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Human activities and resultant pressures on key European marine habitats: an analysis of mapped resources

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Abstract

Human activities exert a wide range of pressures on marine ecosystems, often resulting in the loss of species and degradation of habitats. If effective policies and management practices to restore past damage and reduce future impacts to the marine environment are to be developed, knowledge of the extent, duration and severity of activities and pressures is essential, yet often lacking. As part of the EU H2020 project "Marine Ecosystem Restoration in Changing European Seas", this study uses an exhaustive review of published records, web resources, and grey literature to comprehensively assess the degree to which human activities and pressures are mapped within European seas. The results highlight a number of limitations and gaps, including: (a) limited geographic coverage at both the regional and sub-regional level; (b) insufficient spatial resolution and accuracy in recorded data for the planning of conservation and restoration actions; (c) a lack of access to the background data and metadata upon which maps are based, thus limiting the potential for synthesis of multiple data sources. Based on the findings, several recommendations for future marine research initiatives arise, most importantly the need for coordinated, geographically extended baseline assessments of the distribution and intensity of human activities and pressures, complying with high-level standardisation regarding methodological approaches and the treatment of produced data.

Keywords: mapping; ecosystem restoration; marine spatial planning; conservation

1. Introduction

Human activities such as fisheries, agriculture, transport, tourism, mining and energy generation exert multiple pressures on the marine environment which contribute to ongoing habitat degradation and loss (e.g. Airoldi & Beck 2007; Korpinen et al. 2013). In turn, such changes reduce the capacity of marine ecosystems to deliver valuable ecosystem services and increase their sensitivity to future impacts such as those associated with climate change (Ramirez-Llodra et al. 2011). In addition, they hamper progress towards global, regional and national efforts to conserve, restore and sustainably use the marine environment, such as UN Sustainable Development Goals, the EU Marine Strategy Framework Directive (MSFD) and Marine Biodiversity Strategy, the Maritime Spatial Planning Directive (MSPD) and the EU Blue Growth agenda (Cavallo et al. 2017).

The degree to which human activities impact the marine environment is a function of: (i) the pressures associated with an activity, e.g. the *activity* of trawling may exert the *pressure* of abrasion on the seabed, (ii) the sensitivity of a specific habitat to the above pressures, and (iii) the intensity and duration of the pressures and the spatial and temporal footprint over which they occur. Spatial maps of activities and their associated pressures are therefore essential to monitor, mitigate and reduce their impact, for example through marine spatial planning (Ansong et al. 2017). Specifically, spatial information can be used to highlight where action is needed to remove or reduce stressors (Stewart et al. 2010); forms the basis of species and habitat vulnerability assessments (Lauria et al. 2017) and aids the design and spatial arrangement of marine protected areas (Gonzalez-Mirelis et al. 2014).

Whilst global assessments of human impacts on marine ecosystems, such as those undertaken by Halpern et al. (2008), outline broad scale patterns, the degree to which they accurately represent the magnitude and spatial distribution of human activities and pressures at regional, national and local levels depends upon the representativeness and accuracy of the underlying data. Within Europe, significant effort has been expended documenting, categorising and mapping human activities and their associated impacts (Coll et al. 2011; Micheli et al. 2013; Korpinen and Andersen 2016), for example, through the MSFD (EC 2008; Loizidou et al. 2017) and outputs from multiple EU projects and academic research. Despite significant progress, data gaps persist, along with a poor understanding of the temporal and spatial dimensions of activities and pressures (Costello et al. 2010; Korpinen et al. 2012; Korpinen & Andersen 2016). Nevertheless, whilst such limitations and biases are known to exist, the extent of these gaps and the degree to which they are spatially or temporally biased remains unclear. With this in mind, the aim of this paper is to produce, for the first time, an inventory of available spatial information relating to human activities and pressures within European regional seas in order to identify limitations and gaps in knowledge and drive future research efforts and data collection where it is most needed.

2. Methodology

2.1. Activities and pressures of interest

Activities and pressures were defined as follows: *activity* - a human action or endeavour that has the potential to create pressures on the marine environment, e.g. aquaculture or tourism (Scharin et al. 2016); *pressure* - the mechanism through which an activity has an actual (or potential) impact on the ecosystem (Robinson et al. 2008). Following Elliott (2011) pressures are divided into two types: *endogenous*, i.e. those emanating from within the system and both their causes and consequences can be managed (e.g. abrasion on the seabed caused by trawling activities) and *exogenous*, i.e. those emanating from outside the system and only their consequences can be managed locally (e.g. a change in seabed morphology from tectonic events).

In total thirteen activities, as well as twenty-six endogenous and seven exogenous pressures were considered (Table 1), based on those defined in the MSFD and Smith et al. (2016); definitions and examples for those are provided in Table S1-Supplemetary Material.

Table 1. List of activities and pressures (endogenous and exogenous) acting on marine habitats considered in the present study; definitions in Smith et al. (2016).

Activities	Pressures (endogenous)	Pressures (exogenous)
Agriculture	Abrasion	Change in wave exposure
Carbon sequestration	Aesthetic pollution	Emergence regime change
Coastal and marine infrastructure	Barrier to species movement	Geomorphological changes
Defense and security	Change in wave exposure (local)	pH changes
Extraction of living resources	Changes in siltation and light regime	Salinity regime change
Extraction of non-living resources	Collision	Thermal regime change
Land-based industry	Electromagnetic changes	Water flow rate changes
Non-renewable energy generation	Emergence regime change (local)	
Production of living resources	Input of organic matter	
Renewable energy generation	Introduction of microbial pathogens	
Research and conservation	Introduction of non-synthetic compounds	
Tourism/recreation	Introduction of other substances	
Transport	Introduction of radionuclides	
	Introduction of synthetic compounds	
	Introduction/translocations of non-indigenous species	
	Litter	
	Nitrogen and phosphorus enrichment	
	Noise	
	pH changes (local)	
	Salinity regime change	
	Selective extraction of non-living resources	
	Selective extraction of species	
	Smothering	
	Substratum loss	
	Thermal regime change	
	Water flow rate changes (local)	

2.2. Sourcing and inventorying information

A systematic search of resources was conducted to identify spatial information relating to activities and pressures within European regional seas (see below for a full list and relevant definitions). A standard web search was performed, supplemented with queries in two research databases (ISI Web of Science and Scopus) in order to ensure full coverage of the published evidence. Searches were targeted using keywords and keyword combinations relating to mapping of the activities and pressures considered within the area of interest (a full list of keywords used is provided in Table S2-Supplemetary Material). The first 100 results of each search, ranked by relevance, were examined for extraction of relevant information. Specific web resources of international organizations, commissions and agencies active on marine conservation (EEA, IUCN, UNEP-MAP-RAC/SPA, HELCOM, OSPAR, FAO, OCEANA, MarLIN) and European projects registered in the European Marine Spatial Planning platform (e.g. MEDTRENDS, CoCoNet, MESMA, PERSEUS, ADRIPLAN, THAL-CHOR, BALANCE) were also queried for all available material (including downloadable reports). The results of the above search were complemented by input from the MERCES consortium experts who were asked to use their expertise and regional knowledge to fill data gaps where possible. Searches extend to all records available as of the end of 2016.

For each resource identified, the following information was collected and inventoried:

1. Presence of the specific activities and pressures considered (see above for categorization).

2. The region and sub-region of spatial coverage; this includes:

   - The MSFD region of the study: Baltic Sea; North-East Atlantic; Mediterranean Sea; Black Sea or Other (such as Norwegian waters, or seafloor banks in the international waters of North-East Atlantic).
   - The sub-region: North-East Atlantic (Greater North Sea, including the Kattegat, and the English Channel; Celtic Seas; Bay of Biscay and the Iberian Coast), Macaronesian biogeographic region (Azores; Madeira and Canary Islands), the Mediterranean Sea (Western Mediterranean; Central Mediterranean; Adriatic; Ionian and the Aegean-Levantine Sea).

3. Particular habitat type(s) examined (see below for categorization), if applying; lacking specific indication regarding habitat, the source was characterized as ‘broad-scale’.

4. The following specific features of the data presented in the maps were queried: (a) are they qualitative (i.e. presence/absence) or quantitative? (b) are they based on single or cumulative pressures? (c) are they derived from empirical studies (i.e. surveys, observations) or from modelling? (d) if modelled data, are projections contemporary, hindcast or forecast? (e) if modelled data, is uncertainty considered or not?

5. The type of information provided: map image; map viewer (interactive image on-line); GIS georeferenced file.

6. The source of information: on-line resource/website; scientific paper; report; conference proceedings; expert/unpublished.

