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The shallow-deep-sea connection: a strategic route for marine Research, Conservation, and Management

Abstract – Deep-sea ecosystems represent the world's largest biome. The deep sea includes highly complex and heterogeneous ecosystems including extreme habitats. Most of it is still almost completely unknown. Deep-sea ecosystems are extremely diverse and some are tightly connected to shallow water systems in many ways. These bidirectional interactions are largely unknown, hampering our understanding the complex ecological factors shaping populations, assemblages and ecosystem functioning in a holist way. The anthropogenic inputs of materials and contaminants are extending into the deep sea. The deep ocean is an historical repository of litter, waste and dumping, including the micro-plastics. Global change is expanding into deep waters, causing warming, acidification, oxygen depletion and synergistic impacts on deep-sea assemblages. The Marine Strategy Framework Directive (MSFD) is paving the way to provide baselines and tools to assess the good environmental status of marine ecosystems, including the deep sea. To implement the MSFD on deep-sea ecosystems some key actions can be proposed: 1) identify the essential ecological variables enabling the monitoring of deep-sea habitats; 2) define standard protocols and sampling strategies for their monitoring; 3) identify the key areas for long-term observations and monitoring; 4) identify the baselines for future deep-sea monitoring studies based on regional descriptors and indicators; 5) create a platform to share the available information from different databases on deep sea and unifying the data repositories; 6) identify the key areas deserving protection and the procedure and conditions to establish off shore and deep-sea protected areas, within the frame of transnational cooperation agreements.

Keywords: Deep Sea, Global Change, MSFD, Impact, Conservation

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1. *Introduction*

Deep-sea ecosystems include the waters and sediments beneath approximately 200 m depth. They represent the world's largest biome, covering more than 65% of the earth's surface and including more than 95% of the global biosphere [Danovaro *et al.*, 2014]. The deep sea encompasses many extremes on Earth, with an average depth of ca 3,750 m, lack of sunlight, average temperatures <4 °C and average hydrostatic pressure of approximately 400 atm.

We now recognize the deep sea as a highly complex and heterogeneous ecosystem containing several different, and sometime contrasting habitats. The deep-sea biosphere also includes Earth's largest regions partially or completely devoid of free oxygen (i.e., hypoxic and anoxic environments), which include the oxygen minimum zones (expected to largely expand in relation to the global change [Danovaro *et al.*, 2017a]), the deep hypersaline anoxic basins, and the deep Black Sea (the single widest anoxic region in the world). Until today, researchers have documented life everywhere in the deep sea, with active metabolic life from -2 to >100 °C, even in sediments at 10,000 m depth and microbial life at 1,000 m below the seafloor [Lomstein *et al.* 2012; Danovaro *et al.* 2014].

Despite its huge dimension, our knowledge of both pelagic and benthic deep-sea diversity is still very scant. In the last decades, an increasing number of studies have been conducted to investigate deep-sea biodiversity in several regions of the world. But, these studies focus on a limited number of taxa and are typically characterized by a limited spatial or temporal scale of investigation due to the high costs of ship time and technologies needed to perform deep-sea investigations [Danovaro, 2010a].

The global deep seafloor accounts for a total area of more than 434 million of km^2 and contain a huge amount of resources that are attracting an increasing attention for industrial exploitation [Danovaro *et al.*, 2017b]. At the same time, detailed habitat mapping of the deep seafloor is still extremely limited and without an improved knowledge of deep-sea topographic features at different spatial scales is difficult to understand of the relevance of these resources as well as the factors driving deep-sea biodiversity. These gaps hamper our ability to define high-sea and deep-sea areas deserving.

2. *Deep-sea biodiversity*

The deep ocean harbours several types of habitats and varied structure and landscapes, from open slope systems to canyons, from seamounts and volcanic ridges, to deep-water coral reefs, from hydrothermal vents and cold seeps to abyssal plains.

The presence of several peculiar, heterogeneous and diversified habitats and landscapes, can influence the abundance and distribution of deep-sea species. However, a comparative analysis of the deep-sea benthic diversity across different ecosystem types is difficult because of the different amount of data collected and the presence of different animal groups in each system.

