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Crise, A.; Kaberi, H.; Ruiz, José Luis Martinez; Zatsepin, A.; Arashkevich, E.; Giani, M.; Karageorgis, A.P.; Prieto, L.; Pantazi, M.; Gonzalez-Fernandez, D.

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Viewpoint

A MSFD complementary approach for the assessment of pressures, knowledge and data gaps in Southern European Seas: The PERSEUS experience

A. Crise [a,*], H. Kaberi [b], J. Ruiz [c], A. Zatsepin [d], E. Arashkevich [d], M. Giani [a], A.P. Karageorgis [b], L. Prieto [c], M. Pantazi [b], D. Gonzalez-Fernandez [e], M. Ribera d'Alcalà [f], V. Tornero [e,f], V. Vassilopoulou [b], X. Durrieu de Madron [g], C. Guieu [h], P. Puig [i], A. Zenetos [b], B. Andral [j], D. Angel [k], D. Altukhov [l], S.D. Ayata [h], Y. Aktan [m], E. Balcıoğlu [m], F. Benedetti [h], M. Bouchoucha [j], M.-C. Buia [f], J.-F. Cadiou [j], M. Canals [n], M. Chakroun [o], E. Christou [b], M.G. Christidis [b], G. Civitarese [a], V. Coatu [p], M. Corsini-Foka [b], S. Cozzi [q], A. Deidun [r], A. Dell'Aquila [s], A. Dogrammatzi [b], C. Dumitrache [p], D. Edelist [k], O. Ettahiri [t], S. Fonda-Umani [u], S. Gana [o], F. Galgani [j], S. Gasparini [h], A. Giannakourou [b], M.-T. Gomoiu [v], A. Gubanova [l], A.-C. Gücü [w], Ö. Gürses [w], G. Hanke [e], I. Hatzianestis [b], B. Herut [x], R. Hone [y], E. Huertas [c], J.-O. Irisson [h], M. İşinibilir [m], J.A. Jimenez [z], S. Kalogirou [b], K. Kapiris [b], V. Karamfilov [aa], S. Kavadas [b], Ç. Keskin [m], A.E. Kideyş [w], M. Kocak [w], G. Kondylatos [b], C. Kontogiannis [b], R. Kosyan [d], P. Koubbi [ai], G. Kušpilić [ab], R. La Ferla [q], L. Langone [q], S. Laroche [j], L. Lazar [p], E. Lefkaditou [b], I.E. Lemeshko [ac], A. Machias [b], A. Malej [ad], M.-G. Mazzocchi [f], V. Medinets [ae], N. Mihalopoulos [af], S. Miserocchi [q], S. Moncheva [ag], V. Mukhanov [l], G. Oaie [v], A. Oros [p], A.A. Öztürk [m], B. Öztürk [m], M. Panayotova [ag], A. Prospathopoulos [b], G. Radu [p], V. Raykov [ag], P. Reglero [ah], G. Reygondeau [aj,ak], N. Rougeron [j], B. Salihoglu [h], A. Sanchez-Vidal [n], G. Sannino [s], C. Santinelli [q], D. Secrieru [v], G. Shapiro [y], N. Simboura [b], T. Shiganova [d], M. Sprovieri [q], K. Stefanova [ag], N. Streftaris [b], V. Tirelli [a], M. Tom [x], B. Topaloğlu [m], N.E. Topçu [m], K. Tsagarakis [b], C. Tsangaris [b], G. Tserpes [b], S. Tuğrul [w], Z. Uysal [w], D. Vasile [j], K. Violaki [af], J. Xu [y], A. Yüksek [m], E. Papathanassiou [b]

[a] OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale), Borgo Grotta Gigante 42/C, 34010_22 Sgonico, Trieste, Italy
[b] Hellenic Centre for Marine Research, 46.7 km Athinon – Souniou Ave., 19013 Anavyssos, Greece
[c] Agencia Estatal Consejo Superior de Investigaciones Cientificas, Instituto de Ciencias Marinas de Andalucia, Avda Republica Saharaui 2, 11519 Puerto Real, Cadiz, Spain
[d] P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences, Nakhimovsky Ave. 36, 117997 Moscow, Russia
[e] Institute for Environment and Sustainability, Joint Research Centre, European Commission, Via Enrico Fermi 2749, 21027, Italy
[f] Stazione Zoologica Anton Dohrn, Villa Comunale, 80121 Napoli, Italy
[g] Centre National de la Recherche Scientifique, Centre d'Etude et de Formation sur les Environnements Méditerranéens, Université de Perpignan Via Domitia, 52 avenue Paul Alduy, 66860 Perpignan, France
[h] LOV UPMC CNRS Laboratoire d'Océanographie de Villefranche, France
[i] Institut de Ciencies del Mar (CSIC), Passeig Joan de Borbo s/n, 08039 Barcelona, Catalonia, Spain
[j] Institut Francais de Recherche pour l' Exploitation de la Mer, 155 Rue Jean Jacques Rousseau, Issy-Moulineaux 92138, France
[k] University of Haifa, Mount Carmel, Abba Khoushi Blvd, 31905 Haifa, Israel
[l] A.O. Kovalevskiy Institute of Biology of Southern Seas, Nakhimov Avenue 2, 99011 Sevastopol, Ukraine
[m] Istanbul University, Istanbul Universitesi Center Campus, 34452 Beyazit/Eminonu-Istanbul, Turkey
[n] Universitat de Barcelona, Departement d'Estratigrafia, Paleontologia i Geociènces Marines University of Barcelona, Zona Universitaria de Pedralbes, 08028 Barcelona, Spain
[o] SAROST SA, Immeuble SAADI Tour EF 8ème étage El Menzah IV, 1082, Tunisia
[p] Institutul National De Cercetare-Dezvoltare Marina, Grigore Antipa, Mamaia Blvd 300, 900581 Constanta, Romania
[q] Consiglio Nazionale delle Ricerche, Piazzale Aldo Moro 7, 00185 Roma, Italy
[r] Universitata Malta, University Campus, Tal-Qroqq Imsida MSD20_1180, Malta
[s] Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile, Lungotevere Grande Ammiraglio Thaon di Revel 76, 00196 Roma, Italy
[t] Institut National de Recherche Halieutique, Rue Tiznit 2, 20000 Casablanca, Morocco
[u] Consorzio Nazionale Interuniversitario per le Scienze del Mare, Piazzale Flaminio 9, 00196 Rome, Italy
[v] Institutul National de Cercetare-Dezvoltare Pentru Geologie si Geoecologie Marina, Dimitrie Onciul Street 23-25, 024053 Bucharest, Romania
[w] Middle East Technical University, Dumlupinar 1, Cankaya 06800, Turkey
[x] Israel Oceanographic and Limnological Research, Tel Shikmona, 31080 Haifa, Israel
[y] University of Plymouth, Drake Circus, PL4 8AA Plymouth, UK

* Corresponding author. Tel.: +39 040 2140 205, mobile: +39 3207468277.
E-mail address: acrise@inogs.it (A. Crise).