2.3. Habitats over which activities and pressures take place

Fifteen habitats or keystone species of high ecological importance, conservation interest and/or those which are known to be particularly sensitive to human activities (e.g. EU Habitat Directive 92/43/EEC, OSPAR List of Threatened and/or Declining Species and Habitats, OSPAR 2008, UNEP/MAP-SPA/RAC 2018 Annex II List of Endangered or threatened species, Ramirez-Llodra et al. 2011; Smith et al. 2014) were considered, as outlined below:

Sublittoral soft-bottom:

- Seagrass beds (*Posidonia*, *Zostera*, other seagrasses)
- Other

Sublittoral hard-bottom:

- Maërl beds
- Coralligenous formations
- Gorgonian forests and sponge beds
- Macroalgal forests/beds (*Cystoseira* or other canopy-forming algae)
- Other

Deep-sea (>200 m depth):

- Coral gardens
- Sponge aggregations
- Mixed coral/sponge aggregations
- Seamounts
- Hydrothermal vents
- Carbonate mounds
- Canyons
- Other

Broad-scale:

- No specific habitat identified

3. Results

In total, 264 records with relevant information were retrieved, of which 194 included maps of activities, 147 included maps of endogenous pressures, and 43 included maps of exogenous pressures. A considerable number (101) reported both activities and endogenous pressures.

3.1. Information by source and format

Nearly half of the records (49%) originated from peer-reviewed journals (Figure 1A); however, a substantial amount of information was derived from grey literature: 27% from project reports, 19% from web resources, 4% from conference proceedings, and 1% from unpublished information (unpublished data/expert opinion). The majority of records contained plain map images (86%); interactive map viewers were limited to 9% and downloadable georeferenced files (e.g. shapefiles) to 5% (Figure 1B).

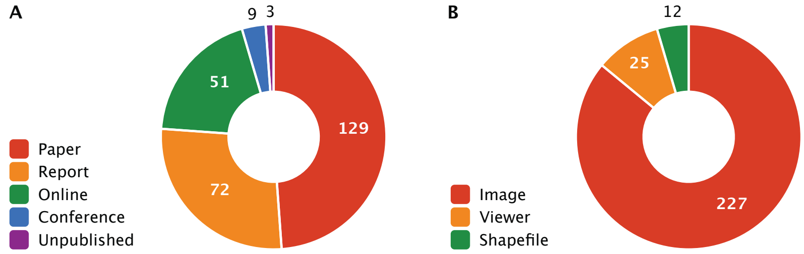

Figure 1. Sources (A) and format (B) of records containing spatial information on anthropogenic activities and/or pressures.

3.2. Information by geographic area

The majority of records were relevant to the Mediterranean Sea (39%) and the North-East Atlantic (27%), with the Baltic and Black Seas represented to a much lesser extent (16% and 14%, respectively) (Figure 2). At the sub-regional level, the North-East Atlantic was represented mostly by records from the Greater North Sea and the Celtic Seas (54% and 31%, respectively); a small portion of records (6%) included maps at the regional scale. Regarding the Mediterranean Sea, all four MSFD sub-regions were represented, and a significant portion of records (27%) included maps at a pan-Mediterranean scale. “Other” regions (i.e. records with a global coverage, those covering the entire European region, sub-regions outside the EU, or regions which are not MSFD-relevant) represented 16% of the records.

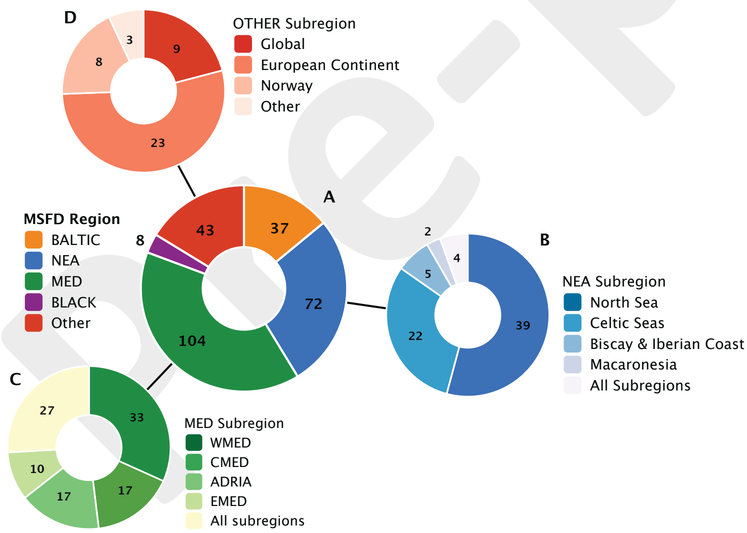

Figure 2. Number of records for European regions and sub-regions. (A) Regional seas (BALTIC: Baltic Sea; BLACK: Black Sea; MED: Mediterranean Sea; NEA: North-East Atlantic; Other: Other regional sea), (B) North-East Atlantic sub-region, (C) Mediterranean Sea sub-regions (WMED: Western Mediterranean; CMED: Central Mediterranean; ADRIA: Adriatic; EMED: Eastern Mediterranean), and (D) Non-MSFD regions.

3.3. Information by habitat

The majority (75%) of the records were characterised as ‘broad scale’, spanning multiple habitats and depth zones without any further details provided (Figure 3). Of the remaining 25%, the majority covered general shallow hard and soft habitats, such as coralligenous reefs (including gorgonian forests), euphotic reefs with macroalgal forests, and seagrass beds. Within the deep-sea category (accounting for 6% of the total records), activities and pressures were most frequently mapped over canyons and coral beds.

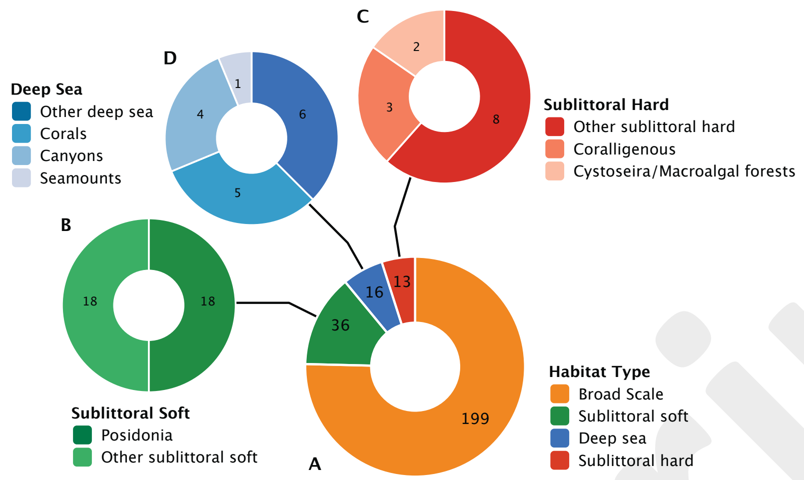

Figure 3. The number of records per habitat type (A), broken down by sublittoral soft (B), sublittoral hard (C) and (D) deep-sea habitats.

The paucity of information relating to specific habitat types was consistent across all geographic sub-regions, although the relative percentages differed (Figure 4). Within the Mediterranean Sea, less than half (45%) of the records referred to specific habitats, with smaller percentages seen in the remaining regions. In the Baltic and Black Seas, only “sublittoral soft bottom” habitats were identified.

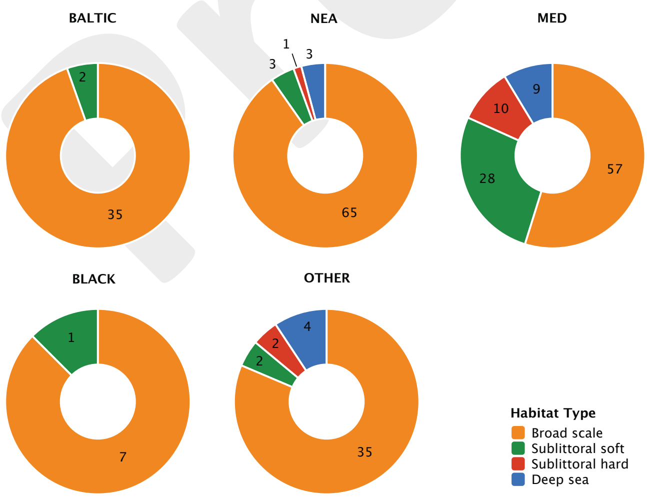

Figure 4. The number of records of habitat types by geographic region (for abbreviations see Figure 2).

3.4. Information by activity

"Extraction of living resources" was found to be the most frequently mapped activity, occurring in 39% of the records (Figure 5). "Coastal and marine structure and Infrastructure", "Transport" and "Production of living resources" were the next most frequent, mapped in 29%, 27%, and 26% of the records, respectively. "Research and conservation" was relatively poorly represented (only 8%), whilst "Carbon sequestration" (i.e. offshore CO_2 storage requiring seabed intervention) and "Agriculture" had the lowest number of records.

