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REVIEW

Adding the Third Dimension to Marine Conservation

Noam Levin[1,2], Salit Kark[3], & Roberto Danovaro[4,5]

[1] Department of Geography, The Hebrew University of Jerusalem, Mount Scopus, Jerusalem 91905, Israel
[2] School of Earth and Environmental Sciences, ARC Centre of Excellence for Environmental Decisions, University of Queensland, Brisbane, Queensland, Australia
[3] The Biodiversity Research Group, The School of Biological Sciences, ARC Centre of Excellence for Environmental Decisions and NESP Threatened Species hub, Centre for Biodiversity & Conservation Science, The University of Queensland, Brisbane, Queensland, Australia
[4] Department of Life and Environmental Sciences, Polytechnic University of Marche, 60131, Ancona, Italy
[5] Stazione Zoologica Anton Dohrn, Naples, Italy

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Correspondence
Noam Levin, Dept. of Geography, The Hebrew University of Jerusalem, Mt Scopus, Jerusalem 91905, Israel. Tel: +972-2-5881078; fax: +972-2-5820549.
E-mail: noamlevin@mail.huji.ac.il
Salit Kark, The School of Biological Sciences, ARC Centre of Excellence for Environmental Decisions and NESP Threatened Species hub, Centre for Biodiversity & Conservation Science, The University of Queensland, Brisbane, Queensland, Australia.
Tel: +61-7-336-51376;
E-mail: s.kark@uq.edu.au

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Abstract

The Earth's oceans are inherently 3-D in nature. Many physical, environmental, and biotic processes vary widely across depths. In recent years, human activities, such as oil drilling, mining, and fishing are rapidly expanding into deeper frontier ocean areas, where much of the biodiversity remains unknown. Most current conservation actions, management decisions and policies of both the pelagic and benthic domains do not explicitly incorporate the 3-D nature of the oceans and are still based on a two-dimensional approach. Here, we review current advances in marine research and conservation, aiming to advance towards incorporating the third dimension in marine systematic conservation planning. We highlight the importance and potential of vertical conservation planning and zoning from the sea surface to the seafloor. We propose that undertaking marine conservation, management and environmental decisions in 3-D has the potential to revolutionize marine conservation research, practice and legislation.

Highlights

1. The marine realm is inherently 3-D.
2. Conservation and policy decisions are often based on benthic ecosystems.
3. The deep sea includes the majority of ocean volume.
4. However, is it often not explicitly addressed in conservation plans.
5. We provide a first review of existing 3-D marine planning.
6. We develop a framework for explicitly including depth in marine conservation.

Ecological gradients along the water column

The world's oceans cover nearly 71% of the Earth's surface, and within them, offshore and deep-sea areas represent the largest biome on Earth, covering >65% of the globe. Offshore and deep-sea areas hold >95% of the planet's water volume (Danovaro *et al.*, 2010) and provide most of the sea fish harvested and consumed by humans (Game *et al.* 2009). The Earth's oceans encompass vast gradients ranging from sea level down to ca. 12,000 m, from territorial waters to the High Seas, and from

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tropical to polar climates. Marine biodiversity and communities vary widely along the water column, yet our knowledge of deep pelagic ocean biodiversity remains very limited, especially for pelagic and demersal species found below 1,000 m depth (Webb *et al.* 2010). A major structuring variable of the water column includes depth, which co-varies with temperature, salinity, pressure and the penetration of sunlight (Smith *et al.* 2008; Levin & Dayton 2009; Gambi *et al.* 2014). This results in a layering of open-ocean pelagic ecosystems (Ramirez-Llodra *et al.* 2010) into bathomes, including the mesopelagic, bathypelagic, and abyssopelagic zones (see Glossary of terms; Figure 1).

has been largely documented in the oceans (Rex *et al.* 2005). Albeit the knowledge gaps, we now know that pelagic and deep-sea biodiversity is highly complex and rich, with unique deep-sea habitats (e.g., seamounts, submarine canyons, hydrothermal vents, cold seeps) sustaining unique marine populations and endemic species (Carr *et al.* 2003; Van den Hove & Moreau 2007; Danovaro *et al.* 2014). Therefore, if we aim to conserve marine biodiversity, it is essential that biodiversity features of interest for conservation be identified in a more systematic way for different depths and parts of the water column, including the seabed and deep waters.