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[z] Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya, BarcelonaTech, c/Jordi Girona 1-3, Campus Nord ed D1, Barcelona 08034, Spain
[aa] Institute for Biodiversity and Ecosystem Research at the Bulgraian Academy of Sciences, 2, Gagarin Street, 1113 Sofia, Bulgaria
[ab] Institute of Oceanography and Fisheries, Seatliste Ivana Mestrovica 63, 21000 Split, Croatia
[ac] Marine Hydrophysical Institute, Ukrainian National Academy of Sciences, 2, Kapitanskaya Street, 99011 Sevastopol, Ukraine
[ad] Nacionalni Institut Za Biologijo, VecnaPot 111, 1000 Ljubljana, Slovenia
[ae] Odessa National I.I. Mechnikov University, Dvoryanskaya Str 2, Odessa 65082, Ukraine
[af] University of Crete, Panepistimioupoli Rethymnon, 74100 Rethymnon Kritis, Greece
[ag] Institute of Oceanology, Bulgarian Academy of Sciences, Parvi May Str 40, 9000 Varna, Bulgaria
[ah] Instituto Espanol de Oceanografia, Corazon De Maria 8, Madrid, Spain
[ai] Unité Biologie des organismes et écosystèmes aquatiques (BOREA, UMR 7208), Sorbonne Universités, Muséum national d'Histoire naturelle, Université Pierre et Marie Curie, Université de Caen Basse-Normandie, CNRS, IRD; CP26, 57 rue Cuvier 75005 Paris, France
[aj] Center for Macroecology, Evolution and Climate, National Institute for Aquatic Resources, Technical University of Denmark (DTU Aqua), Kavalergården 6, 2920 Charlottenlund, Denmark
[ak] Fisheries Centre, 2202 Main Mall, Aquatic Ecosystems Research Laboratory, The University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z4

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A B S T R A C T

PERSEUS project aims to identify the most relevant pressures exerted on the ecosystems of the Southern European Seas (SES), highlighting knowledge and data gaps that endanger the achievement of SES Good Environmental Status (GES) as mandated by the Marine Strategy Framework Directive (MSFD). A complementary approach has been adopted, by a meta-analysis of existing literature on pressure/impact/knowledge gaps summarized in tables related to the MSFD descriptors, discriminating open waters from coastal areas. A comparative assessment of the Initial Assessments (IAs) for five SES countries has been also independently performed. The comparison between meta-analysis results and IAs shows similarities for coastal areas only. Major knowledge gaps have been detected for the biodiversity, marine food web, marine litter and underwater noise descriptors. The meta-analysis also allowed the identification of additional research themes targeting research topics that are requested to the achievement of GES.

1. Introduction

The Marine Strategy Framework Directive (2008/56/EC, European Commission 2008) (MSFD) is one of the several legal instruments existing worldwide (Oceans Act in the USA, Australia or Canada; EC Water Framework Directive (WFD), National Water Act in South Africa, European Regional Sea Conventions etc.) that have been adopted in order to protect more effectively the marine environment. The MSFD requires that all EU Member States (MSs) take measures to maintain or achieve Good Environmental Status (GES) in their seas by 2020. It calls for an "ecosystem-based approach" whereby management of marine activities is expected also to protect and preserve the marine environment as a whole. The implicit assumption is that it should be possible, at the present level of knowledge on the functioning of the marine ecosystem, to determine how to keep the collective pressure of human activities within levels compatible with the preservation or restoration of GES. This in turn implies that human pressures should not exceed the capacity of the marine ecosystem to withstand human-induced changes, whilst enabling the sustainable use of the marine environment now and in the future (MSFD Article 1(3)).

MSFD is innovative under several aspects if compared with previous regulatory EC directives. Contrary to the WFD, which follows a "deconstructing structural approach", the MSFD follows a "holistic functional approach" identifying the set of 11 descriptors (Table 1), which collectively represent the state and functioning of the whole system (Borja et al., 2008, 2010). The concept of GES *sensu* MSFD integrates physical, chemical and biological aspects, together with the services provided by ecosystems, including elements on the sustainable use of marine resources by society. Another difference is spatial overlapping between the MSFD and the WFD, which covers the coastal waters only (up to 1 nautical mile, except for chemical status, where 12-mile territorial waters are also included) making the MSFD a new challenge for environmental protection strategies for the open seas. The holistic view of MSFD is clearly reflected in the descriptors (Table 1) that, despite their qualitative or semi-qualitative character, address key requisites of a healthy ecosystem such as diversity, food web robustness, sustainable inputs of xenobiotic substances and biological immigration or physical perturbations.

The MSFD operational approach is based on marine regions and sub-regions according to geographical and ecological criteria, taking into account the trans-boundary nature of marine waters. EC Member States sharing a marine region or sub-region shall cooperate in developing their national marine strategies to ensure coherence and coordination (Art. 5.2, MSFD). Implementation of the MSFD is conceived as an adaptive process. It started with an analysis of the essential characteristics and current environmental status, following the requirement of Article 8 of the MSFD, i.e. to report on Initial Assessments (IAs). The IAs highlighted the "*predominant pressures and impacts (including human activity)*" on the environmental status, the economic and social impacts regarding the use of the marine environment and the cost of its degradation. To be effective, IAs and further actions foreseen by the implementation of the MSFD (the monitoring phase and adoption of proper mitigation measures), must be agreed with the stakeholders at transnational level and based on solid scientific knowledge. The effort required for producing IAs has been huge and there is general agreement that this is only the starting point of a long-term iterative process. Analysing the IAs reports, Laroche (2013) and, later, Palialexis et al. (2014) demonstrated that the available information was heterogeneous and incomplete. The methodological approaches were diverse and highly variable among countries depending on the descriptors selected (without common reference standards) and the assessments have been obtained from not significant data sets, as will discussed later in Section 4.2.

In relation to the Regional Sea Conventions (RSCs) in other European seas, OSPAR (for the North East Atlantic Seas) and HELCOM (for the Baltic Sea) are developing regional plans to improve adequacy and coherence in the implementation of marine policies. Efforts are dedicated to identify knowledge gaps and prioritize actions in relation to MSFD, using the outcome of the Initial Assessments performed by Member States, but also their own regional knowledge as described in draft documents (OSPAR

Table 1
List of Descriptors as stated by the Marine Strategy Framework Directive (2008/56/EC).

Number	Nickname	Descriptor
1	Biological diversity	Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions
2	Non-indigenous species	Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystem
3	Commercially exploited fish and shellfish	Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock
4	Marine food webs	All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity
5	Eutrophication	Human-induced eutrophication is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algal blooms and oxygen deficiency in bottom waters
6	Sea-floor integrity	Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected
7	Hydrographical conditions	Permanent alteration of hydrographical conditions does not adversely affect marine ecosystems
8	Contaminants	Concentrations of contaminants are at levels not giving rise to pollution effects
9	Contaminants in fish and other seafood	Contaminants in fish and other seafood for human consumption do not exceed levels established by Community legislation or other relevant standards
10	Marine litter	Properties and quantities of marine litter do not cause harm to the coastal and marine environment
11	Underwater noise and other forms of energy	Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment

COMMISSION, 2014[1]; HELCOM, 2015[2]). Further, OSPAR benefits from the outcomes of FP7 STAGES project with regards to the work done on pressures and impacts by MSFD (OSPAR Science Agenda, OSPAR COMMISSION, 2014.[3])

In parallel with the institutional activities of Member States, FP7 PERSEUS (Policy-oriented Environmental Research in Southern European Seas) provides an attempt to evaluate pressures exerted by human activities and natural processes, identifying their impacts on Mediterranean and Black Sea ecosystems, linking them to the MSFD descriptors, criteria and indicators. The ambition of this project is to identify the major pressures jeopardizing the environmental state of Southern European Seas (SES) and link them directly to possible impacts in a coherent and integrated manner. This assessment provides an evidence-based analysis of existing gaps in scientific knowledge in support of a strategy to fill them.

Two further elements differentiate the project strategy from MSFD IAs: the trans-national dimension (i.e. involvement of scientists from different countries, even beyond EU borders, in the evaluation process) and a knowledge synthesis strategy, meaning that the meta-analysis was not driven by the need to comply with MSFD indicators but by the intention to connect the descriptors to known mechanisms or to highlight knowledge gaps as regards the link. The knowledge synthesis strategy aims at distilling required information from data, refining the process from one level to the subsequent one (Fig. 1), as will be discussed further in this paragraph.

