce underwater noise and its impacts on biota, allowing the underwater sound community (e.g. scientists, engineers, consultants, operators, authorities) to take advantage of MSP to reach MSFD targets. Finally, conclusions are drawn in Section 6.

2. Maritime Spatial Planning and underwater noise

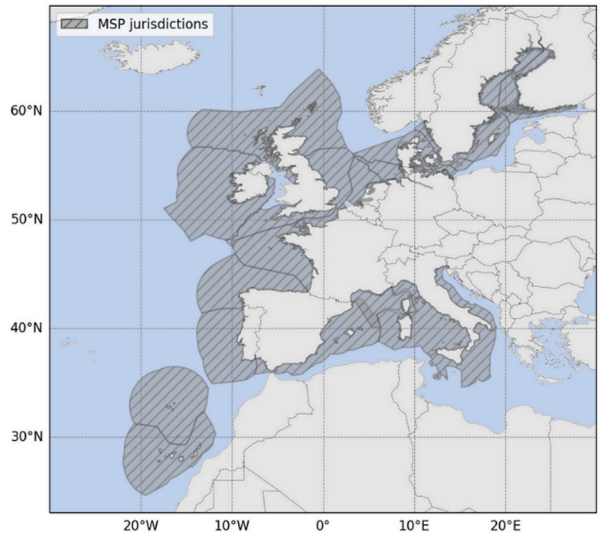
MSP is often described as a public and transparent process for the temporal and spatial allocation and regulation of human activities at sea to simultaneously achieve ecological, economic and social objectives [29,30]. In 2014, the EU adopted its MSP Directive (MSPD) [31], which is considered "the world's first legal requirement for countries to create transparent planning-at-sea systems" [32]. Although some countries (e.g.; Germany, Belgium, Netherlands) had started working on Maritime Spatial Planning years before, the adoption of the MSPD provided a common framework to all EU countries and acted as one of the key drivers for the implementation of MSP in the marine waters under their jurisdiction. The great majority of EU countries have MSP plans approved or under approval, and some countries are in their second or third cycle of planning [33].

Among its multiple objectives, MSP aims at promoting the sustainable development of maritime and coastal socio-economic activities and the sustainable use of marine and coastal resources [34]. This is done while adopting an ecosystem-based approach [35], as recalled in several points of the MSPD (preambles 3, 14 and 22 and article 5) and in line with the provisions of the Marine Strategy Framework Directive (MSFD - 2008/56/EU) [36]. The MSFD is often regarded as the environmental pillar of the EU's Integrated Maritime Policy [37], providing an EU-wide framework for the protection of the marine environment and its biodiversity, aiming at the achievement of its Good Environmental Status (GES) [38]. MSP is acknowledged as a tool which can and should greatly contribute to the MSFD goals and the achievement of GES [39]. As such, MSP entails the proper management of human activities to reduce pressures and impacts on the marine environment, in addition to minimising conflicts and developing synergies between different activities at sea.

Anthropogenic underwater noise is one of several pressures that MSP is required to take into consideration. Underwater noise does not affect marine biodiversity in isolation, but acts in combination with several other human pressures determining cumulative and cascading effects on marine species. Continuously gaining insight on the impacts of noise and on the way they interact with other human induced environmental stressors – including those related to climate change – is of particular importance to support science-based management of this specific challenge through MSP. On the other hand, given its cross-cutting nature [40,41], MSP – together with MSFD and other environmental policies – provides the framework to tackle the impacts of anthropogenic underwater noise through an integrated approach, while also looking at interactions with other human pressures [42]. MSP is expected to deal with underwater noise in several ways: assessing and mapping noise-related pressures and impacts, identifying marine areas and marine species of priority attention, defining objectives to reduce noise impacts on the environment and identifying related spatial and regulating measures focusing on sources and/or ecological targets of anthropogenic underwater noise, promoting balanced coexistence of noise sources (e.g. offshore wind farms and maritime transport) with other sea uses. Embedding underwater noise into MSP is expected to be beneficial for a number of reasons. By bringing together a variety of stakeholders within the same discussion arena [43,44], it allows for knowledge to be shared around different aspects of underwater noise. Such stakeholders may be researchers interested in sharing new data, tools and assessments, economic operators (more involved in technological and operational aspects), public agencies (for management and regulatory aspects), or NGOs (keen on protection priorities and awareness raising aspects). Moreover, according to articles 11 and 12 of the framework directive, MSP is expected to increase cooperation among EU Member States, as well as between these and third countries, to tackle challenges of common interest. This is rightly the case of underwater noise, given the transboundary dimension of some of its anthropogenic sources (maritime transport in particular) and the mobile nature of several target species (e.g., cetaceans). MSP should consider noise-related aspects along all phases of its policy cycle, from the assessment and planning stages to monitoring and implementation. Monitoring and evaluating whether and how MSP spatial and regulatory measures contribute to reduce noise-related pressures and mitigate their impacts on the environment is of crucial importance to improve planning and adapt to the ever-changing environmental and socio-economic context.