Glossary

3-D habitat mapping: habitat mapping that includes multiple bathymetric ranges of the distribution of biodiversity. This enables to include species distributions by incorporating their life cycle, trophic interactions and exchanges between the water column and the seafloor.

Abyssopelagic zone: water column and its life forms at depths comprised from 4,000 and 6,000 m depth. It is the largest biome of the biosphere both in terms of surface and volume.

Bathome: A biome, or an environmental region, characterized by the bathymetric distribution of its biota.

Bathypelagic zone: water column and its life forms at depths comprised from 1,000 to 3,000–4,000 m depth.

Cold seeps: habitats characterized by fluid emissions at ambient temperatures, containing hydrocarbons and/or high salinity fluids, and hosting a specific and often endemic biodiversity.

Continental shelf: the underwater landmass extending from a continent, usually ending at a point where the slope increases greatly. This area of shallow sea (usually less than 150–200 m deep) was largely exposed during glacial periods.

Deep-sea benthic (or seafloor) biodiversity: the different life forms inhabiting the surface and subsurface sediments (typically in the top 1 m beneath sediment surface for animal life).

Deep-sea ecosystems: ecosystems at depths greater than 200 m, which include all marine ecosystems with the exception of the continental shelves and epipelagic zones (confined to the top 200 m of the water column).

Deep-sea pelagic biodiversity: the biological diversity and different life forms inhabiting the water column from 200-m depth to the seafloor.

Deep-water corals: banks or reefs of cold-water (also called deep-water) corals (without symbionts) and living at depths comprised from less than 100 m to abyssal depths.

Flag species: megafaunal species of high interest for marine biodiversity conservation, often including charismatic species (marine mammals, reptiles, and top predators).

Hadopelagic zone: water column and its life forms at depths comprised from 6,000 to 11,000 m depth and more. It is a minimal portion of the marine biosphere, comprised within the oceanic trenches.

Hydrothermal vents: deep-sea ecosystems typically located along mid-oceanic ridges characterized by emissions of fluids at high temperatures and hosting a specific, highly adapted and largely endemic biodiversity.

Manganese nodule fields: Found on the deep-sea floor, generally at bathyal/abyssal depths characterized by presence of manganese nodules and other raw materials and host a fauna that exploits the soft and hard substrates of the systems.

Mesopelagic zone: water column and its life forms at depths comprised from 200 to 1,000 m depth.

Nictemeral cycle: also known as the circadian or diurnal cycle, the regular variation between day and night, light and darkness

Open seas, open oceans: also known as the pelagic zone (derived from Greek πέλαγος [pélagos], meaning "open sea"). Marine areas, which are neither close to near the shore nor the bottom.

Photic layer: the water layer where light penetration allows photosynthetic primary production. Generally assumed to be from the surface down to around 200 m depth.

Seamounts: mountains rising more than 1,000 m from the deep-seafloor without reaching the sea surface.

Submarine canyons: submarine incisions from the shelves to the bathyal or abyssal plains that create topographically complex deep-sea habitats, rich in biodiversity.

Upwelling: wind-driven and/or topographic-induced movement of water masses from the nutrient-rich deep-sea to the photic zone.

While our knowledge on marine biodiversity is heavily biased towards near shore and shallow marine areas (Costello *et al.* 2010; Danovaro *et al.* 2014), marine species richness does not necessarily decline with depth (Van den Hove & Moreau 2007). A unimodal pattern of benthic biodiversity with peaks around depths of 1,500-2,500 m

Connections between shallow and deep areas and conservation implications

Shallow and euphotic habitats and deep-sea systems can be tightly interconnected. Many pelagic and benthic species, particularly macro and megafaunal components,