The process followed under the PERSEUS project has been inspired by a truly international vision, thanks to 55 member-institutions belonging to both EU and non-EU countries. This approach proved particularly beneficial for covering the first priority of this study (the retrospective analysis of existing data and knowledge), thus increasing spatial coverage, acknowledging sub-regional contributions, and aggregating a broader community aiming to tackle, in a coherent way, the trans-boundary effects of selected environmental pressures and provide a clear link with MSFD descriptors and indicators in neighbouring EU and non-EU countries. The latter point is of great relevance in the case of trans-boundary issues (e.g. marine pollution, habitat loss or overfishing) affecting an area that falls under the jurisdiction of several countries, either EU or non-EU.

The second element of the process was to elicit the existing knowledge and to 'project' it on the descriptors. The 'knowledge synthesis' approach moves in the opposite way when compared to IAs, where a list of pre-assigned indicators was used to 'take the pulse' of the European oceans and seas. In the PERSEUS approach, the focus has been on identified pressures in the SES, the observed or presumed impacts and the assessment of the robustness of the hypothesized causative link between them. In this respect, it is complementary to the MSFD, which focuses mostly on assessing the environmental status.

This article is a commented summary of the above effort and its conclusions aim at highlighting the existing gaps in data and knowledge. It is organised according to the following points:

– highlight of some methodological aspects connected also with MSFD conceptual aspects, relevant to the PERSEUS approach;
– identification of the major scientific gaps (in data and knowledge) filtered by the expert judgment produced by a high-level multidisciplinary scientific community from the scientific literature and data bases;
– comparison of the major scientific gaps with the findings of the gap analysis based on the review of MSFD Article 8 IA documents of the MSs;
– final remarks and suggestions for the MSFD adaptive implementation.

So far, no such exercise of comparison of assessment approaches (as presented here by PERSEUS) has been performed for the Northern European Seas. On the other hand, OSPAR distinguishes coastal and offshore waters using the 12 nm (Territorial Waters limit) in the assessment process for certain sections of their Quality Status Report 2010, e.g. hazardous substances in sediment and biota (CEMP assessment report, OSPAR, 20095). Meanwhile, HELCOM establishes their own coastal areas and open sea (offshore) areas, referring the latter to waters beyond 1 NM seaward from the baseline). Like in the SES, monitoring efforts are concentrated in coastal waters.

[1] http://ospar.org/html_documents/ospar/html/ospar_regional_plan_action_msfd_imp.pdf.
[2] http://portal.helcom.fi/meetings/GEAR%209-2015-219/MeetingDocuments/31%20HELCOM%20Plan%20on%20improving%20regional%20coherence.pdf.
[3] http://www.ospar.org/documents/dbase/publications/p00642/p00642_ospar_science_agenda.pdf.

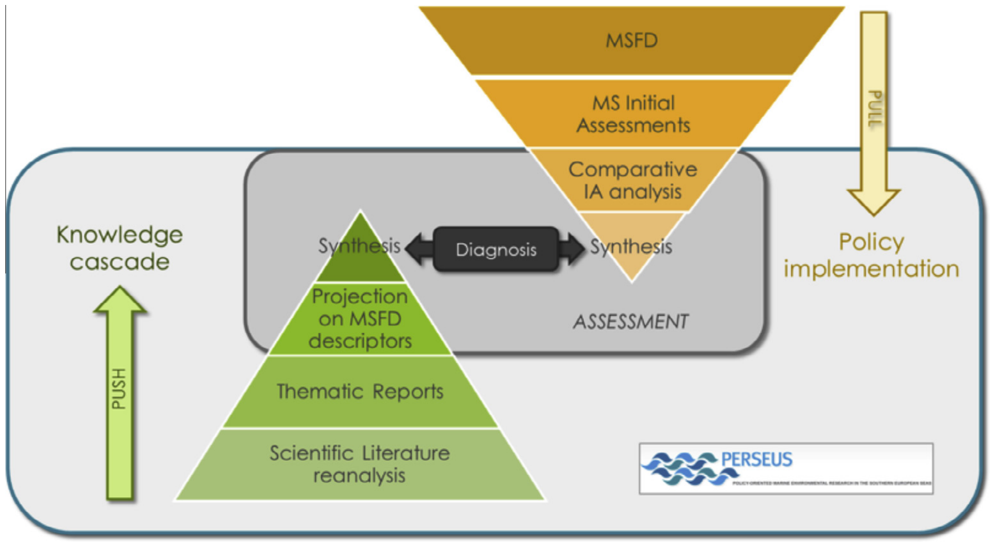

Fig. 1. The "knowledge synthesis" process (green) represents the PERSEUS efforts in synthetizing the knowledge to be diagnosed (at the same level of aggregation) against the Initial Assessment driven by the Policy implementation driver (light brown). The large box (light grey) includes the activities carried out within PERSEUS, while the smaller box (dark grey) identified the assessment activities presented in this work.

2. The MSFD philosophy and the PERSEUS approach

In the terminology of the MSFD, pressures are identified as perturbations that exert changes in forcing and/or fluxes (see descriptions in Table 2, Annex III of the MSFD). The rationale behind this is the conception that pristine ecosystems have, by definition, achieved GES that can be altered only by pressures, i.e. changes in fluxes and forcing. In other words, only the detailed holistic knowledge of the pressures exerted on marine environments allows identification of the best practices to mitigate the impacts and to improve the environmental status of the seas. The analysis of the anthropogenic pressures and the natural pressures (that call for specific adaptation measures) will help identify the most effective mechanisms and the actions able to restore GES conditions. The PERSEUS approach privileged the understanding of the pressures and their roles in altering environmental status.

Previous 'Strategies' or 'Directives' (e.g. WFD) were characterized by the assignment of thresholds for specific state variables, whereas the MSFD assesses the status of environmental components considering ecosystem structure and function and links it to specific drivers/pressures. GES diagnosis through state variables (represented by 56 quantitative indicators) is therefore only a component of its assessment, since the complex interactions among processes, pressures and state will require a global assessment of status.

The values of the indicators (Table 1, Annex III of the MSFD) are expected to vary in time according to specific time scales (i.e. seasonal, interannual or decadal). They are also often interdependent. To draw a rather simple image, the 'status' of an ecosystem can be compared to an orbit of a planet, which describes a trajectory constrained in a limited volume, while continuously changing its position. The 'space' spanned by the indicators is multidimensional and their variability directly drive the orbit representing the status (Tett et al., 2013; Micheli et al., 2013; Halpern et al., 2012). In this vision, GES is therefore a subspace in which the indicators are confined within prescribed thresholds.

The ecosystem orbit is however not necessarily periodic, as the Commission Staff Working Paper SEC 1255 (2011) recognized, in the presence of climatic trends and abrupt 'regime shifts' (Moellmann et al., 2009) and their possible recovery (Oguz and Velikova, 2010). These transitions call for a determination of GES that needs to be adapted over time to take into account the ongoing changes.

The implicit hope is, however, that marine ecosystems are resilient enough to allow driving the descriptor back to their pristine orbits by adopting appropriate sets of measures aimed at reducing the pressures and minimizing the impacts on the state.

Acknowledgment of the importance of pressures indeed clarifies why pressure-impact connections play a crucial role in the identification of the actions requested to keep/restore the marine ecosystems structure in conditions that sustainably provide goods and services and why PERSEUS centred its analysis on this key point.

3. Methodological procedures

This study includes two parallel methodological approaches, one developed by PERSEUS analysis and the other for the comparison of IAs.