Most EU countries now have their MSP plans in place, while a few others have significantly progressed towards finalisation of their plans. The upcoming phases of the MSP policy cycle (implementation, monitoring, evaluation and revision) serve as an opportunity to better integrate underwater noise into MSP. More in general, it is now time for a comprehensive analysis of adequacy of the plans with respect to the objectives of Directive 2014/89/EU and coherence to the MSFD goals [45]. It is also the time to look forward, giving further attention to essential aspects like Ecosystem-Based MSP [46,47], connections to climate change [48], socio-economic implications of MSP [49], relationships with MPAs and marine habitat restoration [50,51], not to mention the wide range of contributions to knowledge-based MSP offered by the capitalization of results from numerous recent and

Step 1: Identification of MSP plans and collection of material



Step 2: Structured review

MSP phase		Key questions
Analysis & Interpretation	1	UWN considered qualitatively/quantitatively?
	2	UWN sources described and mapped?
	3	UWN target species described and mapped?
	4	UWN impacts on marine environment described and mapped?
	5	UWN analysed in CEA framework?
Planning	6	Planning goals and objectives explicitely considering UWN and its sources?
	7	Are there specific planning measures related to UWN and its sources?
	8	Are different planning scenarios / pool of measures taking also into account UWN and its sources?
	9	Is there evidence from the stakeholder consultation of awareness on UWN issues and discussion around UWN measures?
Implementation, monitoring and evaluation, adaptation phase	10	Mention or identification of mechanisms targeting the coherent and coordinated implementation of MSP with other UWN-relevant policies?
	11	Are UWN and its sources explicitely considered in monitoring MSP implementation? Through specific indicators?
	12	Are there UWN observing systems in place, meant to be used to monitor effects of planning measures and eventually adapt the MSP plan?

Step 3: Interviews for integration and validation

Step 4: Formulation of results

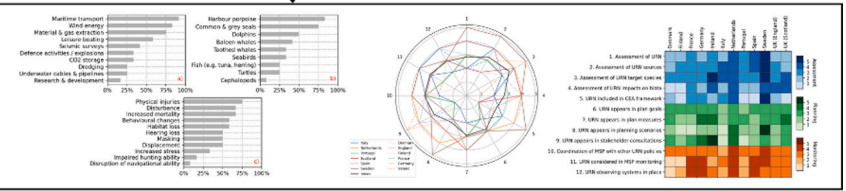


Fig. 1. Methodology adopted for the review and analysis of the maritime spatial plans and related materials of 12 different countries and their approach in managing underwater noise through MSP. UWN is short for underwater noise, here.

ongoing research projects funded by Horizon Europe and other programmes.

3. Materials and methods

A thorough analysis of maritime spatial plans and related materials was carried out with the aim of identifying mechanisms currently linking underwater noise and MSP. Comparing existing approaches across different countries allows to pinpoint key issues and strengths and grants a solid background for understanding the role of MSP in providing solutions to underwater noise. The four-step methodology used to investigate how noise is taken into account in formal MSP plans and processes is summarised in Fig. 1. Such methodology can be further extended to other countries and plans, and can be updated to take into account how the situation, which is still highly dynamic, is evolving.

3.1. Step 1: Collection of materials

The first step consisted in the identification of 27 Maritime Spatial Plans from 11 countries (Finland, Sweden, Germany, Denmark, The Netherlands, France, UK (England and Scotland), Ireland, Portugal, Spain, Italy) and in 4 different EU sea basins (Baltic, North Sea, Atlantic, Mediterranean), all either already approved or under finalisation. The full list of plans and materials consulted (i.e., the plans, SEA reports and studies, MSFD reports, other studies and strategic documents) can be found in Table 1 of the Supplementary Materials. This pool of documents is not intended to be exhaustive in describing MSP in European sea basins, but is considered representative in terms of numerosity, geographical distribution and spatial coverage of the ongoing situation and main trends in place (see map in Fig. 1). It is important to note that MSP is not the only piece of policy currently dealing with underwater noise. Other management tools, such as SEA, MSFD, Regional Sea Conventions (RSC) and International Maritime Organisation (IMO) Guidances, are often referenced in relation to noise and incorporated in the plans. The present review has a specific MSP focus, while taking into account all additional policies which are highly relevant to underwater noise in MSP.

3.2. Step 2: Structured review

The collected materials were analysed in step 2 according to 12 key questions, covering all main phases of a typical MSP plan (Fig. 1): i) assessment, analysis and interpretation, ii) planning and iii) implementation, monitoring and adaptation. Key questions for the assessment phase intend to investigate if and how underwater noise was considered, whether qualitatively or quantitatively and in a spatially explicit form; e.g., through the description of main sources and biological targets, the evaluation or estimation of pressures and risks, whether as a single pressure or as part of a Cumulative Effects (or Impacts) Analysis (CEA). Key questions for the planning phase address issues like planning goals and objectives, scenarios and measures in relation to underwater noise. A specific question also investigates whether stakeholders involved in the MSP consultation process were aware of the importance of underwater noise and its linkages to MSP, as well as inquiring whether feedback from stakeholders influenced the final plan in this sense. Finally, key questions for the implementation, monitoring and evaluation phase target the issue of observing systems and noise-related indicators to monitor the plan and guide adaptation. Particular attention was given to any provisions or mechanisms aimed at connecting MSP implementation to other policy streams (e.g., Regional Sea Conventions, IMO, MSFD and other directives) based on the understanding that MSP alone cannot suffice in effectively regulating underwater noise sources and risks.