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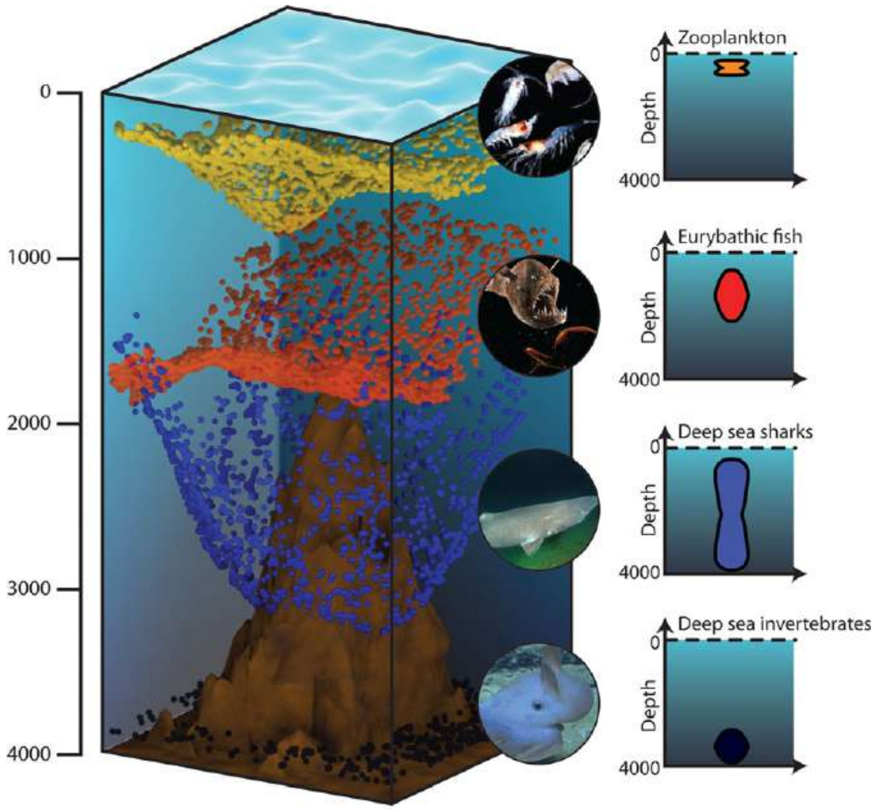

Figure 1 Illustration of the three-dimensional structure of deep-sea ecosystems. The figure includes both the benthic component (seafloor) and the pelagic component (water column), with an example of the diversity of various planktonic components across depths and some life cycles and behavioral aspects. The mesopelagic deep ocean (also called the twilight zone) is generally defined as the part of the water column between 200 m and ca. 1,000 m depth. The upper limit coincides with the maximum depth of seasonal variability in temperature, the seasonal thermocline, and the penetration of sunlight sufficient to support photosynthesis. Between 200 to 1,000 m depth, light can penetrate and influence the nictemeral cycle of many planktonic and benthic species. Below 1,000 m begins the entirely dark portion of the oceans. The zones beneath the mesopelagic (see Glossary of terms), which are the bathypelagic and abyssopelagic zones, comprise nearly 75% of the volume of the oceans and are generally less influenced by the seafloor and its ecological communities. Light, chemical, and physical clines are barriers to marine species across depths; the photic cline, thermocline and the halocline can limit the photosynthetic production and export of primary production, and hamper the biological exchange among specific classes of organisms.

show life cycles that include meroplanktonic larvae spread by currents in offshore and deep-sea areas. Downslope and upslope currents can transport larvae, propagules and juveniles across depths and ecosystems allowing a continuous exchange between shallow and deep waters (Lee *et al.* 1992). The deep-seafloor also hosts several commercially important species, which seasonally or periodically move to shallow water regions, replenishing the overexploited shallow populations (Demestre & Martín 1993; Costantini *et al.* 2010).

The relevance of the three-dimensional (3-D) structure of the oceans and connectivity of the deep-sea ecosystems is also evident in terms of refuge habitats. Daily vertical migrations are known for zooplankton which, depending on size, can move up to 2 km or even more during the night to the surface to feed and then return to the deep to escape predation. For example. in Antarctica, krill finds refuge from predation at abyssal depths (Quetin & Ross 1991) and several species of plankton, including copepods, euphausiacea, decapoda, and fish (e.g., the Antarctic silverfish, *Pleuragramma antarticum*) recruit at depths of 500–1,000 m and below. Several charismatic species, from sperm whales to sea lions and even penguins have been observed hunting and feeding on large plankton specimens in the deep-sea, down to depths below 2,000 m (Figure 1). In addition, dynamic ocean management (Lewison *et al.* 2015; Maxwell *et al.* 2015), which considers temporal changes in species movements, should be enhanced. Some examples of efforts to incorporate depth in marine conservation and management exist, such as the case of the southern Bluefin tuna, where the management plan