PERSEUS analysis was conducted by grouping the ecosystems in two broad categories: the open sea (henceforth OS for the open sea), where larger spatial homogeneity and reduced impact of human activities are expected, and the coastal hot spots (henceforth CS for the coastal systems), where a superposition of different pressures is noted. More details on the review analysis for OS and CS are respectively provided in the PERSEUS reports by Karageorgis et al. (2013) and Tornero et al. (2013). Hence, two groups of natural and human pressures have been identified: those directly linked with specific MSFD pressure descriptors, and those that jeopardize the environmental status considered by GES (i.e. connected to more than one descriptor). The pressures were discussed along with their potential impacts, at different spatial scales. During the above process, attention was paid also to data and knowledge gaps that were identified during the review analysis.

In the open sea case, the SES have been divided into 4 areas (Western Mediterranean, Central Mediterranean, Eastern Mediterranean and Black Sea) in order to assess the relevant natural processes and anthropogenic pressures and their impacts (and potential interactions) on the ecosystems.

In coastal areas, human pressures and their environmental impacts have been analysed for selected sites in the SES (7 in the Western Mediterranean, 2 in the Adriatic Sea, 3 in the Eastern Mediterranean, and 8 in the Black Sea) in order to identify and

Table 2
Pressures (in brackets the referenced descriptors, if different), Impacts, and knowledge gaps for the open sea.

Pressure	Impacts	Knowledge gaps/research priorities
Changes in thermohaline properties and pH of seawater (hydrographic conditions)	Positive trends of temperature in the upper layer of the Mediterranean Sea induce stronger stratification. Potential modification of the primary production of the basins	The combined effects of thermohaline properties and pH trends on the conditions of SES interiors are still unclear
	The combination of foreseen pH decrease and surface warming will potentially impact on calcifying organisms and ocean CO_2 drawdown	Large uncertainty on the long-term effect of acidification on the whole food web
Atmospheric input of nutrients, organic carbon	Atmospheric deposition is supposed to provide a substantial input in an otherwise largely oligotrophic system	The role, the spatial and temporal variability of the atmospheric deposition (its organic component in particular) needs to be further investigated
Contamination by hazardous substances (contaminants and contaminants in fish and seafood)	Maritime transport is the main source of petroleum hydrocarbon pollution in the Mediterranean Sea	Unclear relationship between contaminants in different matrices and those found in biota and species of commercial interest
	Atmospheric deposition significantly contributes to the PAHs introduction in the open sea	Transfer of contaminants from coastal waters to the open sea is not well quantified; the role of shelf-slope exchange processes needs further study. Lack of data and information on emerging pollutants. Increased number of species should be considered in the evaluation of the contaminants impacts
	Down slope processes can transfer contaminants in the deep basins.	
	Hg stock of the Mediterranean Sea has significantly increased since industrial times. Hg concentration in the Black Sea is 4–10 times than in the Mediterranean and other open ocean waters. The methyl mercury levels are often higher in Mediterranean fish species than in the Atlantic	
Physical damage and loss of habitats (sea-floor integrity)	Offshore engineering (oilrigs, pipelines, cables) activities will increase in the Mediterranean and Black Sea. The drilling operations produce drilling mud, brine wastes, deck runoff water and pipeline leaks	Quantification of the damages and the loss of habitats in open water via an accurate seabed mapping is requested for SES, at least for the areas with expected higher pressure
	Limited deep-sea trawling in the NW Mediterranean	Impact of the deep-sea trawling on benthic habitats
Introduction of non-indigenous species (non-indigenous species – NIS)	Habitat alterations may favour the NIS rapid dispersal outside the areas of introduction. NIS may perturb the food web structure, displace the native species by out-compete them for resources, modify the genetic pools by hybridization, introduce pests and parasites	Development of methodologies to quantify the impact of NIS on the marine ecosystem functioning, its carrying capacity and resilience
		Identification of the anthropogenic vectors of invasions and their dispersal mechanisms
		Enhanced taxonomic expertise targeted to exotic species
Overfishing (commercially exploited fish and shellfish)	Important offshore fishing activities for large pelagic species (blue-fin tuna, swordfish) take place in the Mediterranean and particularly illegal overharvesting of blue-fin tuna populations has resulted in their dramatic decrease in recent years, facing the risk of extinction. Offshore deep-water fisheries targeting deep water shrimps (Giant red Shrimp, Blue and red Shrimp) also take place in the Mediterranean Sea. The status of these stocks, wherever assessments are available, is found to be overfished	Effective control of fishermen actions to strengthen compliance of TAC enforcement measures
		Improvement of by-catch mitigation techniques
		Stock assessments are available for very few deep-water species
Dumping of marine litter and microplastics (marine litter)	Plastic, glass, metal and clinker are the most abundant litter components in Mediterranean waters. Shallow areas generally show higher proportion of plastics than deeper regions, where heavy litter predominates, mostly originating along major shipping routes	Unknown spatial distribution of marine litter and microplastics (both as floating objects and on the seabed), their pathways and fate
	Submarine canyons channel and accumulate large debris towards the open sea	Lack of census of seabed marine litter and its effects as potential new substrata for colonization
	Microplastics may act as carriers of contaminants and can enter the food web	Microplastics as direct and indirect (i.e. toxic chemicals carrier) risks for marine biota (including large filter feeders)
Underwater noise and other forms of energy	The underwater noise impacts have not been specifically assessed in the SES. Noise from heavy and increasing maritime traffic and oil and gas explorations represent a permanent and widespread pressure over the SES. Noise is increasingly being considered as a threat to marine mammals (abundant in certain Mediterranean regions) and some fishes	Assessment of space/time variability of the noise and its spectral signature (Sound Exposure Levels)
		Acoustic propagation patterns in heavily impacted areas (i.e. seismic surveys)
		Impacts of various noise sources on Mediterranean marine mammals and on other organisms

Table 3
Pressures (in brackets the referenced descriptors, if different), Impacts, and knowledge gaps for coastal systems.