3.3. Step 3: Interviews

The compiled review was consolidated, integrated and validated in step 3 through a series of interviews with MSP Competent Authorities or experts directly involved in the preparation of MSP plans in the countries inventoried in step 1. The interviewed parties were directly involved in the preparation of the analysed MSP plans or Marine Strategies and, where available, underwater noise experts were present. One interview per case study (where England and Scotland are considered separately, as they have distinct MSP plans) was conducted remotely. The interviews consisted in going over the analysis built in step 2 with the purpose of obtaining confirmation, denial or further details on the topics shown in Fig. 1 (step 2) from the relevant experts. In the one case where a live interview was not an option, information was exchanged through email and document sharing. Background materials (i.e., framework and objectives of the study, applied methodology, interview questions, results of the review and analysis) were shared in advance with the interviewed experts, who were also asked to confirm the interviews' outcomes. Interviews proved very effective in: i) properly and fully understanding published plans and reports; ii) identifying additional material to examine; iii) sharing evaluations based on expert judgement; iv) bringing attention to any ongoing activities at country level to improve the plans while taking into account underwater noise sources, levels and targets in a more robust and quantitative way.

3.4. Step 4: Formulation of results

The formulation of results from this analysis (step 4) followed an iteration of step 2, where needed. Results are expressed in qualitative form. A parametric qualitative score from 1 "poor" to 5 "very good" is assigned to each key question based on the authors' understanding of how accurately or in depth each topic is addressed in the relevant plan and supporting materials. The criteria adopted for assigning the score are equally applied to all countries, allowing to produce a heatmap and radar plot (Fig. 2) for a comparative analysis among different countries and their approaches. A binary (yes/no) method was chosen to gain insight on key questions 2–4 and thus produce the bar plots in Fig. 3. The figure shows the number of countries mentioning each underwater noise source, targeted species and negative impact on marine animals. Sources, species and impacts had to be mentioned explicitly and in relation to underwater noise in the plans or related materials to obtain a 'yes'. Finally, planning approaches with regard to underwater noise are represented in Fig. 4. The authors were able to identify three general planning approaches by integrating the information on planning objectives and measures gathered from steps 1 trough 3. The approaches range from a list of recommendations for the reduction or mitigation of negative impacts due to underwater noise ("recommendations"), to cases where extensive guidelines are given on how to perform EIAs and apply for licensing for noise-producing activities at sea ("licensing"), to a more spatial approach where underwater noise influences the allocation of human uses to marine areas ("zoning").

4. Results

An overview of the current situation in terms of the inclusion of underwater noise in Maritime Spatial Planning, to the best of the authors' knowledge, is presented in this section. The MSP process consists of three macro phases: i) assessment, analysis and interpretation, ii) planning, iii) implementation, monitoring and adaptation. Results are presented for each one of these phases and all key questions are addressed in order in the corresponding subsections.

4.1. Assessment, analysis and interpretation

The initial phase of MSP, after preparation, consists in analysing environmental status and pressures and their impacts, to set a foundation for planning. This means identifying the human activities generating the most significant pressures (including underwater noise) and assessing, where present, their environmental and socioeconomic

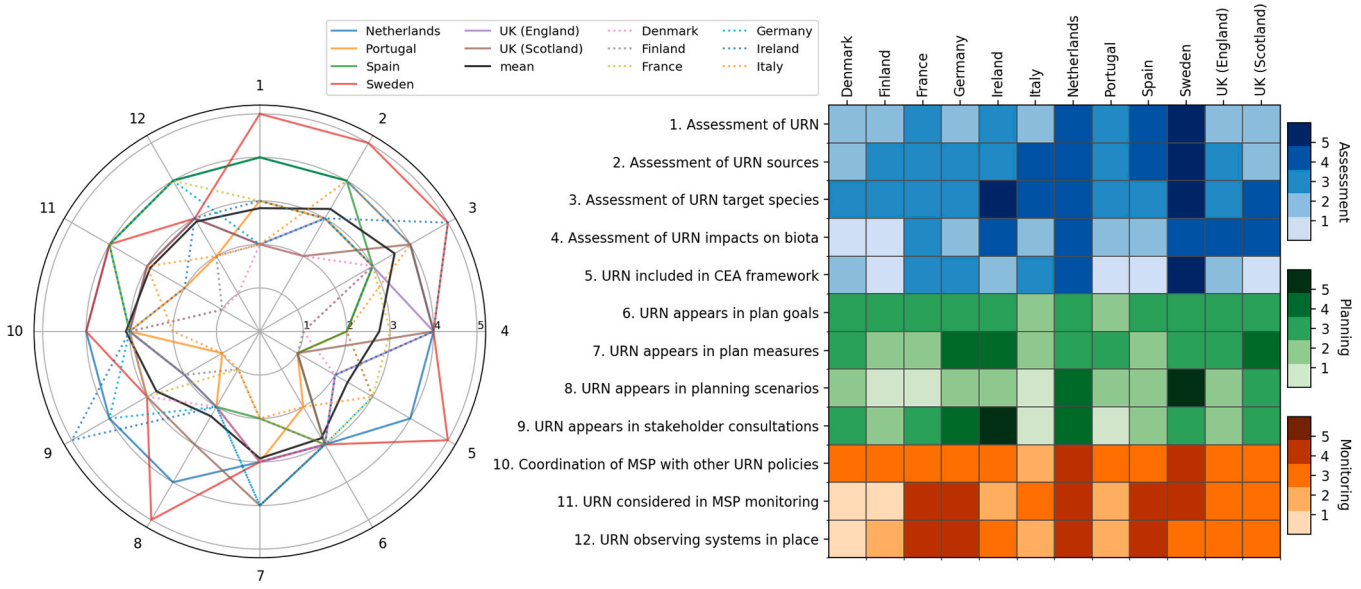


Fig. 2. A qualitative score is assigned to each key question for all countries. Questions correspond to those seen in Fig. 1. Scoring goes from "poor" (1) to "very good" (5). Results are visualised in radar and matrix form.