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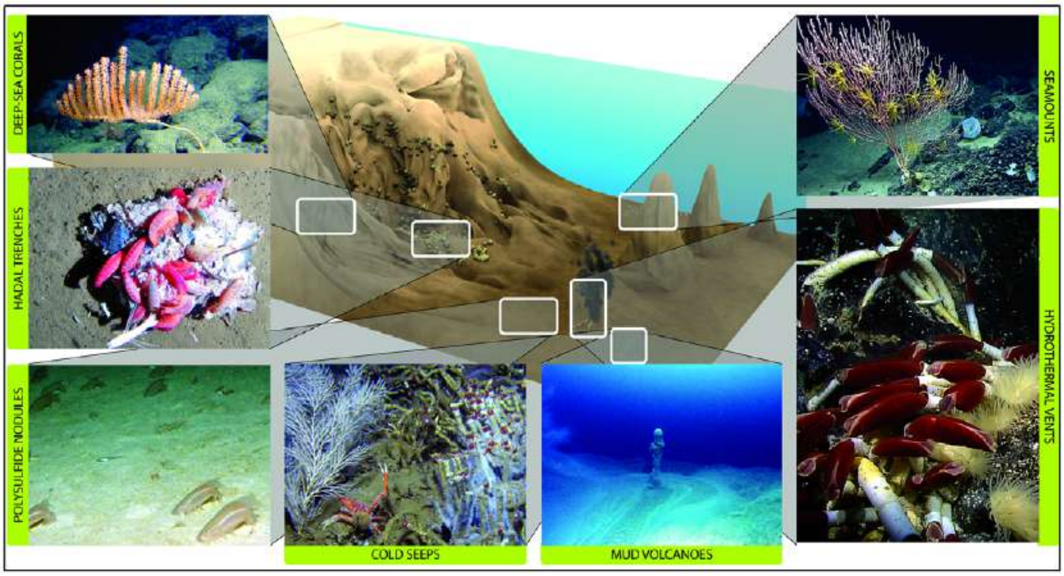

Figure 2 An example of the diversity in vulnerable marine habitats, with special focus on offshore and deep-sea systems. Various deep-sea habitats of the mesopelagic and bathypelagic zones are shown, clockwise from the top-right: seamounts, hydrothermal vents, mud volcanoes, cold seeps, polysulfide nodules, hadal trenches, deep-sea corals.

uses habitat preferences predicted in 3-D based on pop-up satellite archival tags (Hobday *et al.* 2010).

Since 1840, at least 30 new ecosystem types and a host of newly identified marine species have been discovered at depths ranging from 200 m (Danovaro *et al.* 2014) to 11,000 m deep. A series of recent discoveries have enhanced our knowledge of unique deep-sea habitats and ecosystems deep-sea (Ramirez-Llodra *et al.* 2010; Danovaro *et al.* 2014). A specific feature of all of the newly discovered deep-sea ecosystems is that they host previously unknown biodiversity and species new to science (Snelgrove & Smith 2002). These deep-sea habitats include seamounts, canyons, ridges, cold seeps, hydrothermal vents, manganese nodule fields, deep-water coral areas, and other unique habitats (Figure 2).

Seamounts and canyons are emblematic examples of the complexity and difficulty in expanding marine conservation into the deep-sea. Seamounts serve as important hotspots for pelagic species (Morato *et al.* 2010) and host many endemic species. Studies in New Zealand suggest that the degree of endemism of seamount habitats is close to 50% (de Forges *et al.* 2000). Since these systems are a priority target for bottom trawling fisheries and mining of economically important metals, their protection should be one of the highest priorities. Of 9,951 seamounts mapped globally by Harris *et al.* (2014), 6% were partly or fully located within marine protected areas (MPAs) based on WDPA; (IUCN & UNEP-WCMC 2015). Thus, at present only a small portion of the pelagic and benthic seamount biodiversity is protected, well below the Aichi protection target of 10% for marine ecosystems (CBD 2011).