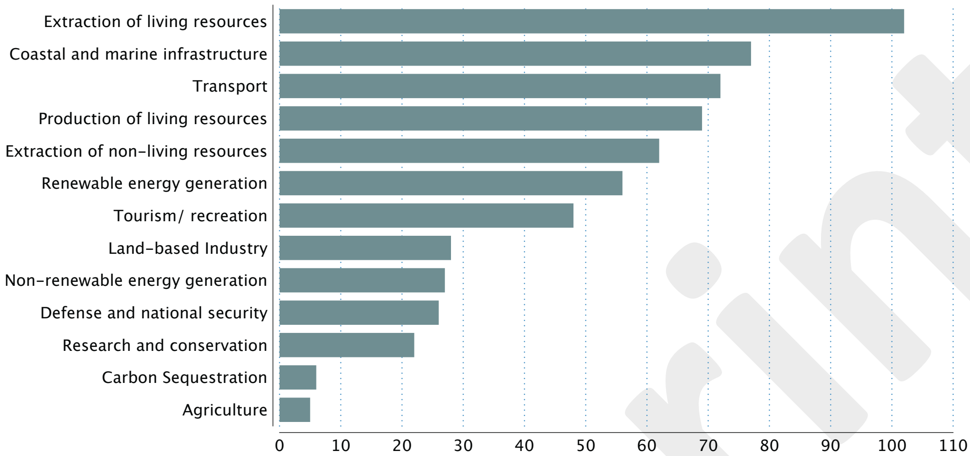

Figure 5. Mapped activities ranked by number of records.

Multiple records of all activities (except for "Agriculture" and "Carbon sequestration") occurred in the North-East Atlantic, Mediterranean and Baltic Seas but their relative importance varied (Figure 6). An abundance of mapped sources for "Production of living resources" (i.e. aquaculture) and "Tourism/recreation" were found in the Mediterranean Sea, reflecting the importance of these sectors in the specific region. Whilst mapping of "Extraction of non-living resources" and "Renewable energy generation" was pronounced in the North-East Atlantic, similar to "Transport" in the Baltic Sea and Norway. Limited records regarding mapped sources of activities were found in the Black Sea.

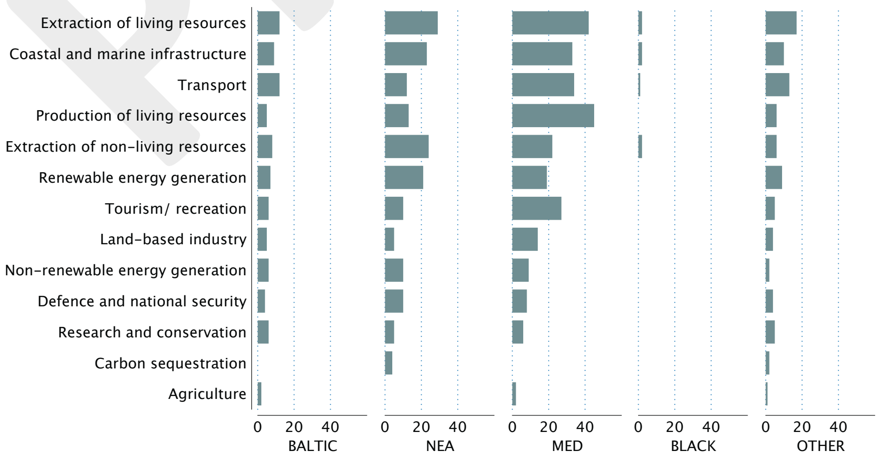

Figure 6. Mapped activities by geographic region (for abbreviations see Figure 2).

3.5. Information by endogenous pressure

Overall, pressures relating to chemical substances and chemical influxes accounted for the highest number of records, with “Nitrogen and phosphorous enrichment”, “Introduction of other substances” and “Input of organic matter” present in 17%, 15%, and 13% of the records, respectively (Figure 7). Of the other endogenous pressures that collectively accounted for more than 20% of the records, “Abrasion”, “Introduction of non-indigenous species” and input of “Litter” were the most frequently noted. There were few records relating to local “Thermal regime changes”, input of “Underwater noise”, “Selective extraction of non-living resources”, and “Barriers to species movement”.

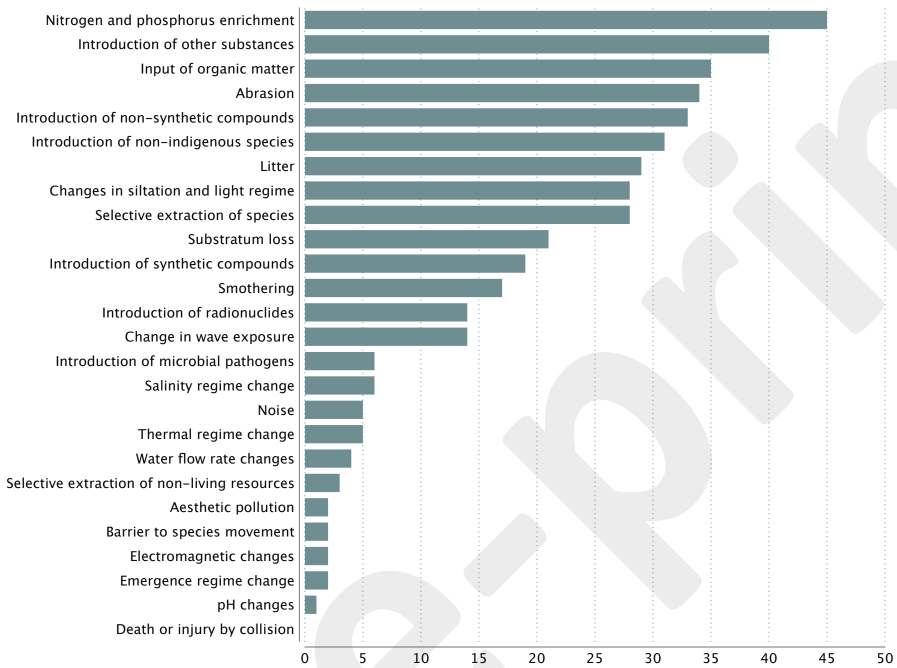

Figure 7. Mapped endogenous pressures ranked by number of records.

The majority of endogenous pressures are recorded in all regions, with relative frequency varying regionally (Figure 8). “Introduction of non-indigenous species” and “Litter” are frequently mapped in the Mediterranean Sea, while local “Change in wave exposure” appears only mapped in this region. Hydrological change and other physical disturbance-related pressures (e.g. “Smothering”, “Abrasion”) are most often mapped in the North-East Atlantic. “Introduction of substances” –such as non-synthetic compounds and radionuclides– is relatively more frequently mapped in the Baltic Sea; however, the latter is the only region with no maps available for marine litter. The Black Sea appears relatively deprived regarding mapped sources of pressures acting on its marine environment.

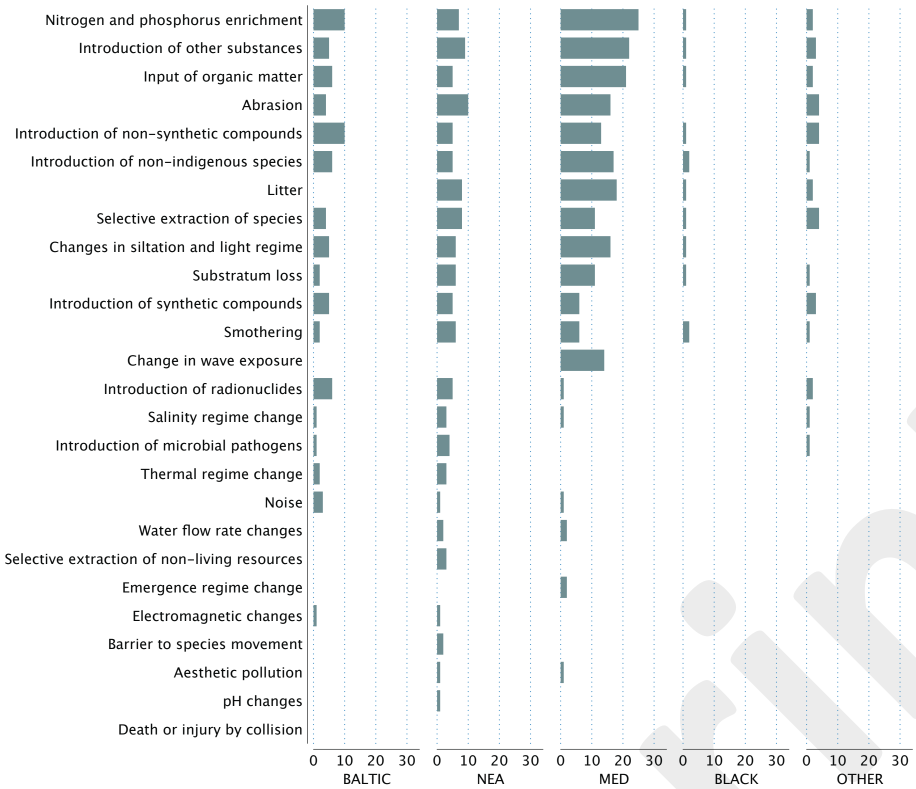

Figure 8. Mapped endogenous pressures by geographic region (for abbreviations see Figure 2).