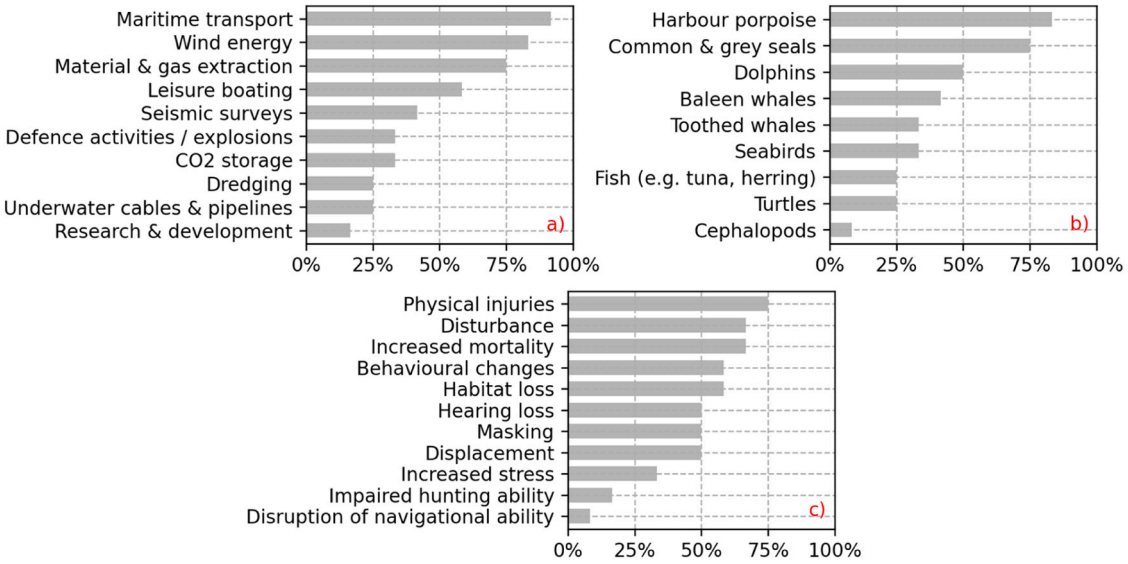


Fig. 3. Semi-quantitative representation of the main a) sources, b) target species and c) impacts on biota of underwater noise in the analysed plans. The percentage refers to the number of case studies in the sample which explicitly mentioned each item as a significant source, species or potential impact of underwater noise in their plans or related materials.

impacts. This analysis can be quantitative or qualitative, and may include geospatial evidence. The first key question in Fig. 2 seeks to diagnose this aspect i.e., the type of assessment that underwater noise receives in MSP and its extent. No country received the lowest score for this question, demonstrating that underwater noise is acknowledged as a significant pressure in all cases. However, half of the sampled countries presented either a general description or a simple qualitative assessment of underwater noise, denoted by a score of 2 (light blue).

4.1.1. Sources

Underwater noise sources are generally identified and described in the SEA, at times followed by maps of their distribution (Fig. 2, Question 2). Detailed analysis of single sources is reported in Fig. 3a. The general consensus among the considered plans sees marine traffic (11 out 12 cases, ~92 %) and offshore wind farms (10 cases, 83 %) as the main sources of underwater noise, for continuous and impulsive noise respectively. Other human uses mentioned in relation to noise are, in order: material or gas extraction (75 %), recreational boating (58 %), underwater explosions from military activities and CO_2 storage (33 %), dredging (25 %), construction of underwater cables and pipelines (25 %), and, finally, research and development (17 %).

4.1.2. Impacts on affected species

Regarding the assessment of species vulnerability to underwater noise (Fig. 2, Q3), 7 cases receive a score of 3, 3 receive a score of 4 and only 2 obtain the highest score. Ireland, in particular, provides maps of distribution of common dolphin, bottlenose dolphin, grey and harbour seal, leatherback turtle and seabirds in the plan and online geoportal. The maps are continually updated, setting out the best available knowledge in relation to the distribution of highly mobile and migratory species to support MSP in managing, among other things, underwater noise. All countries provide a list of marine species that are most affected