Much uncertainty with regard to biodiversity and its management also applies to submarine canyons. Submarine and deep-sea canyons (see Glossary) are major incisions into the continental slope and rise, down to the abyssal floor (Harris & Whiteway 2011). They act as key avenues for transportation of sediment, organic carbon and nutrients from the land to the deep ocean floor and vice versa. Submarine canyons are highly dynamic zones being more common along active continental margins, creating a highly variable seafloor, often supporting complex ecosystems and highly diverse assemblages (Harris & Whiteway 2011). As demonstrated by Porter-Smith *et al.* (2012), drainage analysis algorithms can be used to quantify habitat heterogeneity and classify submarine canyons. These systems play unique ecological and functional roles, serving as feeding areas for large cetaceans, yet they are intensively trawled for the exploitation of commercially relevant species such as red shrimp (Ramirez-Llodra *et al.* 2010; Puig *et al.* 2012).

Expansion of human activities into the deep ocean

Marine protected areas (MPAs) are aimed at conserving marine species richness and biomass, preventing habitat (e.g., coral) loss, and sustaining fisheries management

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outside protected areas (Halpern 2003; Selig & Bruno 2010). However, MPAs presently cover less than 7% of delimited exclusive economic zones globally, are very unevenly distributed across the Earth's countries and oceans, and were mostly established in coastal areas in the past (Watson *et al.* 2014). However, even in countries that have greatly expanded their MPA coverage, MPAs are not representative of all marine ecosystems present in the region, as suggested by Barr & Possingham (2013) for Australia.

Until the 1960s, human activity, exploitation of marine resources, and consequently marine conservation efforts, were focused on near-coast and shallow regions (Merrie *et al.* 2014). However, the remote areas of the offshore open oceans and the deeper seas are no longer considered "virgin" frontier areas and are experiencing a dramatic intensification in the extent and intensity of human uses and threats to biodiversity natural ecosystems (Merrie *et al.* 2014), such as fishing, drilling, and deep-sea mining (Taranto *et al.* 2012). This is evident, for example, in the global scale depletion of some pelagic fisheries in recent decades (Juan-Jordá *et al.* 2011), especially for large fish (Sibert *et al.* 2006), accompanied by an increase in the average depth of trawling (50-100 m increase per decade; Glover & Smith 2003; Gordon 2001). More fishing activity is now being conducted in the deep-sea beyond the continental shelf (Roberts 2002; Morato *et al.* 2006). Major recent discoveries of large marine hydrocarbon deposits, including natural gas fields and increasing operations for their utilization, make it clear that urgent actions are needed to advance the conservation of the oceans (Kark *et al.* 2015; Cordes *et al.* 2016). However, current conservation approaches, key to achieving this goal, are mostly 2-D in nature and are limiting our expansion of marine conservation to the entire water column and to the deep-sea (McCook *et al.* 2009). Extending the vast system of protected areas to offshore and deep areas located within exclusive economic zones and in the High Seas beyond national jurisdiction requires both advancing the conservation of deep-sea areas (Barbier *et al.* 2014; Van Dover *et al.* 2014), and explicitly taking a 3-D approach to conservation research, planning, management, and actions.

Systematic conservation planning aims to optimize the representation of biodiversity, while minimizing threats to biodiversity and costs associated with achieving conservation targets (Margules & Pressey 2000). In the oceans, where a third dimension is inherent, this requires a full consideration of the third dimension, from the sea surface, throughout the water column to the sea floor.

We here review the advances in the literature of marine conservation considering the third dimension, and reconcile these to propose a framework advancing the explicit incorporation of the third dimension into conservation planning. A framework for a 3-D marine conservation planning to prioritize vertical zones for conservation and management of biodiversity includes a series of steps as detailed below (see also Box 1 and Figure 3):

1. Characterizing the 3-D properties of marine ecoregions and habitats (Box 1a);
2. Determining target biodiversity features for different vertical zones along the full water column, differentiating between those features that cross multiple water depths and those that are confined to unique habitats (Box 1b–e; Figure 3A–D);
3. Determining the threats to biodiversity originating from different vertical layers along the water column and their possible flows to other vertical layers (Box 11f);
4. Determining the management, enforcement and restoration costs of conservation actions for different vertical layers along the water column (Box 1g–h; Figure 3E).
5. Prioritizing and selecting vertical zones (3-D planning units) for conservation and management actions based on their conservation features, conservation targets, costs, and threats (Box 1h; Figure 3F).