3.6. Information by exogenous pressure

Overall, "Thermal" and "Emergence" regime changes (wide-area, e.g. climate-induced change) were the most frequent exogenous pressures identified in the records (13% and 9%, respectively), followed by changes in pH (Figure 9). However, in general, there is limited information and regional maps of exogenous pressures with the majority occurring in the Mediterranean and "Other" regions (Figure 10).

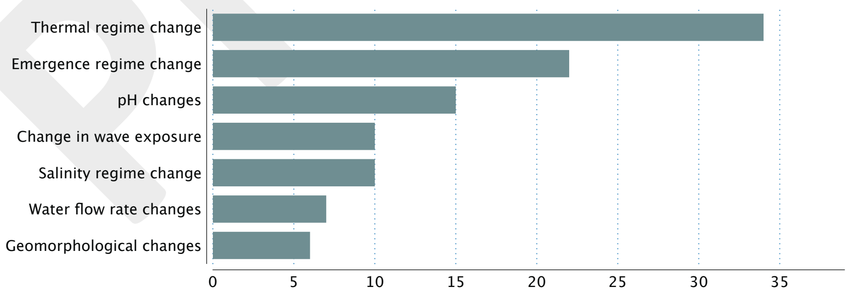

Figure 9. Mapped exogenous pressures ranked by number of records.

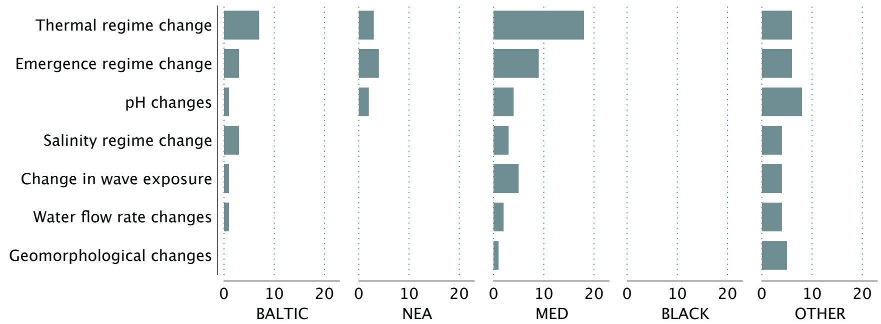

Figure 10. Mapped exogenous pressures by geographic region (for abbreviations see Figure 2).

3.7 Nature of the mapped data

As regards to the nature of the mapped data, 108 entries (41%) map quantitative data (e.g. concentrations of pollutants, values of environmental variables), while 100 (38%) map qualitative data (e.g. location of infrastructures, sightings of disturbances, etc.). The remaining 21% (56 records) map both types of data. However, only 15% of the records map cumulative pressures, while single pressures are more commonly mapped (210 entries, corresponding to 80% of the total records).

Of the 264 catalogued mapped resources, 141 (54%) present exclusively empirical data, i.e. derived from surveys and observations, while 59 (22%) maps are based exclusively on modelled data (i.e. using mathematical algorithms to either filter and interpolate data or make projections to the future or the past). The remaining 64 (24%) records include both kinds of data. Out of 123 entries which include modelled data either alone or in combination with empirical data, the majority (92%) depict the present state of the system, i.e. maps are based on interpolation and manipulation of contemporary data. Only 12 (10%) present forecast projections, and 6 (5%) map projection to the past (hindcast models). The level of uncertainty of modelled data is rarely considered in the catalogued maps, as only 15 (12% of the relevant entries) include probability.

4. Discussion

European seas and coastal areas have a long history of intense development and substantial economic relevance (Randone et al. 2017), with economic assets within 500 metres of their coastline valued from 500 to 1000 billion Euros (EEA 2007). Consequently, European seas are also among the most severely degraded marine systems worldwide (e.g. Coll et al. 2011; Benn et al. 2010; Costello et al. 2010). Recently, an increased political and societal awareness of the status of the marine environment and a recognition of its importance to society have resulted to concerted efforts to transition to a more sustainable and ecologically conscious future (Boyes et al. 2014; 2016). This has resulted in substantial time and funds being spent classifying, documenting and mapping human activities and pressures in European waters (e.g. through the Water Framework Directive along with the MSFD and MSPD, work by the European Environmental Agency, EMODnet, OSPAR and HELCOM and an array of research efforts such as the VECTORS, DEVOTES, PERSEUS, CoCoNet, BENTHIS, ADRIPLAN and Med-IAMER projects). However, due to differences in capacity between regions and institutions, and biases in political and scientific focus, current level of knowledge is fragmented and incomplete.

The comprehensive review and analysis undertaken here highlights limitations and gaps in our current level of understanding, which –if filled– would provide crucial information to support conservation, policy, and economic sectors.

4.1. Coverage of human activities and pressures

The extraction of living resources (i.e. fisheries) is the most frequently documented activity and is generally expressed as the area of fishing activity, the amount of catch, the size of the fishing fleet or fishing effort. Such information, supplemented by new data from Vessel Monitoring Systems (VMS) and Automatic Identification Systems (AIS), make this activity relatively easy to track and quantify (e.g. see Eigaard et al. 2016; Benn et al. 2010; McCauley et al. 2016; Kroodsma et al. 2018). However, accurate catch data are rarely available (Piroddi et al. 2015; 2017), while the coverage is at present incomplete due to the absence of VMS data for certain fleets (e.g. small artisanal fishing boats) and also the sensitive nature of the data, thus preventing effective and transparent assessments of fishing activities and pressures. The production of living resources (i.e. aquaculture), is also relatively well-documented and often mapped at the national level; this information can then be combined to provide a regional overview (e.g. Trujillo et al. 2012). Oil and gas exploitation and exploration is another commonly mapped activity (e.g. Piante & Ody 2015), with information available on the location of pipelines and landing points. Furthermore, since such operations are often planned years into the future, it is also possible to obtain designated locations, helping inform conservation activities and marine spatial planning.

As far as pressures are concerned, many endogenous pressures are commonly represented in maps, such as the introduction of chemicals and compounds (e.g. EEA, 2015), marine litter (e.g. Pham et al., 2014) and abrasion (usually directly linked to trawling patterns and intensity, e.g. Eigaard et al. 2016). However, other pressures appear to be under-represented (e.g. underwater noise or change in wave exposure), or absent (e.g. death of large vertebrates, such as cetaceans, by collision). This may be due to these pressures not being significant in particular study areas, or more likely, not being frequently assessed, or because knowledge gaps hamper assessments (e.g. underwater noise was only recently made a priority for assessment under the MSFD, see Crise et al. 2015).

Compared to endogenous pressures, the location and intensity of exogenous pressures are very poorly documented. Whilst warming trends, sea-level rise and acidification are mapped, albeit to a lesser extent, other pressures such as changes in salinity and water flow are somewhat neglected, despite the significant impact they can have on marine species and ecosystems (Harley et al. 2006; Danovaro et al. 2017) and their high ranking as drivers of environmental change among experts (Boonstra et al. 2015).

There is also variation in how activities and pressures are mapped, and the degree to which they were quantified, which is often related to the nature and type of the activity (i.e. fixed or mobile). Specifically, locations of mining or hydrocarbon extraction, fish farms, shipping routes, and ports are predominately mapped as geographic points indicating the presence of the activity, whilst other activities such as fishing effort, density of marine traffic, intensity of tourism, are depicted as concentrations of activities over set areas.

4.2. Breakdown by region(s)

Regional cooperation is of paramount importance for a number of flagship EU directives and policies (e.g. MSFD, MSPD), as well as the sustainable management of resources (e.g. shared fish stocks – Heffernan 2014) and the attainment of conservation goals (e.g. managing non-indigenous species – Katsanevakis et al. 2015); it is therefore important that comparable attention is given to all regions and that additional research effort is directed to those areas that are data deficient.

The majority of mapped resources extend over the Mediterranean Sea and North-East Atlantic, presumably due to the highly active scientific fora and advisory bodies such as CIESM and ICES, as well as the long history of human use and exploitation in these areas. In addition to specific regions, a substantial portion of records is on the global or European scale, an expected outcome since those arise from much larger scale initiatives (e.g. Nelleman et al. 2009).

The Baltic Sea is especially well documented in terms of pressures (Korpinen et al. 2012), biodiversity (Ojaveer et al. 2010) and impacts (e.g. HELCOM 2009) presumably due to basin-wide management programmes coordinated through the Helsinki Commission (HELCOM). The lower number of records from the Baltic Sea cannot be attributed to data deficiency, but –contrastingly– is the result of substantial efforts made by HELCOM in synthesizing available information and different data sources in harmonised pan-Baltic maps; this coordinated effort renders a substantial amount of data available at the pan-Baltic level and therefore has high information value.