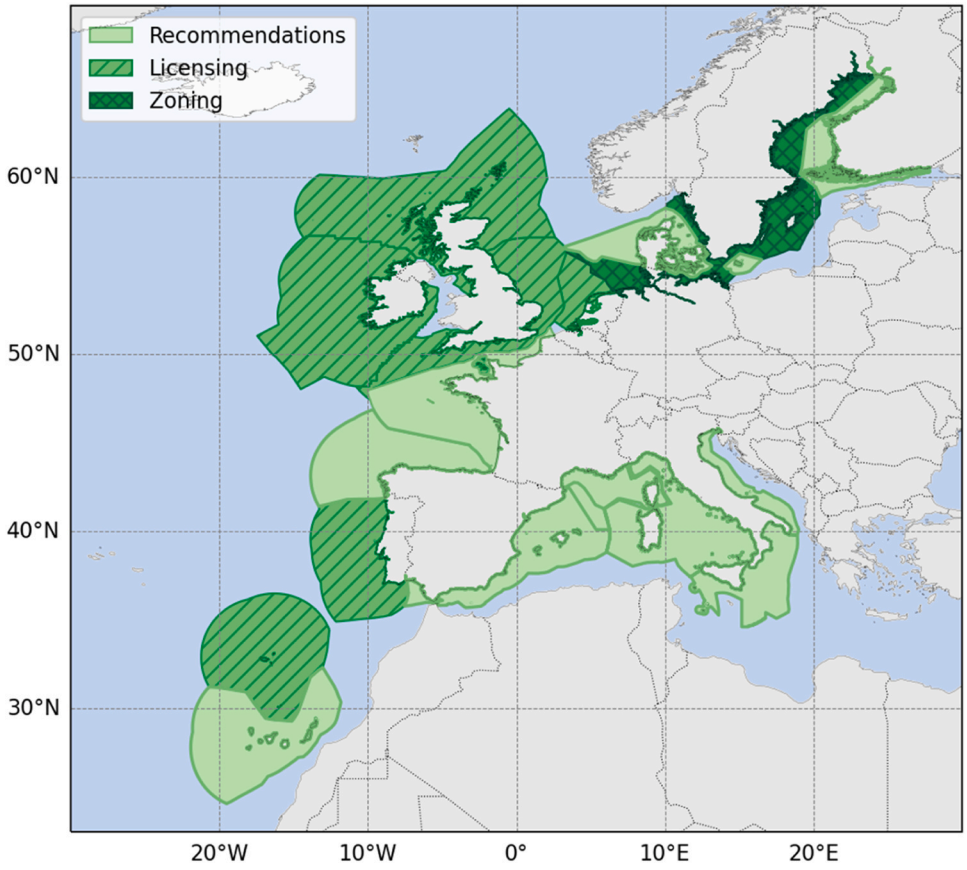


Fig. 4. Planning approaches adopted in relation to underwater noise. Polygons represent the planning domains of MSP plans considered in this study. The green shading refers to the chosen approach, from a list of recommendations (lighter shading), to particular attention being given to underwater noise in the guidelines on how to perform EIAs and apply for licensing (medium shading), to a more spatial approach where underwater noise influences the allocation of human uses to marine areas (darkest shading). The planning approaches are to be understood as overlapping layers, i.e., countries shown here to have adopted a "zoning" approach may also provide recommendations, but not vice versa. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by underwater noise. Marine mammals appear at the top of this list (see Fig. 3b), with harbour porpoise (10/12 cases, 83 %) and seals (75 %) receiving the most mentions in the analysed documents. A variety of cetacean species follow, from common dolphins, coming up in half of the analysed examples, to baleen whales and other toothed whales showing up at 42 % and 33 %, respectively. Awareness is growing around potential negative effects on other taxa, too, such as sea seabirds (33 %), fish (e.g., herring and tuna) (25 %), and cephalopods (only mentioned in one case).

The negative impacts of anthropogenic sound on marine biota are widely acknowledged in the plans and SEAs, with varying levels of insight (Fig. 2, Q4). Countries in this sample are particularly concerned with, in order: physical injuries like hearing loss (75 %), disturbance and increased mortality (67 %), behavioural changes and habitat loss (58 %), masking of communication, displacement and increased stress (50 %) (Fig. 3c). Only in one case underwater noise is said to also cause disruption of navigational ability and difficulties finding reproductive partners in marine mammals.

4.1.3. Cumulative impacts

The least performing question within the assessment section is the one regarding Cumulative Effects Assessments (Fig. 2, Q5). Despite cumulative effects, and the contribution of underwater noise to them, being recognised as a key issue, only in one case a quantitative and structured CEA in support of the maritime plan is found, covering the entire MSP area and including a variety of pressures and environmental components. Sweden's CEA tool, Symphony [52], combines maps of underwater noise from different sources with maps of distribution of sensitive species, such as harbour porpoise and seals (see L. Hammar et al., 2018, "Symphony - Integrerat planeringsstöd för statlig havsplanering utifrån en ekosystemansats", pp. 24–31). According to the MSP representatives interviewed in the course of this project, similar methodologies are currently being developed and tested in a few of the other cases, often focusing on a specific sector or human activity as a starting point, with the aim of including them in the next cycle of MSP. In the Netherlands, for instance, underwater noise is considered in a Cumulative Impacts Assessment in relation to offshore wind developments and marine mammals (see F. Heinis et al., 2022, "Framework for Assessing Ecological and Cumulative Effects 2021 (KEC 4.0) – marine mammals").