Characterizing marine ecosystems and conservation targets in 3-D

The first stage in the proposed conservation framework involves mapping, as is common in much of the work in spatial modelling and planning. Most maps present us the world from above as a 2-D plane, often disregarding the third dimension. In recent years, cadastral registration systems on land have begun to incorporate the third dimension, with the aim of devising a 3-D and spatial cadaster, allowing different owners and rights of use defined in the third dimension, and not only horizontally (Stoter & van Oosterom 2010). In addition, it has been recognized that Geographic Information Systems should explicitly incorporate the third dimension, not only in visualization, but also in building topological relationships between 3-D objects (Ellul & Haklay 2006). Whereas software exist for visualizing and analyzing oceanographic data in four dimensions (x, y, z and time), e.g., Ocean Data View freeware (Schlitzer 2002), spatial prioritization of conservation in marine areas is typically done without the explicit incorporation of the third dimension of planning units.

Marine habitats are usually defined based on the sea bottom, as in the recent global mapping of the geomorphology of the oceans (Harris *et al.* 2014), and in the EU Habitat Directive (Fraschetti *et al.* 2008; Levin *et al.*

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2014). Including the 3-D nature of near shore waters is a challenge, and even more so in offshore areas where the large third dimension (i.e., large volume) of the water column and its largely unknown dynamics make it difficult and challenging to design MPAs for pelagic habitats (Game *et al.* 2009). Previous attempts have been made to incorporate time series data and oceanographic processes in conservation planning (e.g., Grantham *et al.* 2011), yet this has rarely addressed the deep-sea. An example of the complexity of marine habitats, and of the 3-D of life "occupancy" of the marine ecosystems (Figure 1).

in addition to the representation of biodiversity features using species distribution ranges (Perry *et al.* 2005; Box 1b–d). The connectivity within ecological systems (such as larval dispersal) can be incorporated into 3-D systematic conservation planning and applying them to 3-D planning units (see example in Beger *et al.* 2010).

One of the first attempts for classifying the pelagic environment through a comprehensive analysis of the entire water column was presented by Lyne *et al.* (2005), in their attempt to present a national marine bioregionalization

Box 1: **Proposed framework for incorporating the third dimension into marine conservation**

	Stage in systematic conservation planning	Present common 2-D practice	What needs to be done to incorporate the third dimension in conservation planning practice
a	Define study area and planning units	2-D planning units–pixels (units defined by area)	3-D planning units–voxels (units defined by volume) which can overlap on a planar view, based on the water column depth and on vertical ecological gradients (Figure 3)
b	Compile data on the biodiversity of the planning region–distribution, rarity, and IUCN status	Compile data on the spatial extent of species distribution range and habitat	Define 3-D marine ecoregions through 3-D habitat mapping, based on bathymetry, connectivity, benthic structure, and currents. Compile data on the bathymetric range of species' use of the water column throughout their life cycle. (Figure 3a-c)
c	Identify links between shallow and deep species, assemblages and functions	Species and assemblages mapped for their horizontal distribution or depth ranges	Connectivity (in the framework of the genetics, hydrology, topography) between shallow and deep-sea assemblages should be quantified (e.g., the dependencies of species on resources from benthic, pelagic or at the sea surface).
d	Identify links between deep regions of different biogeographic areas	Species and assemblages mapped for their horizontal linkages	Source and sink assemblages should be identified and mapped across different bathymetric zones
e	Identify conservation targets for the planning region	Targets are identified based on species distribution area, endemicity/rarity, and risk of extinction	Targets should be defined separately for each species/assemblages at different vertical layers of the water column down to the seafloor, based on their IUCN status, endemism/rarity, ecological needs and on their distribution volume
f	Define costs (including management and opportunity costs, restoration costs, etc.) and threats	Conservation costs and threats to species are mapped in 2-D	Conservation costs and threats to species should be assessed based on the bathymetric gradients where they originate from, and where they might have an impact (Figure 3e).
g	Review existing conservation areas	Map where protected areas already exist	Distinguish between conservation actions already in place at different vertical levels
h	Select additional conservation areas	Identify complementary planning units to achieve conservation goals	Identify planning units so that they form compact regions in 3-D, allowing for vertical zoning–differential uses along the water column (Figure 3f).