In comparison, the Black Sea, which is 30% larger than the Baltic Sea, only has a small number of records and is certainly under-represented in terms of mapping initiatives and available data. This is likely attributable to a reduced research effort and/or limited communication/publication of study results in the Black Sea region. Nevertheless, this is likely to change in the future as several initiatives have recently been launched in the region which will increase the state of knowledge (e.g. through IP projects such as MARSPLAN-BS, MISIS, CoCoNet and PERSEUS). Furthermore, the European Commission is also supporting research institutes and public stakeholders from all Black Sea countries to pool together existing data in order to create a single digital map of the Black Sea seabed, including its geology, habitats and marine life (based on the EMODNET example).

4.3. Breakdown by habitat(s)

The majority of maps do not indicate the presence of, or impact on, specific habitats. While this is in part due to the scope of the present analysis (i.e. to identify maps documenting activities/pressures at the regional or national level), it also highlights a clear limitation in our current knowledge. Whilst it is possible to overlay maps of activities and pressures with habitat distribution in order to infer likely impact, quantifiable evidence is obviously more informative. Consequently, maps of human pressures should ideally be coupled with habitat-specific thresholds and sensitivities in order to obtain a more refined picture of the severity of cumulative impact across habitats (e.g. see Bevilacqua et al. 2018).

4.4. Contextual information

Context is essential to help translate maps of activities and pressures from indicators of possible impact to more informative indicators of predicted impact (Andersen & Stock 2013, Stelzenmüller et al. 2018) and therefore increase their utility to inform adaptive management policies and develop successful restoration projects. For example, whilst a specific activity (e.g. fishing) has the potential to cause a specific pressure (e.g. abrasion), the latter may only apply in a particular location (e.g. where a specific habitat is present) or time period, but also over large spatial scales and in the deep sea (Puig et al. 2012; Pusceddu et al 2014). Furthermore, even if a pressure is present, its impact upon the marine environment will vary as a function of its timing, frequency, intensity, duration and spatial footprint (Knights et al. 2015). Cumulative pressure impact assessments try to account for some of these issues although other challenges remain, for example: (i) non-linear pressure responses and non-additive (antagonistic or synergistic) pressure effects are not well understood (Halpern & Fujita 2013) and (ii) modelled outputs from large basin-wide studies (e.g. Halpern et al. 2008; Korpinen et al. 2012; Micheli et al. 2013; Goodsir et al. 2015) have questionable ability to represent real conditions at the local scale (Guarnieri et al. 2016) although finer scale applications at the habitat level do begin to appear (Bevilacqua et al. 2018).

Unfortunately, contextual information is generally lacking: whilst certain types of information (e.g. VMS) have highly accurate geo-positioning (10 m accuracy), their frequency of recording is low and by the time the data are processed and made available, the activity is often presented at a coarser 2000 m resolution. Furthermore, differences in the spatial resolution of fishing pressure lead to ambiguity about the spatial footprint of the activity, especially in areas where depth changes occur, thus reducing the ability to assess the habitats affected (Eigaard et al. 2016). Yet, these limitations could be overcome in the near future via widespread use of real-time AIS and public release of VMS data (Kroodsma et al. 2018).

Similarly, whilst interpolated maps based on modelled data provide a good indication of activities and pressures, especially in data-poor regions, they are often relatively coarse in scale, making it difficult to infer the true extent of an activity and thus hindering the development of effective regulatory policies. Furthermore, modelled "footprints" often lack actual parameters on intensity, temporal variation, and duration and depict a single snapshot in time, making it difficult to infer the frequency over which certain pressures and activities operate. Finally, the majority of data sources do not provide downloadable georeferenced files which limits their use in further synthesis, analyses and conservation planning.

The coastal zone is crowded and subjected to an ever-increasing demand for space (EEA 2015). A better understanding of the temporal patterns of human activities will aid the development of more efficient spatial plans (also accounting for future changes) and facilitate the integration of planning where hotspots of human pressure occur and where critical habitats and species' movements (e.g. migrations or spawning and breeding areas) are present and in need for conservation in order to reduce negative impacts (Colloca et al. 2015). Furthermore, the scarcity of downloadable georeferenced files hampers efforts to make inferences for certain sensitive habitats or determine the actual spatial footprint of activities from which impacts can be derived.

A specific attempt to produce a census of available maps of key European marine habitats has been recently completed by Bekkby et al. (2017). Furthermore, whilst outside the scope of this review, there is also a pressing need to combine activity and pressure maps with biological information to obtain a more nuanced understanding of the degree of impact (Eigaard et al. 2016; Rijnsdorp et al. 2016).

4.5. Dealing with uncertainty

Acknowledging, quantifying, accounting for and communicating uncertainty in environmental policy and human impact assessments is essential to strengthen management and spatial prioritization (Borja et al. 2016; ICES 2016; Katsanevakis & Moustakas 2018; Troupin & Carmel 2018) and increase trust and faith in science used for policy advice (Fischhoff & Davis 2014). Decision-making can be undermined by various sources of uncertainty, affecting the choice of actions and prioritizing the management of detrimental human activities and areas for protection (Knights et al. 2014; Stock & Micheli 2016; Troupin & Carmel 2018). The majority of maps examined herein imply some associated degree of uncertainty, although only a small part (approximately 10%) of the records explicitly address the confidence and uncertainty of data inputs or outputs (but see notable exceptions in Issaris et al. 2012, Katsanevakis et al. 2016, Piante and Oddy 2015). There are numerous typologies and types of uncertainty including context, model, parameter, scenario and future uncertainty (Ascough II et al. 2008; Borja et al. 2016; Stock & Micheli 2016; Troupin & Carmel 2018; Floor et al. 2018). Uncertainty can surround the performance of an action, input data quality (e.g. spatial and temporal variability, state of an indicator), target and threshold setting, and outputs and the future forecasted state post action (Knights et al. 2014 and references therein), but can also derive from incomplete knowledge (e.g. uncertainty on the status or introduction pathways of alien species, Katsanevakis et al. 2018) or unpredictability of a system. Aspects of knowledge uncertainty have been noted above in terms of accuracy/resolution or reliance on interpolated data as depicted in mapping outputs that could be used to support policy decisions. A recent detailed analysis of data quality, encompassing accuracy, precision, and (spatial, thematic, and temporal) uncertainty, and their impacts on habitat maps in a conservation context warns that while habitat maps have become an invaluable tool to inform and assist decision-making, results can vary dramatically since habitat maps are very sensitive to how they are produced (Lecours 2017).

In addition to resource management and conservation planning, uncertainty is also a major issue in estimating cumulative impacts and ocean health assessments (Halpern et al. 2008; Micheli et al. 2013; Korpinen & Andersen 2016; Borja et al. 2016; Frazier et al. 2016; Gissi et al. 2017). Uncertainty in this case is attributed not only to several issues noted above (e.g. pressure-state relationships, types of cumulative impacts), but also to various modelling uncertainties related to data quality, spatial extent and scale issues (Goodsir et al. 2015), as well as missing data and gap filling methods required for several habitat datasets used to calculate global Ocean Health Index goals (Frazier et al. 2016). However, investing in quantifying and communicating all types of uncertainty and their effect in integrative assessments, incentivizes future data collection and increases confidence in the use of science and spatial outputs in decision-making (Borja et al. 2016; Frazier et al. 2016; Lecours 2017).

4.6. Summary of gaps, limitations and recommended next steps

- **Static data**: The majority of spatial information is limited to images of maps, greatly reducing their usability and applicability to other studies. These images are static in time, while activities and pressures in marine habitats (as well as the marine habitats themselves) are temporally dynamic.

- **Potential interactions between pressures:** Pressures can interact in complex ways, and cumulative and non-additive effects have been demonstrated to be common in nature. However, precise knowledge regarding the outcomes of interaction between multiple pressures and causative effects of human activities is still lacking.
- **Spatial resolution**: Maps are usually at broad-scale and low-resolution. This has considerable implications for precision and accuracy. While low resolution information may be sufficient for setting conservation priorities (see Giakoumi et al. 2015) it cannot be considered appropriate for actual conservation, effective management, and restoration actions.
- **Modelled data**: A number of the maps contain high levels of modelled/predicted data with a great degree of interpolation between actual data points. This has the potential to increase the uncertainty of the information and may limit its utility to policy makers and conservation practitioners. In current maps with modelled data, estimates of uncertainty are rarely provided.
- **Geographic coverage**: In European seas, geographic under-representation is an issue in the current information, both at regional (e.g. Black Sea) and sub-basin (e.g. Eastern Mediterranean Sea) levels.
- **Hotspots of conflict between activities and habitats**: There is a lack of maps which simultaneously identify where high human activity coincides with vulnerable key habitats (important in the planning and geographic positioning of MPAs).
- **Representation of habitats**: Some habitats (e.g. seagrass meadows) have more information than others (e.g. seamounts). This is most likely due to their use by many stakeholders, their perceived or legislative importance, or their accessibility for study.
- **Representation of activities and pressures**: Maps of exogenous pressures are generally lacking. There is a bias in the types of activities and pressures mapped, with a greater focus on resource exploitation activities with a long history (such as fishing or mining) and a lesser emphasis on emergent activities and pressures (such as changes in thermal conditions or noise stemming from new subsea installations such as tidal power).
- **Information availability**: Grey literature (e.g. dissemination publications, technical and project reports) is an important source for useful activities/pressure maps and can expand the knowledge that can be obtained by standard ISI journals; however, these sources are not directly visible or easily retrievable through standard literature platforms.