4.2. Planning

4.2.1. Planning objectives

The general awareness around the pressing issue of underwater noise in the assessment phase of MSP translates into the definition of strategic goals and planning measures aiming to tackle this issue. High-level MSP objectives regarding protection of marine biodiversity or conservation of marine mammals, existing in all plans considered, implicitly pertain to noise (Fig. 2, Q6). European countries make a direct connection with Descriptor 11 of the Marine Strategy Framework Directive, requiring that the introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment. MSFD objectives, indicators and criteria for the achievement of GES under D11 are then directly incorporated within national marine strategies. Threshold values for continuous and impulsive underwater sound for the achievement of GES under Descriptor 11 have very recently been made public by MSFD TG-Noise with the conservation objective of 80 % of the target species habitats [53,54]. At the time this study was conducted, such thresholds were not yet available, making it difficult to find quantitative targets for underwater noise in the current cycles of MSP. However, examples of noise-specific MSP objectives exist and, in this context, impulsive noise is often better represented than continuous noise. For instance, Sweden proposes a strategic goal on human

activities "not causing harmful impulsive noise in marine mammal distribution areas during periods when the animals are susceptible to disturbance", but there is no equivalent objective for continuous noise (see Swedish Agency for Marine and Water Management, 2019, "Miljökonsekvensbeskrivning av havsplaner för Bottniska viken, Östersjön och Västerhavet", p. 297). The Spanish maritime spatial plan, on the other hand, introduces an MSP goal for shipping routes not to compromise the connectivity of ecosystems, especially corridors used by migratory species which may be affected by masking of communication, and urges to reduce harmful emissions from ship propulsion, including radiated noise (see MITECO 2023, "Resumen Ejecutivo - Planes De Ordenación Del Espacio Marítimo", p. 18).

4.2.2. Planning measures

In terms of planning measures (Fig. 2, Q7), all plans abide by the precautionary principle, and the current situation can be summarised via the adoption of one or more out of three general approaches, depicted in Fig. 4. The most lenient consists in a series of recommendations for the reduction, mitigation or avoidance of activities that cause noise emissions. This approach to underwater noise management is followed by all sampled countries, whether they provide their own instructions or refer to existing guidelines for e.g., marine mammal protection or noise management (OSPAR, ACCOBAMS). An additional layer of attention is given to underwater noise in 5 cases, including Ireland and UK (Scotland), where detailed instructions are given on how to execute an Environmental Impact Assessment (EIA) while applying for a licence to conduct noise-producing activities. The Irish Department of Arts, Heritage and the Gaeltacht provides exhaustive guidelines on the management of risk to marine mammals from man-made sound sources in Irish waters. Similar guidelines are found in Scotland, including an in-depth report addressed to marine developers on how to perform a risk assessment and obtain permission to conduct activities with potential negative impacts due to noise (Marine Scotland's "The protection of Marine European Protected Species from injury and disturbance - Guidance for Scottish Inshore Waters"). The licensing process applies to many activities emitting impulsive noise, but not to maritime transport, whether commercial or recreational, which is regulated by other bodies (IMO, MMO), leaving out a significant portion of the existing soundscape. Finally, the strictest approach, which is found in only two of the considered cases (Sweden and Germany), is the one titled "zoning" in Fig. 4. Such a spatial approach implies that the knowledge around underwater noise and its adverse impacts on the marine environment played a part in the allocation of uses to areas. In Sweden, for instance, attention towards negative impacts from noise was given when allocating areas with particular attention to nature values, denoted by "n" in the Swedish marine plan (Swedish Agency for Marine and Water Management, 2019, "Miljökonsekvensbeskrivning av havsplaner för Bottniska viken, Östersjön och Västerhavet", p. 29). No noise-specific measures are however implemented in these areas at this stage. Spatial planning provisions specifically related to underwater noise are found only in the German plan, which designates a temporary reservation area for harbour porpoises during reproductive periods (May-August), as a result of the noise abatement concept developed in 2013 by BMU (see Bundesanzeiger Verlag 2021, "Annex to the Spatial Planning Ordinance for the German exclusive economic zone in the North Sea and in the Baltic Sea", p. 35). As a consequence, a significant disturbance resulting from construction-related underwater noise can be avoided if the sound event level (SEL) of 160 dB or the peak sound pressure level (SPL) of 190 dB is not exceeded at a distance of 750 m from the emission point and sufficient evasion areas are available in the German North Sea.

4.2.3. Plan alternatives and scenarios

Underwater noise and its sources play a part in the comparison of SEA alternatives (i.e., looking at a business-as-usual alternative, a "proposed plan" alternative and a vision for the future, as required by the SEA Directive - 2001/42/EC) in four of the sampled cases (Fig. 2, Q10). It is less common for underwater noise to emerge as a key pressure in the testing and comparison of MSP scenarios i.e., hypothetical futures defined by changing trends in uses of the sea and their potential impacts, often adopted to inform spatial planning [55]. This occurs in Sweden, where underwater noise played a crucial part in the formulation of scenarios about the shifting of shipping lanes, and in the Netherlands, where a scenario analysis is carried out around wind farm developments (see F. Heinis et al., 2022, "Framework for Assessing Ecological and Cumulative Effects 2021 (KEC 4.0) – marine mammals").