Available studies based on small to large faunal diversity components indicate that deep-sea canyons, for instance, can act as essential habitats for certain megafaunal species, including either planktonic and benthic species. Here the species find a suitable environment for feeding, reproduction, and growth, often related to the increased availability of organic matter due to the enhanced transport of particles from the shelf down the canyon [Ramirez-Llodra *et al.*, 2009; Sardà *et al.*, 2004; 2009a; Gili *et al.*, 2000; Vetter and Dayton, 1998; Tyler and Ramirez-Llodra, 2002]. Moreover, higher sessile megafaunal diversity is reported in several deep-sea canyons when compared to its adjacent open slopes. This pattern apparently does not hold for smaller faunal components.

Open slopes of continental margins host most of the peculiar and diverse deep-sea ecosystems. Among them, cold-water corals create complex seabed structures, which provide refuges for many species and increases habitat heterogeneity, creating a suitable environment for recruitment and growth of many other species. This is confirmed by the large number of megafaunal species observed in these habitats and by the extremely high values of smaller faunal (meiofaunal) diversity, which displayed significantly higher values in coral systems than in any other ecosystem type. In addition, deep-water coral forests and sponge fields contribute to increase the spatial heterogeneity of the deep-sea habitats. Their census and mapping are in progress, but it is already evident that these ecosystem engineers provide and important contribution to the overall deep-sea biodiversity, by hosting exclusive species or contributing to the beta diversity of the area [Bianchelli *et al.*, 2013; Cerrano *et al.*, 2010; Bo *et al.*, 2013 and 2014; Cau *et al.*, 2015; Angeletti *et al.*, 2015 Deidun *et al.*, 2014]. Open slopes host also a number of cold seeps and other associated structures, characterised by primary production due to chemoautotrophic bacteria, which fuel the benthic community with a supplementary and continuous food source not found in the heterotrophic deep-sea ecosystems.

3. *The Shallow-deep connection*

The continental margins (100–4000 m depth) comprise approximately 15-20% of the seabed surface. These are dynamic, heterogeneous systems shaped by several factors and largely influenced by coastal and terrestrial inputs. Water masses with distinct hydrographic characteristics overly the bottom, creating cascading events, strong bottom currents, sharp gradients in several variables (pressure, temperature, oxygen). Shallow and deep–sea ecosystems are intimately linked in many ways, including the food supply from the photic zone to the deep sea and the mutual exchange of organisms, their larvae/propagules. Huge daily migrations of plankton and nekton characterise the water column till abyssal depths [Levin *et al.*, 2018]. Deep-water upwelling fuel primary production on continental shelves and most of the continental slopes show an intense and bidirectional exchange of materials, energy and organisms. These features make the continental margins the most active and dynamic connecting systems between shallow and deep. Canyons, furrows, mounds and banks interact with currents to create flow conditions suitable for reefs of corals, sponges, cnidarians, and giant bivalves. These species are ecosystem engineers (i.e, structure-forming species) which contribute to create new habitats, which in turn host a number of vertebrate and invertebrate species. As a result of their abiotic and biotic heterogeneity, continental margins host unexpectedly high rates of population differentiation and some of the planet's highest species diversity. The present of bidirectional interactions between shallow and deep-sea ecosystems suggests that our current approach and knowledge to the study of marine science is absolutely insufficient to identify the driver of change in coastal ecosystems and to understand the complex ecological factors shaping populations, assemblages and ecosystem functioning in the deep sea.

4. *Status of conservation of deep-sea species and habitats*

Data regarding the conservation and endangered status of many deep-sea species and habitats is quite limited. Offshore and deeper-water species are indeed much less investigated than shallower counterparts. Deep-sea sharks, rays, and chimaeras appear extremely vulnerable to overfishing and bycatch and many of them are considered threatened or near threatened to disappear at global scale. The study of sharks and rays in the deep-sea appears particularly challenging, and little is known about their ecology and population status. Even less is known regarding the potential impact of human activities. Many of these slow-growing, long-living species are impacted by the proliferation of shark fisheries and by the harmful fishing practices that have expanded over the past few decades. Larger and more powerful vessels and improved technology (more accurate navigation and fish detection equipment) developed during recent years represent a risk for their status, allowing to fish in deeper waters. The deep sea hosts also a variety of deep-sea anthozoans species most of which are still not included in the Annex II of the SPA/BD Protocol of the Barcelona Convention or in other IUCN lists for endangered species. Despite their important role in ecosystem functioning, deep-sea corals are not sufficiently protected by the existing MPA network, which is weak in its coverage of deep-sea benthic habitats [Gabrié *et al.*, 2012]. In order to improve deep-sea biodiversity, it is crucial to include into the existing regulations additional deep-sea species to the current lists of threatened species (e.g. anthozoans, sponges, molluscs). It is also important that regional and national bodies collaborate to eliminate destructive fishing practices through effective management measures and establish a coherent and comprehensive network of MPAs, by identify potential new and open sea MPAs including deep-sea benthic habitats.