Pressure	Impacts	Knowledge gaps/research priorities
Changes in fresh water and sediment riverine fluxes (hydrographic conditions)	The entire SES are threatened by increased erosion rates due to reduced sediment fluxes (e.g. Nile-Egypt, N. Aegean, etc.)	Impact and resilience of benthic biocenoses to exceptional floods. Impact and vulnerability of benthic biocenoses to the changes of riverine regimes. Change in sediment size spectrum due to reduction of sediment transport related to anthropogenic use of water on land, and consequences of their dispersion in the coastal belt
	The pressure is significant in the north-western Black Sea and the Danube delta, with impacts on fish habitats and alterations on algal and sea grass communities	
Nutrients and organic enrichment (eutrophication)	The elevated concentration of nutrients and organic matter in the water column is observed only in proximity of highly populated areas or where the influence of river inputs is high(the Po prodelta, the Rhone and Ebro estuaries and the Danube delta)	Link between high nutrient load, phytoplankton response in terms of community structure, HABs and mucilage production
	Reduction of nutrient concentrations has been recently recorded in several coastal areas (northern Adriatic, Saronikos Gulf, Haifa harbor, NW Black Sea). Observed impacts include changes in chlorophyll concentration, shifts in the food web structure, decrease of diatoms and increase of small phytoplankton species, and increase of opportunistic and tolerant vs sensitive benthic fauna	Mechanisms of impact of change in nutrients, nutrient ratios and organic molecules on the structure of food web and carbon fluxes
Contamination by hazardous substances (contaminants and contaminants in fish and seafood)	Organic pollutants and heavy metals at levels which might be of toxicological concern have been found in many areas: the northwestern Mediterranean Sea, the Adriatic Sea, the Naples harbor, Haifa, the Saronikos Gulf, the Sea of Marmara, and the northwestern Black Sea. Observed impacts include gastropod species associated with TBT exposure and impacts on seabirds associated with oil chronic pollution. Oxidative stress in mussels and shifts in zoobenthic community's structure have also been suggested	Transfer of contaminants through the marine food-web. Potential toxic effects of combined contaminants (e.g. heavy metals and organic compounds)
		Causal relationships and mechanistic processes between contaminants and their effects on biota. This includes mixture effects or interactions between contaminants and other environmental stressors, and the extent to which contaminants change the genetic composition of populations
Physical damage and loss of habitats (sea-floor integrity)	Construction of ports and other infrastructure represents a significant pressure all around the Mediterranean and Black Seas. Associated impacts include sandy beach erosion and need of beach nourishment. Sea meadow destruction and changes in the food webs have been also usually observed and related to dredging, bottom trawling, anchoring, discharges of wastewaters, and littering. Desertification due to harvesting and destructive fisheries has been described in the Naples area, the southeast Adriatic, the Burgas Bay and the northwestern Black Sea	Changes and/or losses of habitat former/engineering species and the functional consequences of these changes
		Effects of different combinations of stressors (coastal infrastructures, abrasion, fishing, dredging) as well as related to climate changes
Introduction of non-indigenous species (non-indigenous species – NIS)	The pressure is high in the Mediterranean and Black Sea. Most relevant impacts include local replacements (e.g. *Asparagopsis taxiformis* instead of *Cystoseira* spp. in the gulf of Naples), negative impacts on fishing gears and tourism associated with jellyfish blooms in Haifa and the sea of Marmara, and drastic changes in the food web structure were caused by introduction of non-indigenous ctenophores in the Black Sea	Abundance, distribution, introduction and dissemination (including climate change considerations) of NIS. Biology and ecology of NIS as well as the induced ecological impacts on native ecosystems
		Cumulative impact of more than one invasive species
Overfishing (commercially exploited fish and shellfish)	Decline of landings of demersal and pelagic stocks over the past few decades.	Low number of species for which stock assessments are available even in EU countries. Lack of knowledge on shared stocks particularly with non EU countries Standardized monitoring and data analysis on a basin-wide scale
Dumping of marine litter and microplasticsin seawater (marine litter)	Although data are scarce, the pressure seems to be high in the Mediterranean and Black Sea. Occlusion, tangling and strangulation of marine turtles, birds and mammals due to high amount of plastics ingested are the most evident impacts	Impacts on marine organisms that live in the water column and on the seafloor
		Impact due to waste reduction measures Litter as substrate for polyp attachment Litter as carrier for harmful chemicals, invasive species and bacteria

(*continued on next page*)

Table 3 (*continued*)

Pressure	Impacts	Knowledge gaps/research priorities
Underwater noise and other forms of energy	Very few data. The pressure is moderate to high in the areas where it has been determined, like the Mediterranean French coast. Impacts only observed under laboratory conditions	Impact of impulsive and continuous noise on marine species, particularly on mammals
		Measures for the mitigation of noise impacts

prioritize the knowledge gaps for follow-up work. This compilation focused on areas with a high level of disturbance, i.e. big coastal cities and ports, coastal areas under the influence of large rivers, and on issues considered as major threats to the achievement of GES. The coastal 'hot spots' have been characterized in terms of site-specific physical, chemical and biological features, main human activities and (when available) regulations for environmental management.

The results of the compilation of several PERSEUS reports (22 organized by geographical region/sub-region and 15 coastal site-related) are summarized in two pressure/impact tables (Tables 2 and 3). Despite the significant analysis efforts, the reports succeeded only partially to provide an even coverage of the regions and pressures. All the listed impacts were derived from expert judgment based on scientific literature that is largely older, and therefore irrespective of the MSFD. This means that a considerable effort and additional expertise was required in reworking the material and making them consistent with the MSFD framework. For the sake of simplicity, all the references to the scientific articles used for compiling the pressure/impact tables are not quoted here and can be found in the abovementioned OS and CS project reports.

The assessment elements used in the IAs of the five EU MSs participating in PERSEUS (Spain, France, Greece, Cyprus and Romania), were reviewed and analysed in order to summarize and assess the main methodological approaches and identify eventual methodological issues as well as gaps in data availability and knowledge. The IAs have been evaluated with respect to both the methodological consistency and the availability of data and workable knowledge. Table 5 summarizes the reference methodologies used in the IAs.

A comparison of the results regarding the gaps in data and knowledge has been performed to evaluate consistencies and discrepancies in the results. The outcomes of this comparison are reported here in Section 5.

4. Results

4.1. Pressures/impacts and gaps in data and knowledge

The PERSEUS analysis results target the identification and evaluation of the pressures (i.e. the only controllable vectors of changes) and their presumed impacts, instead of the assessment of a status that provides a limited insight into possible intervention policies. MSFD indicators are conversely identified as indicators of state (D1, D3, D4, D6) and pressure (D2, D5, D7, D8, D9, D10, D11). The pursued approach also reflected some basic assumptions that have been implicitly retained in the analysis:

- intrinsic differences between coastal systems and open seas, and also within a specific sub-region;
- identification as 'pressures' of some driving mechanisms that are well recognized and that can be supposedly related to the effects on the marine (eco) system;
- projection of these pressures on the descriptors.

The results will be discussed in an aggregated way, even if a sub-regional approach has been followed in PERSEUS, since substantial homogeneity in the results emerged despite the geographical approach. Thus, efforts were made to identify common features rather than to highlight the differences that make every area a *unicum* where site-dependent intensity, variability and superposition of pressures interact. This offers a good opportunity for the adoption of generic (i.e. site-independent) measures, even if some flexibility must be retained.

A synthesis of the main outcomes of the analysis is reported in Tables 2 and 3, to which the reader should refer for a complete view. In parallel, the major gaps in data have been identified and a synthesis of the results is presented in Table 4.

The presence of data is rated as good (the state/pressures/impacts can be properly identified and quantified and additional data/information would not substantially improve policy options), medium (additional data can ameliorate policy options), poor (expert judgment will be still needed even in case of substantial new data availability) and none (virtually no data is available).

The general patterns and pressures/impacts that may, in our view, be controversial are discussed below.

In general, there is good agreement on the pressures identified in open seas (8 pressures) and those active in coastal systems (8 pressures) (Tables 2 and 3). The considered pressures have been found active in both cases with the exception of eutrophication and hydrographic conditions. These last two descriptors are not strictly applicable to SES open seas. Conversely, other pressures were identified that are relevant to trophic conditions and to the circulation of SES open waters, and therefore the pressure/impact tables have been modified accordingly.

Firstly, the hydrological condition descriptor is related to the changes in fresh water and sediment riverine fluxes, which are largely of coastal relevance (with the possible exception of Nile damming and the north-western Black Sea shelf), and hence it appears that the pressures related to this descriptor turns are not applicable to open sea regions. The long term variability introduced by climatic and anthropogenic modifications in the atmosphere (e.g. CO_2 increase) has been considered instead.

The eutrophication descriptor, confirmed also by "high" data availability (Table 4), is not appropriate for non-eutrophic basins and SES; no evidence of eutrophication processes has been found or any risk of substantial modification of trophic conditions is foreseen for the open SES. Instead, potential modification of the stratification due to global warming can reinforce the oligotrophic regime typical of the Mediterranean Sea. Even if eutrophication sites are reported in Table 3, there are signals that the trophic conditions in some continental shelves and coastal areas are veering to oligotrophic because of stricter regulations on macronutrient inputs in coastal waters (Giani et al., 2012; Tsiamis et al., 2013). In Tables 2 and 3 atmospheric input is instead considered since it substantially contributes to the trophic budget at basin scale and acts as a major driver of the primary and bacterial production in Low Nutrient Low Chlorophyll areas (Guieu et al., 2014).