4.2.4. Stakeholder consultations

Mentions of underwater noise were present in stakeholder consultations of all countries, where available and with varying levels of detail (Fig. 2, Q9). NGOs were particularly vocal about the importance of taking into account impacts of underwater noise on organisms other than marine mammals, as research and knowledge grow in that direction. Among other things, stakeholders expressed dissatisfaction with MSFD Descriptor 11 as not sufficient in describing the impact of noise on marine fauna. Another aspect deemed problematic during consultations was the lack of consideration for noise as a contributor to cumulative impacts on biota. Overall, stakeholder awareness around the issue is strong, as well as the understanding that more research is needed to better interpret impacts on a variety of marine species at population level and to define quantitative thresholds for their protection.

4.3. Implementation, monitoring and adaptation

4.3.1. Coordination with existing policy

Maritime spatial plans are expected to coordinate or refer to other policies [26] to effectively manage underwater noise (Fig. 2, Q10). European plans are either the direct implementation of MSFD and MSPD simultaneously, or see MSP as a tool for the achievement of MSFD goals for Good Environmental Status. MSP must comply with existing policy and regulations, starting from the United Nations Convention on the Law of the Sea (UNCLOS). It also often contributes to implement, as seen above, Regional Sea Conventions (RSC), such as OSPAR, HELCOM, or the Barcelona Convention and in this perspective MSP plans often directly refer to RSCs (e.g., as Decisions, Protocols, Guidelines), also with regard to underwater noise. Surprisingly, IMO guidelines and provisions are poorly mentioned in MSP plans, even though it is arguably evident how IMO rules are important in regulating underwater noise for the maritime transport sector.

4.3.2. Monitoring and observing systems

Monitoring in relation to underwater noise occurs in two different contexts (Fig. 2, Q11): i) continuous and long-term collection of underwater noise data, stored in national or transnational sound registries, and ii) recurring inspection of effects of existing noise-related planning measures to assess their effectivity and correspondingly adapt the maritime spatial plan. The MSFD requires monitoring programmes for impulsive and continuous noise, with the use of both environmental and socioeconomic indicators. Indeed, these types of monitoring programmes are adopted by around half of the sampled countries. The United Kingdom follows MSFD and SEA requirements in a similar fashion, taking EU regulations as the basis for MSP.

A common requirement for noise-producing activities is to collect data and contribute to sound registries, which exist both at a national (e.g., National Noise Registry at BSH, Germany; UK Marine Noise Registry, held by JNCC) and international level (e.g., Regional Noise Register of the North and Baltic Sea (ICES), which assembles data supplied by OSPAR and HELCOM contracting parties). MSP takes advantage of existing activities that are collecting data on underwater noise sources (e.g., AIS and VMS among the most common), including data collected for MSFD monitoring, which then feeds into MSP for implementation and adaptation (Fig. 2, Q12).

5. Discussion

Most European countries have only recently adopted their first cycle of maritime spatial plans following the implementation of Directive 2014/89/EU, making Europe an area in the world where MSP is highly developed, at least in terms of completed plans [34,56,57]. Still, the relative novelty of MSP in Europe results in an insufficient and ineffective consideration of underwater noise, as is the case for other somehow novel anthropogenic pressures, such as marine litter. While underwater noise emerges as a key issue within the plans and marine strategies of all countries sampled, quantitative or in-depth assessments of underwater noise are rare (see blue section in Fig. 2). This may be due to the lack of internationally agreed upon threshold values for the definition of GES for noise emissions at the time of plan-making, as well as significant knowledge gaps around soundscapes and their variability in time, but also regarding noise-related impacts on biota at population level. Science-based, spatially explicit and quantitative assessments of the existing soundscape are lacking, making it difficult to define the problem in terms of its magnitude and spatial distribution. The MSFD plays a significant role in bringing attention to the issue by including noise among its 11 descriptors, but the need for numerical evidence and tools [58–60] able to contextualise noise data and transpose it into a solid basis for policy-making within MSP remains strong. Despite a growing awareness of its potential and site-specific importance, quite clearly expressed in the plans, underwater noise is not always thoroughly addressed in terms of specific objectives and plan provisions. With that in mind, it is of utmost importance to: i) assess the risks for biological targets [61–63] and quantify the effects of noise exposure on biota at individual, population and ecosystem level, and ii) estimate the effectiveness, costs and applicability of mitigation measures (e.g., spatial, behavioural, technological measures) [26,64–68] through scenario building, scenario analysis and comparison [69]. MSP, together with other relevant policies, is the way to implement a vision on the future sustainable use of marine spaces and resources while reducing risks to the environment, including those related to underwater noise [70]. Underwater noise management is a typical transboundary challenge: the most targeted species are highly mobile (e.g., cetaceans or sea turtles) while some of the major pressures are related to human activities of transboundary dimension (maritime transport in particular). This makes the transboundary dimension of MSP essential, through a substantial and coherent coordination of national MSP plans. Common approaches for assessing the risk for biological targets and defining mitigation measures should therefore be sought and agreed across national boundaries to effectively reduce the underwater noise risk for the environment and the specific underwater noise targets [71].

The variety of sectors and human activities producing underwater noise, as well as its inherently unbounded nature, are additional factors making it a complex technical issue which requires specific methodologies to produce accurate estimates of its distribution and the risks associated with it. These methodologies are variable depending on the desired outcome and on the context (e.g., species, populations, age, sex of the targeted animal) [72]. Moreover, different approaches require different metrics, meaning that there is no universal solution to the problem of underwater noise management and it is difficult to reach international agreement on standard indicators (e.g., SPL, SEL), thresholds and targets. As a result, MSP provisions on underwater noise and underwater noise sources are in most cases based on qualitative or partial assessments and planning objectives are often generic or ambiguous, especially for continuous noise. This is expected to change for the better with the recent release in November 2022 of MSFD TG Noise guidelines on threshold values [53,54] and with the upcoming MSP planning cycles.