5. *Impacts on deep-sea ecosystems and the marine strategy approach to define their quality*

The increasing anthropogenic inputs of materials and contaminants into the ocean are extending the direct human impacts at global scale and down to the deep sea [Llodra *et al.*, 2011]. The deep-sea is characterised by the presence of many species of slow growth, which make them very vulnerable to overexploitation and disturbance.

A paradigmatic example of the human impact in the deep ocean is represented by deep-sea fisheries and the evident resource depletion and environmental damage caused by them [Pusceddu *et al.*, 2014]. Unregulated fishing in the deep sea has also led to the destruction of vulnerable marine ecosystems of the seafloor, such as the deep-water coral banks transformed into fields of coral rubbles [Bongiorni *et al.*, 2010; Robinson *et al.*, 2014].

Dumping of sewage, mining waste, dredge spoil, pharmaceuticals and radioactive waste in the deep sea, although reduced in the last years (apart from illegal dumping), still represents a major threat to the deep-sea ecosystems. Also chemical contaminants (organic pollutants, heavy metals, radioelements, pesticides, herbicides and pharmaceuticals) accumulate in the deep sea. They are taken up by deep-sea organisms and biomagnified (i.e., increasing the concentration of contaminants per unit of biomass of the higher trophic levels).

The deep ocean was historically a repository for litter from shipping, waste and dumping at sea, which is still present and estimated in the order of >636,000 t yr^{-1} of litter discarded into the ocean from shipping including illegal dumping. In particular, litter density is slightly higher in deep-sea basins (1.55±0.57 kg ha^{-1}) compared to continental slopes (1.36±0.34 kg ha^{-1}) and submarine canyons (0.71±0.25 kg ha^{-1}). Sites located in deep basins and continental slopes are dominated by clinker which is the residue of burnt coal [Ramirez-Llodra *et al.*, 2013].

Accidents in the maritime environment, such as industrial accidents and the sink of oil tankers can moreover release vast amounts of hydrocarbons to deep waters, impacting the water column and the deep benthos communities. Oil tankers are not the only ones that contaminate the sea with petroleum hydrocarbons. Also cargo ships, fishing boats, leisure craft and naval vessels discharge oily waste, adding more tons of oil into the sea. Oil spills are more frequently observed along the major shipping routes. Plastic debris is frequently observed in the deep sea. Recent evidence indicates that the deep sea is the major sink for macroplastic debris and microplastic fibres [Ramirez-Llodra *et al.*, 2013; Van Cauwenberghe *et al.*, 2013]. Microplastics can have physical impacts on marine organisms and can be associated to the transport of other pollutants [Zettler *et al.*, 2013]. Chronic inputs of litter from terrestrial sources are another major issue, particularly for plastics and persistent pollutants. Recent studies documented on the presence extensive damage on very fragile coral forest caused by fishing activities and by the presence of extremely numerous lost or abandoned fishing gears in deep areas [Taviani *et al.*, 2015, D'Onghia *et al.*, 2016].

Global change, leading in many cases to surface and deep water warming, acidification, oxygen depletion and possibly shortfalls in productivity will have an impact on deep-sea assemblages. The impact although of global dimension will not be homogeneous and some regions such as polar regions and the semi-enclosed basins, will be primarily impacted.