The pressure/impact tables connect pressures (and the corresponding descriptors) to the expected impacts and gaps in knowledge (Tables 2 and 3). Even if the reports closely followed a geographical organization, an emerging feature is that the pressures are to a large extent ubiquitous. Despite similar pressures, the impacts and their relevance are substantially different in

Table 4
Assessment of data availability as derived from the IAs analysis and from the reports produced under PERSEUS. The qualitative scores reflect the grading system based on the prevailing expert opinions.

Data availability in SES per descriptor				
		Initial Assessments	Scientific Evaluation	
	Descriptor (2008/56/EC)	Data availability	Data availability Coastal systems	Data availability Open sea
1	Biological diversity	medium	medium	low
2	Non-indigenous species	low	low	low
3	Commercially exploited fish and shellfish	medium	medium	low
4	Marine foodwebs	low	low	low
5	Eutrophication	high	high	medium
6	Sea-floor integrity	medium	medium	low
7	Hydrographical conditions	low	medium	high
8	Contaminants	medium	medium	low
9	Contaminants in fish and other seafood	medium	medium	low
10	Marine litter	low	low	low
11	Underwater noise and other forms of energy	low	low	low

coastal hot spots and in open seas, reflecting the diversity of scales, peculiarity of the specific environments and intensity.

For example, although high fishing pressure is exerted on fishery resources of both open sea (OS) and coastal waters (CW) of the Mediterranean Sea, the targets of these fisheries are species with different life history, strategies and hence different resilience to fishing pressure. Mediterranean OS fisheries focus mainly on large pelagics, (i.e. bluefin tuna and swordfish) and deep-water red shrimps (*Aristeus antennatus* and *Aristemorpha foliacea*). The latter species present an overfished status in some sub regions of the Mediterranean Sea; however, blue fin tuna stocks being less resilient to fishing pressure, have shown a dramatic decline in recent years, which was followed by the adoption of strict management measures. Regarding the CW, an overfished status was found for most of the assessed small pelagic and demersal stocks (Cardinale and Osio, 2013); however, the assessment of many stocks is still not possible due to lack of pertinent data (Table 4). Stock assessments are very limited in non-EU countries, thus highlighting the need to initiate monitoring activities and relevant analysis through close collaboration between EU and non-EU countries particularly in the case of shared fishery resources. The pressure exerted by the introduction of non-indigenous species is high for all SES, and is mainly associated to Lessepsian migrators in the eastern Mediterranean and to shipping traffic (including ports and ballast waters) and sea farming in the case of the Black Sea where the comb jelly *Mnemiopsis leidyi* badly affected Black Sea fisheries (Kideys, 2002).

Similar considerations regarding site-specificity and the differences between open sea and coastal hot spots could be valid for the vast majority of pressures and should be considered carefully in all future developments and strategic plans. A series of gaps in the knowledge about the consequences of pressures emerged from the impact analysis, filtered by the expertise of the groups; these are reported in the third column of both tables (Tables 2 and 3). These gaps can be considered as a list of priorities for scientific research in these selected topics. The eventual bridging of these gaps will help to verify the actual occurrence of impacts on the Environmental Status (whose relevance is often a matter of speculation) and will provide a more robust reference framework to be used in the design strategy of the mitigation measures.

The comparison of results shown in Tables 2 and 3 with the independently obtained estimates through the IAs, will be presented in Section 5.

4.2. Results of the analysis of the IAs

4.2.1. Assessment of methodologies

Table 5 summarizes the reference methodologies used in the IAs. The predominant methodological approach used in the MSs IAs as a reference international framework was the WFD. SES member states also used combinations of diverse methodologies, covering from EU Directives (Habitats Directive, Birds Directive, Natura 2000) and regional conventions (Barcelona Convention or Black Sea Convention) to national methods. OSPAR methodologies (North East Atlantic Ocean region) were also mentioned in some cases indicating the existence of methodological gaps in SES

Table 5
Reference methodologies used in the IAs, where WFD: Water Framework Directive; OSPAR: Convention for the Protection of the Marine Environment of the North-East Atlantic; UNEP MAP: United Nation Environment Program: Mediterranean Action Plan; CR EC: Commission Regulation EC 1881/2006 on setting maximum levels for certain contaminants in food stuffs; ICES: International Council for the Exploration of the Sea; GFCM: General Fisheries Commission for the Mediterranean; DCF (CFP): Data Collection Framework (Common Fisheries Policy); ICCAT: International Commission for the Conservation of Atlantic Tunas; US EPA United States Environmental Protection Agency.

No	Nickname	WFD	OSPAR	UNEP MAP	Habitats directive	Birds directive	Natura 2000	ICES	DCF	ICCAT	CR EC	US EPA	Scientific publications
1	Biological diversity	x	x	x	x	x	x						
2	Non-indigenous species												
3	Commercially exploited fish and shellfish							x	x	x			
4	Marine food webs	x	x					x		x			x
5	Eutrophication	x		x									x
6	Sea-floor integrity	x		x	x		x						x
7	Hydrographical conditions	x	x	x									
8	Contaminants	x	x	x				x			x	x	
9	Contaminants in fish and other seafood										x		
10	Marine litter		x										
11	Underwater noise and other forms of energy												x

regions. In the case of fisheries, member states used quantitative approaches based mainly on commercial stock assessments carried out under the umbrella of international organizations such as the International Council for the Exploration of the Sea (ICES), the General Fishery Commission for the Mediterranean Sea (GFCM) or the International Commission for the Conservation of Atlantic Tunas (ICCAT), and on data collected under the DCF (Common Fishery Policy). For stocks that were not reliably assessed, survey-derived indicators were used. Regarding non-indigenous species, none of the methodologies listed in Table 4 was adopted; most of the countries followed a qualitative approach showing the lack of legislative frameworks or international methodologies as well as reference conditions. Marine litter and underwater noise are emerging issues with no international regulatory frameworks at European level, which prevented member states from delivering appropriate assessments.

The overall analysis of the assessment elements revealed the need for (a) harmonized methodologies, (b) development of methodological standards and thresholds, and (c) adaptation of the coastal water methodology to open sea needs. These recommendations are well in line with those put forward in the IDA (Palialexis et al., 2014) for all European countries.

4.2.2. Assessment of the data and knowledge gaps

Most countries reported data on D1 (Biodiversity) acquired either through national monitoring programs or from Regional Sea conventions (Barcelona Convention: Mediterranean Action Plan data bank). However, many data gaps could be attributed to the wide and complex scope of the descriptor. Significant lack of data concerning offshore issues was underlined, whereas the available data covering coastal waters were scarce, disperse and heterogeneous. Time series datasets were missing, as well as data harmonized at spatial and temporal scale. Lack of data was observed regarding the extent, intensity and frequency of the pressures along with their impacts on biodiversity, as well as lack of suitable monitoring networks. Knowledge presented high heterogeneity among countries, while lack of basic knowledge on marine ecosystems was evident.

Lack of data and knowledge concerning D2 (Non-Indigenous Species) was highlighted in the IAs. Data sources were regional or national research programs; however, low data availability was reported by all countries. Additionally, the fragmentary character of available information and heterogeneity were obvious in terms of spatial and temporal coverage. The observed gaps in knowledge concerned local biota, ecology of allochthonous species and ecosystem along with food web functioning. The need for impact assessment studies and for specific monitoring programs was identified.