Based on the above, it is recommended that future mapping initiatives should focus on the following:

- **Generating geo-referenced data**: Open access, geo-referenced data on pressures and activities as well as habitat extent and condition are in high demand for assessments of ecosystem status and health, as well as of cumulative effects. The present study recommends future maps should contain georeferenced information that is easily accessible for use in marine management and conservation efforts.
- **Filling gaps in knowledge**: The study also recommends filling in the geographical and temporal gaps (by digitization of old/historical maps and incorporating fragmented information, e.g. Martin et al. 2014; Telesca et al. 2015) and supporting regional and national mapping initiatives (with dedicated service calls and appropriate funding to compensate for the current trend for reduced government budgets (Borja & Elliott, 2013).
- **Linking habitat, activity, and pressure data:** To better understand how different habitats are affected, or could be affected by pressures, it is necessary to map both habitats

and pressures at the same scale and in the same area. This will enable effective conservation and mitigation efforts.

- **Addressing uncertainty:** Since uncertainty is present in all cases of modelled maps, its assessment is considered essential to support sound management and policy decisions. Acknowledging, quantifying and visualising uncertainty is thus critical for future mapping initiatives.
- **Gaining high-level standardization**: The role of transnational and intergovernmental organizations such as the EU, but also OSPAR, HELCOM, UNEP-MAP and the Barcelona and Black Sea commissions, is crucial in the production, standardization, and integration of data with universal approaches and balanced geographical representativeness.

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6. References

Airoldi L, Beck MW (2007) Loss, status and trends for coastal marine habitats of Europe. Oceanography and Marine Biology: An Annual Review 45: 345–405

Andersen JH, Stock A (eds.) (2013). Human Uses, Pressures and Impacts in the Eastern North Sea. Technical Report, Danish Centre for Environment and Energy, Aarhus University, Roskilde, 134.

Ansong J, Gissi E, Calado H (2017) An approach to ecosystem-based management in maritime spatial planning process. Ocean and Coastal Management 141: 65-81

Ascough II JC, Maier HR, Ravalico JK, Strudley MW (2008). Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. Ecological Modelling, 219 (3-4): 383-399.

Bekkby T, Gerovasileiou V, Papadopoulou K-N, Sevastou K, Dailianis T, Fiorentino D, McOwen C, Smith CJ, Amaro T, Bakran-Petricioli T, Bilan M, Boström C, Carreiro-Silva M, Carugati L, Cebrian E, Cerrano C, Christie H, Danovaro R, Eronat EGT, Fraschetti S, Gagnon K, Gambi C, Grehan A, Hereu B, Kipson S, Kizilkaya I, van de Koppel J, Kotta J, Linares C, Milanese M, Morato T, Ojaveer H, Orav-Kotta H, Rinde E, Sarà A, Scharfe M Srimgeour R (2017) State of the knowledge on European marine habitat mapping and degraded habitats. Deliverable 1.1, MERCES Project, 137 pp.

Benn AR, Weaver PP, Billett DSM, van den Hove S, Murdock AP, Doneghan GB, Le Bas T (2010) Human activities on the deep seafloor in the North East Atlantic: an assessment of spatial extent. PloS ONE 5(9): e12730

Bevilacqua S, Guarnieri G, Farella G, Terlizzi A, Fraschetti S (2018) A regional assessment of cumulative impact mapping on Mediterranean coralligenous outcrops. Scientific Reports 8: 1757

Borja A, Elliott M (2013) Marine monitoring during an economic crisis: the cure is worse than the disease. Marine Pollution Bulletin 68: 1–3

Borja A, Elliott M, Andersen JH, Berg T, Carstensen J, Halpern BS, Heiskanen A-S, Korpinen S, Lowndes JSS, Martin G, Rodriguez-Ezpeleta N (2016) Overview of integrative assessment of marine systems: the Ecosystem Approach in practice. Frontiers in Marine Science 3(20), https://doi.org/10.3389/fmars.2016.00020

Boonstra WJ, Ottosen KM, Ferreira ASA, *et al.* (2015) What are the major global threats and impacts in marine environments? Investigating the contours of a shared perception among marine scientists from the bottom-up. Marine Policy 60: 197–201

Boyes, SJ, Elliott M (2014). Marine legislation –the ultimate 'horrendogram': International Law, European Directives & National Implementation. Marine Pollution Bulletin 86: 39–47

Boyes SJ, Elliott M, Murillas-Maza A, Papadopoulou N, Uyarra MC (2016) Is existing legislation fit-for-purpose to achieve Good Environmental Status in European seas? Marine Pollution Bulletin 111: 18-32

Cavallo M, Elliott M, Touza J, Quintino V (2017) Benefits and impediments for the integrated and coordinated management of European seas. Marine Policy 86: 206–213

Coll M, Piroddi C, Albouy C *et al.* (2011) The Mediterranean Sea under siege: spatial overlap between marine biodiversity, cumulative threats and marine reserves. Global Ecology and Biogeography 21: 465–480

Colloca F, Garofalo G, Bitetto I, et al. (2015). The seascape of demersal fish nursery areas in the North Mediterranean Sea, a first step towards the implementation of spatial planning for trawl fisheries. PloS ONE, 10(3): e0119590

Costello MJ, Coll M, Danovaro R, Halpin P, Ojaveer H, Miloslavich P (2010) A Census of Marine Biodiversity Knowledge, Resources, and Future Challenges. PloS ONE 5(8): e12110.

Crise A, Kaberi H, Ruiz J, et al. (2015) A MSFD complementary approach for the assessment of pressures, knowledge and data gaps in Southern European Seas: The PERSEUS experience. Marine Pollution Bulletin 95(1): 28-39

Danovaro R, Corinaldesi C, Dell'Anno A, Snelgrove PVR (2017) The deep-sea under global change. Current Biology 27 (11), R461-R465

EC (2008) Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environment policy (Marine Strategy Framework Directive). Official Journal of the European Union 164: 19–40

ECORYS (2012). Blue Growth. Scenarios and drivers for Sustainable Growth from the Oceans, Seas and Coasts, Final Report for European Commission, DG MARE, 202 pp.

EEA (2007). Europe's seas and coasts. Europe's seas and coasts. European Environmental Agency, Copenhagen, 13 pp.

EEA (2015) State of Europe's seas. European Environment Agency, Luxembourg

EU (2017) COMMISSION DECISION (EU) 2017/848 of 17 May 2017 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment and repealing Decision 2010/477/EU.

Eigaard OR, Bastardie F, Hintzen NT, Buhl-Mortensen L, Buhl-Mortensen P, Catarino R, et al. (2016) The footprint of bottom trawling in European waters: distribution, intensity, and seabed integrity. ICES Journal of Marine Science 74: 847–86

Elliott M (2011) Marine science and management means tackling exogenic unmanaged pressures and endogenic managed pressures - a numbered guide. Marine Pollution Bulletin 62: 651–655

Floor JR, van Koppen CSA, van Tatenhove JPM (2016) Uncertainties in the assessment of "significant effect" on the Dutch Natura 2000 Wadden Sea site – The mussel seed fishery and powerboat race controversies, Environmental Science and Policy 55: 380–392. doi:10.1016/j.envsci.2015.03.008.

Frazier M, Longo C, Halpern BS (2016) Mapping uncertainty due to missing data in the Global Ocean Health Index. PLOS ONE 11(8): e0160377. https://doi.org/10.1371/journal.pone.0160377

Fischhoff B, Davis AL (2014) Communicating scientific uncertainty. Proceedings of the National Academy of Sciences of the United States of America 111(Suppl 4): 13664-13671, doi:10.1073/pnas.1317504111

Giakoumi S, Halpern BS, Michel LN, Gobert S, Sini M, Boudouresque C-F, Gambi M-C, et al. (2015) Towards a framework for assessment and management of cumulative human impacts on marine food webs. Conservation Biology 29: 1228–1234

Gonzalez-Mirelis G, Lindegarth M, Sköld M (2014) Using Vessel Monitoring System Data to Improve Systematic Conservation Planning of a Multiple-Use Marine Protected Area, the Kosterhavet National Park (Sweden). Ambio 43(2): 162-174

Goodsir F, Bloomfield HJ, Judd AD, Kral F, Robinson LA, Knights AM (2015) A spatially resolved pressure-based approach to evaluate combined effects of human activities and management in marine ecosystems, ICES Journal of Marine Science 72(8): 2245–2256

Halpern BS, Fujita R (2013) Assumptions, challenges, and future directions in cumulative impact analysis. Ecosphere 4: 131

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, et al. (2008) A global map of human impact on marine ecosystems. Science 319: 948–52

Harley CDG, Hughes AR, Hultgren KM, Miner BJ, Sorte CJB, Thornber CS, Rodriguez LF, Tomanek L, Williams S (2006) The impacts of climate change in coastal marine systems. Ecology Letters 9, 228–241

Heffernan JP (2014) Dealing with Mediterranean bluefin tuna: A study in international environmental management. Marine Policy 50, Part A: 81-88

HELCOM (2009) Biodiversity in the Baltic Sea – An integrated thematic assessment on biodiversity and nature conservation in the Baltic Sea. Baltic Sea Environment Proceedings. No. 116B: 188 pp.