Among marine habitats, the smallest absolute changes in biogeochemical parameters are projected on deep-sea habitats by IPCC scenarios combined with empirical deep-sea biodiversity models (e.g. soft- and hard-bottom benthos, seamounts and vents), whereas the largest changes are predicted to occur in shallow-water habitats like coral and rocky reefs, seagrass beds and shallow soft-bottom benthos [Mora *et al.*, 2013], and biodiversity hotspots [i.e. areas with high numbers of species of a particular taxon; Myers, 1988]. Even deep-sea ecosystems, for which the magnitude of biogeochemical shifts will be smaller, will undergo substantial biological responses, mainly because the deep ocean is much more stable, and thus its faunas are likely adapted to narrower ranges of environmental variation than those in shallow marine habitats [Danovaro *et al.*, 2004; Yasuhara *et al.*, 2008]. Yet, the limited accuracy of these projections [Mora *et al.*, 2013] and the specific vulnerability of deep-sea ecosystem to change in environmental conditions and nutritive resources [Levin and Le Bris, 2015] challenge our capacity to efficiently anticipate impacts on a regional and ecosystem-type basis.

6. *Monitoring and managing vulnerable deep-sea ecosystems*

Spatial conservation measures and other forms of sustainable management need monitoring, control, surveillance (MCS) and enforcement of regulations. Improvements in deep-sea technologies such as use of remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) are providing solutions for deep-sea monitoring. However, such technologies are not available to all countries, with the risk of a highly unbalanced monitoring capacity among regions. This problem is already evident for the scientific knowledge acquired on deep-sea ecosystems.

Moreover, deep-sea campaigns are costly, but field work and multidisciplinary approaches are necessary to urgently implement the monitoring strategy of the deep sea. The identification of deep sentinel sites for long-term monitoring of the ecological status including sites with different types of habitats would be a step forward. Furthermore, long-term deep-sea observatories could be implemented with the technology and the tools to appropriate monitor the biological and ecological components over the long-term.

The Marine Strategy Framework Directive (MFSD) is paving the way in this perspective, pushing the EU countries to provide baselines and tools to assess the good environmental status of marine ecosystems, and to extend the monitoring to the deep sea. Although the Directive involves only EU countries, the monitoring approach, tools, and descriptors, which are being defined by EU countries for the monitoring of deep-sea ecosystems could represent a basis for the monitoring of the whole deep-sea basin as the MSFD has the unprecedented advantage of focusing on biodiversity and ecosystem functioning, instead primarily on the chemical or characteristics of the ecosystem. In addition, the use of this approach would have the advantage of having already allocated the needed financial resources and trained the national institutions charged of the monitoring activities in the deep sea.

The present knowledge of the anthropogenic pressures and their effects in the deep sea is limited, but sufficient to start a monitoring program. Significant environmental impacts could be localized in relation to existing oil and gas exploration and deep litter disposal (including weapons, industrial wastes, persistent organic pollutants, and heavy metals). Equally, future threats related to fisheries or other activities on seamount or seafloor with massive sulphides («black smokers areas») as well as the potential use of deep-sea areas for sequestering carbon dioxide or the impact of mining (e.g., manganese nodules) will need to be monitored. For example, fine scale multi-beam could be easily used to detect the presence of trawling in banned areas or SPAMI.

The effects of climate change and related stressors including de-oxygenation and change in surface productivity at depth will be particularly intense in some deep-sea regions (e.g., in areas subjected to the development of minimum oxygen zones) and these effects should be adequately considered in future monitoring strategies. It is probably expected that the response of the deep-sea ecosystems will be different in the western and eastern basins.

Moreover, the impacts of ocean acidification, although not as well constrained as at shallow depths could impact the deep sea, and recent findings confirm that acidification is already affecting the deeper waters in both basins.

7. *Key actions for developing a strategy of deep-sea habitat conservation*

On the light of these considerations the following key actions can be proposed to implement a strategy of deep-sea monitoring:

1. Identify the essential ecological variables for different habitat types, including those enabling the identification of the vulnerable habitats;
2. define common protocols and sampling strategies for the monitoring of deep-sea ecosystems;
3. identify the key areas for long-term observations and monitoring;
4. identify the baselines for future deep-sea monitoring studies based on regional descriptors and indicators;
5. create a platform to share the available information from different databases on deep sea and unifying the data repositories;

6. identify the key areas deserving protection and the procedure and conditions to establish off shore and deep-sea protected areas, within the frame of transnational cooperation agreements.

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