Defining 3-D marine ecoregions (as recommended by Hayden *et al.* 1984), in addition to the 2-D marine ecoregions (as in Spalding *et al.* 2007) may allow more efficient conservation planning and management (Box 1a). A definition of 3-D marine ecoregions should incorporate processes and connectivity of species and habitats (e.g., related to upwelling, currents and gyres) (delimitation of marine ecoregions). Their hierarchically nested classification used physical variables and satellite data, and consisted of latitudinal ocean zones, their underlying 3-D structure, and circulation regimes, to support the planning and management of Australia's oceans (Lyne *et al.* 2005). This approach has been later used for the Southern Ocean (Grant *et al.* 2006), and

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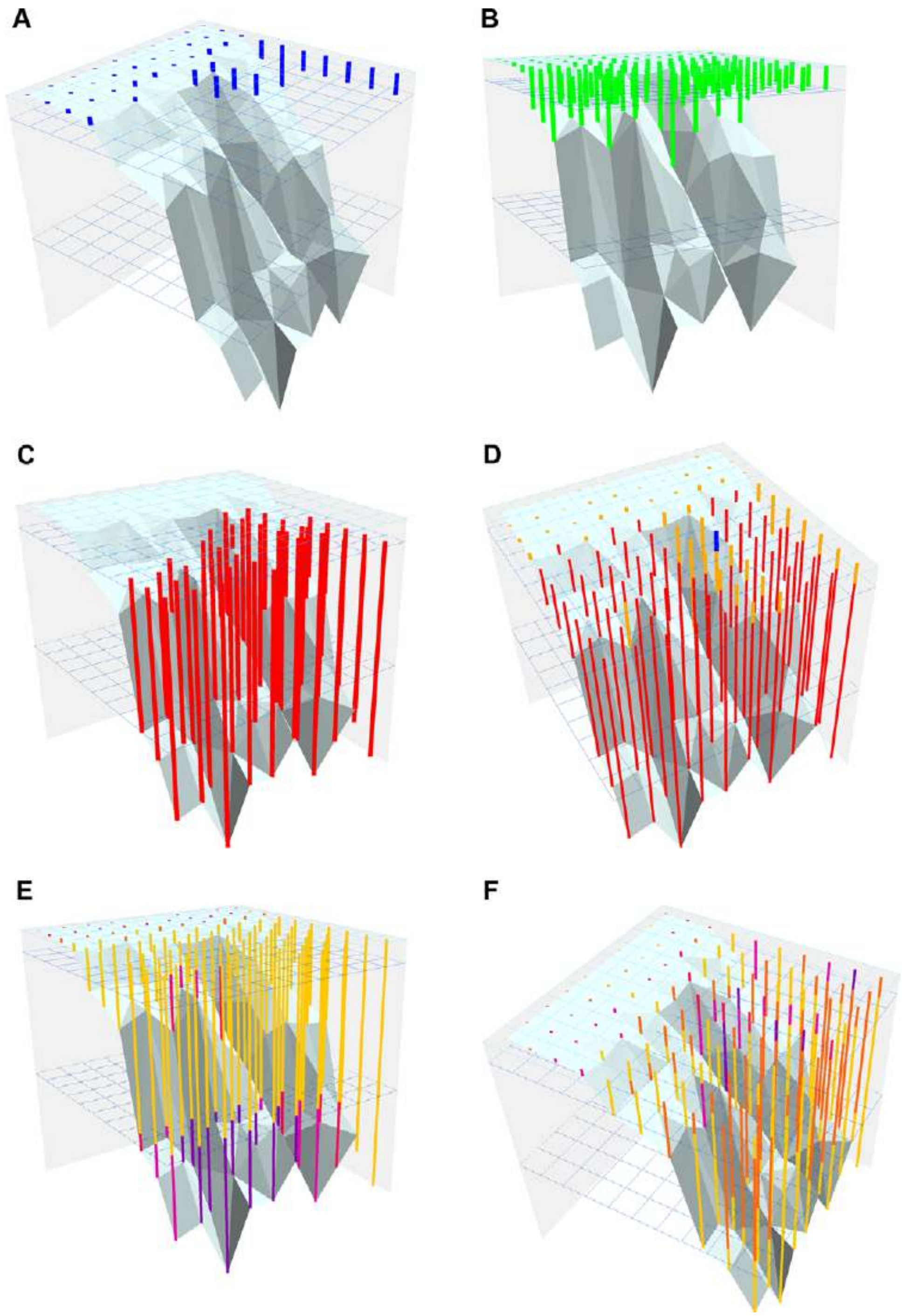