Regarding D3 (Fisheries), the countries used data from the Data Collection Framework (DCF), as well as other national or international data collection programs. Concerning OS fisheries, a shortage of data was reported for deep-water fish and the same was true for CS fisheries targeting a large number of commercially exploited fish and shellfish species, which resulted in a rather small number of stocks that have been assessed so far. Moreover, it should be pointed out that D3 was not considered in the IDA (Palialexis et al., 2014) due to the extensive relevant work conducted by ICES (ICES, 2014). According to the latter, the assessment of GES was only available for a low number of stocks using indicators 3.1.1 (fishing mortality) and 3.2.1 (Spawning Stock biomass) and the need for an agreed strategy for coherent assessment of GES in the Mediterranean Sea were underlined. Regarding the Black Sea, only 5 of the 25 important stocks in the region were assessed. Furthermore, ICES highlighted a lack of reliable estimates of indicators from research surveys, which is believed to be closely connected to the standardization process of the DCF in the region.

Concerning data used for the assessment of D4 (marine food webs), countries referred to monitoring programs implemented under different EU and convention commitments (an international bottom trawl survey in the Mediterranean (MEDITS), ICCAT, WFD quality components, Natura 2000 species). However, general lack of pertinent data was underlined, especially for coastal areas, rocky bottoms and deep areas. The lack of data concerning experimental and functional ecology as well as energy fluxes was also highlighted revealing the existing problem of the knowledge gap and the need for further development.

Most countries had extensive datasets on eutrophication (D5) acquired through national monitoring programs in the framework of WFD implementation or the Regional Sea Conventions. Other sources of data were national or international research programs, technical reports, scientific publications and satellite imagery, especially in coastal areas within the framework of monitoring projects. Regarding data gaps, the countries mentioned mainly the lack of spatial coverage and particularly the lack of offshore data on nutrients, phytoplankton and dissolved oxygen. Furthermore, lack of quantitative data on pressures (monthly/seasonal variation, natural/anthropogenic sources) and of appropriate monitoring programs to allow the use of multimetric indices was reported.

For most countries, data regarding D6 (Sea-floor integrity) had been acquired mainly for coastal waters under national monitoring programs in the framework of the implementation of the WFD, NATURA 2000 and the Habitat Directive. International data sources, such as Regional Sea Conventions, EUNIS (European Nature Information System) and MEDITS were also reported. Additional data sources were sedimentology databases and mapping databases, along with scientific publications. However, lack of data and knowledge was reported relative to habitat modelling, size distribution, ecosystem structure, species' response to impacts, and sensitive or opportunistic species. Furthermore, lack of knowledge on the relation pressure-impacts was mentioned.

D7 (Hydrological conditions) illustrated the difficulty to differentiate between the impact of direct anthropogenic pressures and the consequences of global change. The data sources considered were monitoring programs, research projects, and model products. However, data gaps were reported by almost all countries. The lack of long time-series datasets was emphasised, and therefore monitoring programs need to be optimized.

Regarding D8 (Contaminants), many datasets were available on several contaminant families, such as heavy metals, PAHs, or PCBs, along with data on specific contaminants (e.g. TBT, pesticides, detergents) and other pollutants specified in Annexes IX and X to the WFD. All countries reported the availability of contaminant concentration data in water, sediments and biota matrices. Regarding biota, most countries had mussel data. Some countries also used fish data. In the framework of the MYTILOS/ MYTIMED/ MYTIAD/ MYTIOR programs (using transplanted mussels), harmonized data had been acquired for Mediterranean EU and non-EU countries. Despite the availability of an important amount of datasets and long time series, there was still lack of data for specific contaminants. Furthermore, most of the datasets referred to coastal environments and, consequently, an important lack of offshore datasets; a gap that needs to be filled in by the development of appropriate monitoring programs.

For D9 (Contaminants in fish and seafood), a general lack of data was reported by most countries, highlighting the low number of contaminants analysed and the low number of species considered in the assessment. Data sources included monitoring programs at different levels, national, sub-regional and European monitoring networks, such as the MYTILOS project and MED POL (MAP marine pollution assessment and control program) monitoring. It should, however, be noted that these monitoring networks do not aim to monitor the contaminant levels in products placed on the market.

Data on D10 (Marine litter) was reported as scarce and often incoherent. Again, existing datasets concerned mostly the coastal environment. The lack of data for deep areas was reported, and it constituted a gap for the assessment of the environmental status regarding this descriptor. Lack of knowledge was also a major issue for this descriptor. Whenever available, data came from a few monitoring programs, specific research projects, programs led by NGOs or from MEDITS campaigns (which allowed data collection on seafloor litter). However, available data presented restricted spatial distribution, confirming gaps for most countries.

D11 (Underwater noise) was subject to a major lack of data and knowledge, and thus several countries were unable to include it in their assessment. Data sources referred to scientific publications, impact assessment studies and recording of activities from pressure indicator data.

The overall analysis of data and knowledge gaps in the IAs generally revealed (a) low data availability, (b) fragmented knowledge on biodiversity and ecosystem functioning, (c) limited and heterogeneous knowledge on the processes relating pressures and impacts, (d) the need for long-term time series datasets and (e) the need for establishing suitable monitoring networks.

5. Discussion

In order to understand correctly the pressure/impact tables produced (Tables 2 and 3), some additional comments are required. Firstly, even if the PERSEUS reports did not explicitly mention it, our analysis showed the existence of uneven spatial and temporal distribution of data and information: there was a clear North–South "data and knowledge gradient" due to the chronic scarcity of marine data availability in all the disciplines. This reflects the comparatively larger effort in marine observation carried out in the European sector of the Mediterranean Sea. Similar but less pronounced decrease in data and information was observed along the West–East direction, mainly due to the same reasons.

Similar difficulties were found for the open sea in comparison with coastal systems, where the relative easiness in the observational procedures and the less demanding infrastructures produced a larger amount of data. The relative abundance of coastal data was, however, somehow misleading because the distribution was uneven and often reflected the presence of marine biological stations.

Another relevant factor was the different scales of the processes involved in coastal systems vs open waters. The baroclinic Rossby radius of deformation (that is usually used to define the mesoscale) in coastal areas can be one-to-two orders of magnitude smaller than in the open ocean (being inversely proportional to the depth). Since the mesoscale and sub-mesoscale processes deeply influence the spatial and temporal patchiness of chemical and biological parameters, the sampling rate must be higher in order to sample the signals correctly. Thus, even relatively highly sampled coastal areas cannot retain the complexity of the biogeochemical dynamics in all its aspects. The relatively large number of bioprovinces (areas with coherent seasonal variability of key biological variables) present in SES (i.e. Bianchi and Morri, 2000; D'Ortenzio and Ribera d'Alcalà, 2009) confirms the differences between coastal and open sea processes, but also reaffirm the speciality of the Mediterranean Sea calling for more detailed spatial investigation of the open waters.

The independent analysis of data gaps carried out by exploiting the present knowledge for PERSEUS and by in depth analysis of SES IAs produced interesting results that are summarized in Table 4. The PERSEUS evaluation retains the difference between open sea and coastal hot spots while the IAs review does not explicitly account for this difference, even if this issue has been mentioned now and then in the reports. In both assessments, data availability relative to non-indigenous species, marine food webs, marine litter and underwater noise was rated as poor both in IAs and in coastal and open waters. In this case there is a perfect alignment in the opinions of the two communities. In the case of biological diversity, commercially exploited fish and shell fish, eutrophication, contaminants and contaminants in seafood, the prevailing opinion of medium-to-high (eutrophication) data abundance is confirmed only in the IAs and in the coastal evaluation. Conversely, in the open sea only pressures related to nutrient dynamics and ocean circulation (related but not equivalent to eutrophication and hydrographical conditions) are supported by a sufficient data base. This leads to the tentative conclusion that IAs, aimed at responding to the requirements of the MSFD criteria, tended to extrapolate the existing information (mainly along the coasts) to the open seas. This is a major pitfall in IAs, since the analysis of the pressure/impact tables show how, even considering similar pressures, the states, gaps and impacts are clearly different.