If the three planning approaches described in Fig. 4 are interpreted as three subsequent steps of the same process towards stricter and more space-based planning around underwater noise, the medium-low scorings in the green section in Fig. 2 are justified. It is rare, currently, to find legally binding planning measures regarding underwater noise and only the German MSP plan proposes spatial measures in the form of a reservation area for harbour porpoises. The preferred approach, adopted by the majority of countries, especially in the Mediterranean, is to propose a list of voluntary-based recommendations for mitigation, reduction or avoidance of noise-producing activities. This modus operandi can only go so far, as it leaves considerable decision-making in the hands of developers who depend on these marine activities for their livelihood or income.

Another reason for relatively poor management of anthropogenic sound in the marine environment is the difficulty in identifying and harmonising interactions among existing policies and their respective implementation processes. MSP is one piece of policy dealing with underwater noise, but connections with other policies [73] and their governance mechanisms (e.g., IMO, RSCs, MSFD, Offshore Renewable Strategy) need to be reinforced. Equally, localised research efforts exist and the present review demonstrates the growing tendency towards fully incorporating underwater noise within all phases of MSP, as well as the intention of most MSP Competent Authorities to improve noise-related contents and measures in upcoming plans. However, these efforts are at this stage not well coordinated. Capitalising on the results of past and on-going projects (e.g., SATURN, PIAQUO, JONAS, SOUNDSCAPE, quietMED, BIAS, JOMOPANS, MSP-MED) and research activities within the maritime plans will be an essential step toward a better integration of noise in MSP.

Results of the present study underline the need for a dedicated guidance for noise-proof MSP. The guidance would have to cover all aspects from soundscape and sound sources assessment to risk assessment to identification and analysis of mitigation measures, in a full MSP framework. This means tackling multiple sustainable blue economy and environmental objectives, multiple uses demands and related conflicts and coexistence possibilities as well as integrating all existing pieces of policy, acknowledging and balancing stakeholder views and needs and considering medium to long-term perspectives (e.g., climate change effects and time trends of coastal and sea uses). These aspects have to be approached along all MSP procedural steps, from pre-planning to monitoring and adaptation. The inclusion of noise experts in the pre-planning phase, when defining and establishing planning teams should be carefully considered, to be advised on how to best address the topic, from assessment to risk mitigation. MSP also provides the framework for improving connections between planners and noise experts (from maritime engineers working on the reduction of emissions to experts in marine ecology and bioacoustics). Marine planners can adapt and improve their plans by ensuring that underwater noise and its sources are included in the MSP process. Equally, the underwater noise community (e.g., scientists, engineers, consultants, operators, authorities) can take advantage of MSP to e.g., reach MSFD targets and thus reduce underwater noise and its undeniable impacts on marine biota.

6. Conclusion

Managing sources of anthropogenic underwater noise to mitigate negative impacts on the marine environment without hindering the human activities involved embodies an all-around MSP challenge. With these goals, planning has to take into account the transboundary and multisectoral nature of noise emissions, as well as their contribution to cumulative or cascading effects. European countries have begun to include underwater noise in their MSP plans, particularly following its introduction within the MSFD as Descriptor 11. Nevertheless, this is not always done systematically and in all phases of MSP. Due to a significant lack of quantitative and spatially explicit evidence backing up decision-making, a voluntary-based recommendations approach is often preferred to legally-binding spatial measures. Moreover, the connection with other existing regulations regarding noise needs to be clarified and reinforced, acknowledging that MSP is only one piece of policy dealing with URN, both at the regional and international level. The present

study highlights the need for specific guidelines geared towards making "noise-proof" maritime spatial planning more accessible. The guidelines would serve as a point of convergence among the many facets characterising underwater noise as an MSP challenge and form a common baseline for international cooperation. Finally, a greater involvement of underwater noise experts from the very first steps of the MSP process would ensure the issue is granted the level of priority it requires, given existing knowledge on its negative impacts.

The analysis of documents and interviews carried out for the purpose of this study shows a growing tendency towards underwater noise being thoroughly incorporated within MSP in Europe, in accordance with the high demand that emerged in this sense from stakeholder consultations during planning. Capitalising and expanding on existing projects currently investigating underwater noise at a local or sectoral level, as well as implementing the newly available threshold values released by MSFD TG Noise, represent promising steps in this direction for the upcoming cycles of MSP.

CRediT authorship contribution statement

Sofia Bosi: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Emiliano Ramieri:** Resources, Writing – original draft, Writing – review & editing. **Marta Picciulin:** Resources, Writing – original draft, Writing – review & editing. **Stefano Menegon:** Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Michol Ghezzo:** Writing – original draft, Writing – review & editing. **Antonio Petrizzo:** Writing – review & editing. **Thomas Folegot:** Writing – review & editing. **Fantina Madricardo:** Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. **Andrea Barbanti:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition.

Conflict of interest declaration

No conflict of interest to declare.

Data Availability

The authors do not have permission to share data.

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Appendix A. Supporting information

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