ICES (2016) ICES Advice 2016. Book 1. Introduction to advice basis. 15 pp. http://www.ices.dk/sites/pub/Publication%20Reports/Advice/2016/2016/Introduction_to_advice_2016.pdf

Katsanevakis S, Levin N, Coll M, Giakoumi S, Shkedi D, Mackelworth P, et al. (2015) Marine conservation challenges in an era of economic crisis and geopolitical instability: The case of the Mediterranean Sea. Marine Policy 51: 31-39

Katsanevakis S, Moustakas A (2018) Uncertainty in Marine Invasion Science. Frontiers in Marine Science 5:38. doi: 10.3389/fmars.2018.00038

Katsanevakis S, Tempera F, Teixeira H (2016). Mapping the impact of alien species on marine ecosystems: the Mediterranean Sea case study. Diversity and Distributions 22: 694–707. doi: 10.1111/ddi.12429

Knights AM, Culhane F, Hussain SS, Papadopoulou KN, Piet GJ, Raakær J, Rogers SI, Robinson LA (2014) A step-wise process of decision-making under uncertainty when implementing environmental policy. Environmental Science and Policy 39: 56–64

Knights AM, Piet GJ, Jongbloed RH, Tamis JE, White L, et al. (2015) An exposure-effect approach for evaluating ecosystem-wide risks from human activities. ICES Journal of Marine Science 72: 1105-1115

Korpinen S, Andersen JH (2016) A Global Review of Cumulative Pressure and Impact Assessments in Marine Environments. Frontiers in Marine Science 3: 134–11

Korpinen S, Meidinger M, Laamanen M (2013) Cumulative impacts on seabed habitats: an indicator for assessments of good environmental status. Marine Pollution Bulletin 74: 311-319

Korpinen S, Meski L, Andersen JH, Laamanen M (2012) Human pressures and their potential impact on the Baltic Sea ecosystem. Ecological Indicators 15, 105–114

Kroodsma DA, Mayorga J, Hochberg T, Miller NA, et al. (2018) Tracking the global footprint of fisheries. Science 359(6378): 904–908

Lauria V, Garofalo G, Fiorentino F, Massi D, Milisenda G, et al. (2017) Species distribution models of two critically endangered deep-sea octocorals reveal fishing impacts on vulnerable marine ecosystems in central Mediterranean Sea. Scientific Reports 7: 8049

Lecours V, (2017) On the Use of Maps and Models in Conservation and Resource Management (Warning: Results May Vary). Frontiers in Marine Science 4, 2017. 288, DOI:10.3389/fmars.2017.00288

Loizidou X, Loizides M, Orthodoxou D (2017). Marine Strategy Framework Directive: Innovative and participatory decision-making method for the identification of common measures in the Mediterranean. Marine Policy 84: 82-89

Martin CS, Giannoulaki M, De Leo F, Scardi M, Salomidi M, Knitweiss L, et al. (2014) Coralligenous and maërl habitats: predictive modelling to identify their spatial distributions across the Mediterranean Sea. Scientific Reports 4: 1–8

McCauley DJ, Woods P, Sullivan B, Bergman B, Jablonicky C, Roan A, Hirshfield M, Boerder K, Worm B (2016) Ending hide and seek at sea. Science 351(6278): 1148-1150

Micheli F, Halpern BS, Walbridge S et al. (2013) Cumulative Human Impacts on Mediterranean and Black Sea Marine Ecosystems: Assessing Current Pressures and Opportunities (JP Meador, Ed,). PloS ONE, 8, e79889–10

Nellemann C, Corcoran E, Duarte CM, Valdés L, De Young C, Fonseca L, Grimsditch G. (Eds). 2009. Blue Carbon. A Rapid Response Assessment. United Nations Environment Programme, GRID-Arendal, www.grida.no).

Ojaveer H, Jaanus A, MacKenzie BR, Martin G, Olenin S, Radziejewska T, et al. (2010) Status of Biodiversity in the Baltic Sea. PloS ONE 5(9): e12467

OSPAR (2008) List of Threatened and/or Declining Species and Habitats (OSPAR Agreement 2008-06). Available online at: http://www.ospar.org/v_measures/get_page.asp?v0=08-06e_OSPAR List species and habitats.doc&v1=5

Pham CK, Ramirez-Llodra E, Alt CHS, Amaro T, Bergmann M, Canals M, Company JB, et al. (2014) Marine litter distribution and density in European Seas, from the shelves to deep basins. PloS ONE 9(4): e95839

Piante C, Ody D (2015) Blue Growth in the Mediterranean Sea: the challenge of Good Environmental Status. MedTrends Project. WWF-France

Piroddi C, Coll M, Liquete C, Macias Moy D, Greer K, et al. (2017) Historical changes of the Mediterranean Sea ecosystem: modelling the role and impact of primary productivity and fisheries changes over time. Scientific Reports 7: 44491

Piroddi C, Coll M, Steenbeek J, Moy DM, Christensen V (2015) Modelling the Mediterranean marine ecosystem as a whole: addressing the challenge of complexity. Marine Ecology Progress Series 533: 47–65

Puig P, Canals M, Company JB, Amblas D, Lastras G, Palanques A, Calafat AM (2012). Ploughing the deep sea floor. Nature 489, doi:10.1038/nature11410

Pusceddu A., Bianchelli S, Martín J, Puig J, Palanques A, Masqué P, Danovaro R (2014) Chronic and intensive bottom trawling impairs deep-sea biodiversity and ecosystem functioning. Proceedings of the National Academy of Sciences 111 (24), 8861-8866

Ramirez-Llodra E, Tyler PA, Baker MC, Bergstad OA, Clark MR, Escobar E, Levin LA, Menot L, Rowden AA, Smith CR, Van Dover CL (2011) Man and the Last Great Wilderness: Human Impact on the Deep Sea. PloS ONE 6: e22588

Randone M, Di Carlo G, Costantini M, et al. (2017) Reviving the Economy of the Mediterranean Sea: Actions for a Sustainable Future. WWF Mediterranean Marine Initiative, Rome, Italy. 64 pp.

Rijnsdorp AD, Bastardie F., Bolam SG, Buhl-Mortensen L, Eigaard OR, Hamon KG, et al. (2016) Towards a framework for the quantitative assessment of trawling impact on the seabed and benthic ecosystem, ICES Journal of Marine Science 73: i127–i138

Robinson LA, Rogers S, Frid CLJ (2008) A marine assessment and monitoring framework for application by UKMMAS and OSPAR – Assessment of Pressures and Impacts Phase II: Application for Regional Assessments. (Contract No: C-08-0007-0027 for the Joint Nature

Conservation Committee). University of Liverpool, Liverpool and Centre for the Environment, Fisheries and Aquaculture Science, Lowestoft

Rijnsdorp AD, Bastardie F, Bolam SG, Buhl-Mortensen L, Eigaard OR, et al. (2016) Towards a framework for the quantitative assessment of trawling impact on the seabed and benthic ecosystem ICES Journal of Marine Science 73: 127-138

Scharin H, Ericsdotter S, Elliott M, Turner RK, Niiranen S, Blenckner T, et al. (2016) Processes for the sustainable stewardship of marine environments. Ecological Economics 128: 55–67

Smith CJ, Papadopoulou K-N, Barnard S, Mazik K, Elliott M, Patrício J, Solaun O, Little S, Bhatia N, Borja A (2016) Managing the marine environment, conceptual models and assessment considerations for the European Marine Strategy Framework Directive. Frontiers in Marine Science 3(144)

Smith C, Papadopoulou N, Sevastou K, Franco A, Teixeira H, Piroddi C, Katsanevakis S, et al. (2014) Report on identification of keystone species and processes across regional seas. Deliverable 6.1, DEVOTES Project. 105 pp + 1 Annex.

Stelzenmüller V, Coll M, Mazaris AD, Giakoumi S, Katsanevakis S, Portman ME, et al. (2018) A risk-based approach to cumulative effect assessments for marine management. Science of The Total Environment 612: 1132-1140

Stewart KR, Lewison RL, Dunn DC, et al. (2010) Characterizing Fishing Effort and Spatial Extent of Coastal Fisheries. PloS ONE 5(12): e14451

Stock A, Micheli F, Field R (2016) Effects of model assumptions and data quality on spatial cumulative human impact assessments. Global Ecol. Biogeogr., 25: 1321-1332. doi:10.1111/geb.12493

Telesca L, Belluscio A, Criscoli A, Ardizzone G, Apostolaki E, Fraschetti S, et al. (2015) Seagrass meadows (Po*sidonia oceanica*) distribution and trajectories of change. Scientific Reports 5:12505

Troupin D, Carmel Y (2018) Conservation planning under uncertainty in urban development and vegetation dynamics. PloS ONE 13(4): e0195429.