The PERSEUS approach and the IAs both agreed on the substantial lack of knowledge for many descriptors. The IAs identified more prominent gaps in biodiversity, NIS, food webs, marine litter and noise, while PERSEUS started to list some of the pressures that are better known or that can be tackled (at least partially) during the project lifetime (marine litter and underwater noise). PERSEUS, however, tried to identify some specific research themes (listed in the third column of Tables 2 and 3) needed to reach a better insight of the (eco) systems for their efficient management.

A very poor knowledge of mechanisms and processes governing the D1 (Biodiversity) descriptor has been acknowledged both by knowledge synthesis and IAs assessment. Even if the quantity of observations for some coastal areas has increased in recent years (see Table 4), the assessment of governing mechanisms that rule biodiversity in the marine environment is still at its early stage (e.g. there are no benchmarks for the assessment) because of the intrinsic difficulties in collecting multidisciplinary datasets with the appropriate sampling strategies accounting for the peculiar traits of marine ecosystems. Semi-qualitative evaluations have been based on a subset of organisms, with a robust taxonomic profile, which have been recorded over decades and whose abundance might be plotted over time. However, this would not provide an assessment of the trend in biodiversity but only of the trend in community composition. Some information is available from the decrease in species richness of highly impacted environments, which have been monitored over the last decades because of being hot spots, e.g. the Black Sea (Kideys, 2002). Another reason specific to the pelagic environment, where a key role is played by unicellular plankton, is that a clear definition of diversity is not yet available.

Both IAs analysis and the knowledge synthesis process agree that food web structure is not known with enough detail to answer the D4 question (Marine food webs). Despite the fundamental contributions during the last century in providing general patterns for the structure of the marine food web (i.e. Longhurst, 2010; for an overview of the pelagic environment), new views are emerging on the different components of the food webs, which show a much higher complexity than previously thought. Changes that might be ongoing but are presently overlooked in certain processes can be therefore more difficult to be assessed. A few hypotheses, e.g. the impact of removing large predators from the ocean by intensive fishery (Daskalov, 2002) or strongly increasing nutrient inputs in semi-enclosed coastal sites have been put forward and to some extent have been reflected in the reports, but there is no systematic analysis of the food webs as such.

It is worth noting that biodiversity and food webs, including the microbial loop, are in fact the essential trait of ecosystem functioning and that their poor coverage anticipates the difficulties in producing a sound assessment of the Environmental Status and effectiveness of mitigation measures.

The role played by gelatinous macrozooplankton in the marine ecosystem and its impact on socio-economic activities and on human health was not sufficiently highlighted, but emerged clearly from the scientific analyses of recent data and the success of the Jelly Fish Spotting campaign promoted within PERSEUS. Increased in-depth knowledge of the behaviour and ecology of these species seems therefore timely, owing to the fact that they directly and indirectly affect many descriptors.

A cross cutting theme, which was not properly considered, is related to the resistance and resilience of the ecosystems. The combined analysis of pressures and impacts shows that pressures are not always directly related to the impacts and that the typical response time of the (eco) system is largely unknown. This means that the absence of evident modifications in the environmental status does not automatically imply the absence of driving pressures. Conversely, even if mitigation measures are adopted to reduce the pressures, the improvement of the environmental status will depend on the response time of the ecosystem and the strength of the pressures. Pressures indeed can drive an ecosystem out of its equilibrium, by creating a (potentially) irreversible regime shift.

The time scale of ecosystem response to external perturbations should also be considered during the monitoring phase: even if a set of measures is adopted the eventual improvement can heavily depend of the ecosystem time scale of reaction. This delay should be carefully considered when planning the MSFD monitoring phase.

An open and urgent question is how the GES can be influenced by the cumulative effects of multiple stressors. Multiple and sometimes complex interactions occur or are anticipated between the different natural and anthropogenic pressures (MERMEX group, 2011). Ecosystem response to concomitant multiple stressors is known to be non-linear and its resilience is reduced if compared to the impact of the same stressors applied one-by-one (e.g. Crain et al., 2008). This may result in reducing the ranges of indicators where GES is defined. Besides levels, the typical rate of the induced change should be considered since it is frequently (but not always) much faster when induced by humans.

6. Conclusions

The results obtained during the first phase of the PERSEUS project exploit its international dimension and the scientific excellence of the consortium by implementing a truly transnational science-based bottom-up approach in assessing major natural and anthropogenic pressures (i.e. vectors of change) in open seas, and choke points (i.e. straits, coastal 'hot spots'). At the same time, a joint independent analysis of the Initial Assessment documents from SES member states (top-down driven by the MSFD implementation requirements) has been carried out. In this article these two complementary approaches have been compared, in order to elicit, presenting light of current best knowledge, the gaps in data and in understanding processes and their mutual interactions.

The major achievements can be summarized as follows:

- The PERSEUS approach privileged an overview of the pressures and their roles in altering the environmental status identifying their impacts.
- The science-based consolidated evidence dictated a dual approach for PERSEUS retrospective analysis: the first applied to large scale processes considered as pressures for open sea environmental status, the second one considering coastal hot spots where a superposition of different pressures is present (IAs did not discriminate coastal vs open waters).
- The PERSEUS approach and the analysis of IAs documents exhibit a striking correspondence in data and knowledge gaps analysis, despite the differences in the communities producing the reports, the data bases and the methodologies adopted. Five (6 in the case of PERSEUS) over 11 descriptors suffer scarcity of data.
- There is a large consensus supporting the statement of Commission Decision 2010/477 EU on the substantial need to develop additional knowledge and understanding to implement GES in a truly science-based way. So far, some of the indicators resulted to be almost impossible to be evaluated for operational purposes (e.g. those related to biodiversity, food web structure, marine litter and microplastics, underwater noise and energy input due to human activities).
- No evidence of eutrophication processes has been found or any risk of substantial modification of trophic conditions is foreseen for SES open waters. A potential modification of the stratification due to global warming instead can reinforce the oligotrophic regime typical of the Mediterranean Sea. Despite the presence of eutrophic conditions in some hot spots, contradictory examples have been found in some coastal waters.
- A number of additional targeted scientific priorities have been identified for SES to help reduce the uncertainties and the gaps in data and knowledge in the case of open seas and coastal hot spots. These have been reported in the pressure/impact tables. Among them, the largest gap consists in the lack of a proper understanding of marine biological diversity and food web functioning, which is far to be operational and deserves a targeted study, being the backbone of any holistic approach to the management of the marine environment.

As a general suggestion, the precautionary principle should be adopted in all cases where the Communication from the Commission (European Commission, 2000) conditions can be applied. In addition, new scientific tools are becoming mature enough to evaluate the effectiveness and the associated risks of the mitigation actions and measures. Adaptive scenario analyses incorporating also the socio-economic component (i.e. PERSEUS Adaptive Policy Tool Box) and decision support systems are two relevant examples. These tools should increasingly be used for the assessment of the response of marine ecosystems, whose uncertainty is and will be an intrinsic feature of such 'highly non-linear' complex systems.

It is also commendable that the scope of the MSFD will go beyond a reductionist definition of 'impacts' in order to assess 'impacts' at the level of ecosystem functioning. PERSEUS made an effort to put in practice this vision, though focusing on the robustness of inferred links between pressures (perturbations), which are easier to quantify, once selected, and the impacts, i.e. changes in the state of the ecosystem.

In conclusion, with this article we tried to demonstrate how the PERSEUS approach added value to a common effort of a large scientific community to obtain a sound and extensive analysis and state-of-art of knowledge and understanding of the Southern European Seas state.

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