Trujillo P, Piroddi C, Jacquet J (2012) Fish Farms at Sea: The Ground Truth from Google Earth. PLoS ONE 7(2): e30546

UNEP/MAP-SPA/RAC (2018) SPA/RAC: SPA-BD Protocol - Annex II: List of endangered or threatened species. Available online at: http://www.rac-spa.org/sites/default/files/annex/annex_2_en_20182.pdf

SUPPLEMENTARY INFORMATION

Human activities and resultant pressures on key European marine habitats: an analysis of mapped resources

Table S1. Descriptions and examples of activities and pressures (endogenous and exogenous) acting on marine habitats that were considered in the present study (modified from Smith CJ, Papadopoulou K-N, Barnard S, Mazik K, Elliott M, Patrício J, Solaun O, Little S, Bhatia N, Borja A (2016) Managing the marine environment, conceptual models and assessment considerations for the European Marine Strategy Framework Directive. *Frontiers in Marine Science* 3(144) doi: 103389/fmars201600144).

Activity	Examples and concerns from the activity leading to pressures
Production of living resources	Aquaculture: fin-fish set-up and operations, macro-algae set-up and operation, shellfish set-up and operations, predator control, disease control, stock enhancement methods
Extraction of living resources	Benthic trawling, scallop dredging, fishery wastes, netting (e.g. fixed nets, seine netting), pelagic trawling, potting/creeling, suction hydraulic dredging, bait digging, seaweed and saltmarsh vegetation harvesting, bird eggs and shellfish hand collecting, peels, curios, recreational fishing, extraction of genetic resources
Transport	Litter and debris (unauthorized dumping), mooring/beaching/ launching, shipping, steaming, shipping wastes, passenger ferries, transport of goods, navigation, dredged material disposal
Renewable energy generation	Renewable (tide/wave/wind) power station construction and operations
Non-renewable energy generation	Fossil fuel (coal, oil & gas) power stations, thermal discharge (cooling water), water abstraction, marine fracking, nuclear power, radioactive discharge and storage
Extraction of non-living resources	Inorganic mine and particulate waste, non-living maërl, rock/minerals (coastal quarrying), sand/gravel (aggregates), water for desalination, salt, navigational dredging, marine hydrocarbon extraction, capital dredging, maintenance dredging, substratum removal
Coastal and marine structure and Infrastructure	Artificial reefs, barrages, beach replenishment, communication infrastructure (cables), constructions, culverting lagoons, dock/port facilities, groynes, land claim, marinas, pipelines, removal of space and substrata, bathymetric/ topographic change, sea walls/breakwaters, urban buildings, cables/pipelines/ gas storage/carbon capture, cultural sites such as wrecks, foundations, sculptures
Land-based Industry	Industrial effluent treatment and discharge, industrial/urban emissions (air), particulate waste, desalination effluent, sewage and thermal discharge, power plant discharges
Agriculture	Coastal farming, coastal forestry, agricultural wastes, land/waterfront run-off
Tourism/ recreation	Angling, boating/yachting, diving/dive site, litter, littering/dumping, debris, bathing, public beach, tourist resort, water sports
Defense and national security	Military activities, hazardous material disposal areas, infrastructure (naval bases, ports, airports, degaussing stations), vessels, vehicles, sonars and munitions testing and use at sea, mooring/anchoring/beaching, dumping
Research and conservation	Animal sanctuaries, marine archaeology, marine research, physical sampling, physico-chemical and biological sample removal
Carbon Sequestration	Storage, exploration, construction, operational

Table S1. (cont.)

Pressure (endogenous)	Description
Abrasion	Physical interaction of human activities with the seafloor/seabed flora and fauna causing physical damage (e.g. trawling)
Aesthetic pollution	Visual disturbance, noise and odour nuisance
Barrier to species movement	Obstructions preventing natural movement of mobile species, weirs, barrages, causeways, wind turbines, etc. along migration routes
Change in wave exposure (local)	Change in size, number, distribution and/or periodicity of waves along a coast due to man-made structures.
Changes in siltation and light regime	Change in concentration of suspended solids in the water column (turbidity), deposition/accretion (dredging/run-off)
Collision	Caused by contact between biological components and moving parts of a human activity (ships, propellers, wind turbines).
Electromagnetic changes	Change in the amount and/or distribution and/or periodicity of electromagnetic energy from electrical sources (e.g. underwater cables)
Emergence regime change (local)	Change in natural sea level (mean, variation, range) due to man-made structures
Input of organic matter	Input of organic matter (e.g. industrial/sewage effluent, agricultural run-off, aquaculture, discards, etc.)
Introduction of microbial pathogens	Introduction of microbial pathogens
Introduction of non-indigenous species and translocations	Through fishing activity/netting, aquaculture, shipping, waterways, loss of ice cover, genetic modification
Introduction of non-synthetic compounds	Heavy metals, hydrocarbons, PAH, organometals
Introduction of other substances	Solids, liquids or gases not classed as synthetic/non-synthetic compounds or radionuclides
Introduction of radionuclides	Radioactivity contamination
Introduction of synthetic compounds	Pesticides, antifoulants, pharmaceuticals, organohalogens
Litter	Diffuse introduction of litter
Nitrogen and phosphorus enrichment	Input of nitrogen and phosphorus (e.g. fertilizer, sewage)
Noise	Underwater noise - Shipping, acoustic surveys; surface noise (including aesthetic disturbance)
pH changes (local)	Change in pH (mean, variation, range) due to run-off/change in freshwater flow, etc.
Salinity regime change	Freshwater – seawater balance, seabed seepage
Selective extraction of non-living resources	Aggregate extraction/removal of surface substrata, habitat removal
Selective extraction of species	Removal and mortality of target (e.g. fishing) and non-target (e.g. by catch, cooling water intake) species
Smothering	By man-made structures/ disposal at sea
Substratum loss	Sealing by permanent construction (coastal defenses/wind turbines), change in substratum due to loss of key physical/biological features, replacement of natural substratum by another type (e.g. sand/gravel to mud)
Thermal regime change	Temperature change (average, range, variability) due to thermal discharge (local)
Water flow rate changes (local)	Change in currents (speed, direction, variability) due to man-made structures

Table S1. (cont.)

Pressure (exogenous)	**Description**
Thermal regime change	Temperature change (average, range, variability) due to climate change (large scale)
Salinity regime change	Salinity change (average, range, variability) due to climatological events (large scale)
Emergence regime change	Change in natural sea level (mean, variation, range) due to climate change (large scale) and isostatic
Water flow rate changes	Change in currents (speed, direction, variability) due to climate change (large scale)
pH changes	Change in pH (mean, variation, range) due to climate change (large scale), or volcanic activity (local)
Change in wave exposure	Change in size, number, distribution and/or periodicity of waves along a coast due to climate change
Geomorphological changes	Changes in seabed and coastline changes due to tectonic events

SUPPLEMENTARY INFORMATION

Human activities and resultant pressures on key European marine habitats: an analysis of mapped resources

Table S2. Full list of keywords used for sourcing information through web searches, organized by related human activity.

Activity	Queried keywords
Agriculture	“agriculture”
	“coastal farming”
	“coastal forestry”
Carbon sequestration	“carbon sequestration”
	“carbon storage”
Coastal and marine infrastructure	“coastal infrastructure”
	“coastal structures”
	“artificial reefs”
	“coastal constructions”
	“marinas”
	“harbours” OR “harbors”
	“ports”
	“pipelines”
	“underwater cables”
	“wrecks”
Defense and security	“military”
	“munitions”
	“defense” OR “defence”
	“disposal”
Extraction of living resources	“fisheries”
	“trawling”
	“fishing”
	“harvesting”
Extraction of non-living resources	“aggregates”
	“mining”
	“dredging”
	“hydrocarbons”
	“extraction”
Land-based industry	“industry” OR “industrial”
	“treatment”
	“sewage”
	“discharge”
	“factory”
Non-renewable energy generation	“non-renewable” AND “energy”
	“fossil fuel”
	“coal
	“nuclear”
Production of living resources	“aquaculture”
	“shellfish culture”
	“fish farming”

Activity	Queried keywords
Renewable energy generation	“renewable energy”
	“tidal energy”
	“wave energy”
	“wind energy”
	“wind farms”
Research and conservation	“marine research”
	“conservation”
	“archaeology”
	“marine sampling”
Tourism/recreation	“tourism”
	“yachting”
	“resorts”
Transport	“transport”
	“shipping”
	“ferries”