Figure 3 Schematic figure demonstrating systematic conservation planning in three dimensions. The upper three subfigures show the spatial distribution of three schematic species, common to shallow (A), medium depths (B) and deep areas (C). Species richness is shown in D (the blue column shows where all three species overlap), conservation costs are shown in E (high values in red-purple) and prioritization preferences are shown in F (high values in red-purple). The 100 planning units in this example are also divided vertically in three vertical zones, and are shown as thin columns so that adjacent volumetric planning units will not hide each other. In this schematic figure the planning unit size is 300 × 300 m, and the vertical zonation is between the depths of 0–250 m, 250–1700 m and below 1,700 m.

can be expanded globally (Lyne & Hayes 2006; Last *et al.* 2010). Lyne *et al.* (2005) recommended that 3-D visualization methods should be developed so that this information can be conveyed to end-users. Following a workshop in Mexico City in 2007, the first attempt of classification of the open oceans and deep-sea floors was conducted, and identified 30 pelagic provinces, 38 benthic provinces, and 10 hydrothermal vent provinces globally (UNESCO 2009).

ERSI's Ocean GIS Initiative (Wright 2013) recognizes the need to develop new means for reading, processing, and analyzing oceanographic variables along the water column (such as temperature, salinity, dissolved O_2, nitrate, phosphate and silicate), allowing improved 3-D visualization and 3-D analytics. ESRI's website offering an interactive interface of the Ecological Marine Unit Explorer has been recently made publicly available (http://livingatlas.arcgis.com/emu/). Such a 3-D visualization of conservation features is shown in Figure 3 using ArcGIS ArcScene.

Once 3-D marine ecoregions and habitats are defined, they can be used for the next stages of the proposed conservation framework (Box 1b–e). The 3-D habitats can be used as conservation features, where the aim is to represent all such habitats within the conservation network, with higher targets set for 3-D habitats, whose volume is smaller (i.e., habitats that are rarer). In addition, 3-D habitats can be used to subset the planning region, with targets at the species level set so as to ensure that species that are distributed across several 3-D marine habitats will be adequately represented in the final conservation network.

Many marine species are mobile and use various vertical ocean zones in different life stages. Many pelagic species experience daily excursions (vertical migrations; Robinson *et al.* 2012). Just as species distribution ranges should be modelled in three dimensions (Figure 3A-C), conservation targets for marine species should be defined using measures of sea volume and not merely based on their planar area (Fitzsimons & Wescott 2008) (Box 1e), in addition to taking into account species endemism and the IUCN Red List of Threatened Species, as is common practice in conservation prioritization studies (e.g., Levin *et al.* 2015; Box 1b). Therefore, species whose modelled distribution is smaller (often range-limited and/or endemic to specific regions), should be assigned appropriate conservation targets (when expressed in percentage of their volumetric distribution). In order to incorporate all vertical zones on which species depend within their life cycle, the modelled distribution of each of these species can be subset within the prioritization software, so that conservation targets are assigned for each of the relevant vertical zones (as recommended in the case of cross boundary conservation in Kark *et al.* [2009]– when representation of a species is required each country independently).

The 3-D characteristics of human threats, pressures and costs

After the characterization of marine habitats and species distribution in three dimensions, and the setting of corresponding conservation targets, the following step in the proposed framework involves estimating threats and costs across the water column. At present, mapping threats to marine ecosystems is mostly done in two dimensions, usually without explicitly differentiating between depth zones, and such cumulative threat maps often disregard the vertical dimension of human activities (Halpern *et al.* 2008).

However, seas and oceans are 3-D ecosystems, where sources of impacts and threats can originate at depths that are not visible from the surface and require specific monitoring strategies and dedicated technologies (Danovaro *et al.* 2017). Examples include chemical contamination from sunken wrecks containing toxic waste, unexploded bombs or other dumping, or the impact of dense water spreading in the deep-water layers and altering the functioning of deep-sea ecosystems (Danovaro *et al.* 2004, 2001). Due to knowledge and methodological gaps, most current work on marine conservation planning does not explicitly refer to the third dimension of the oceans, and treats planning units as 2-D features (squares, hexagons or other different spatial geometries; Box 1a; Ball *et al.* 2009), even when both benthic and pelagic features are considered (e.g., Grantham *et al.* 2011). Rather, planning units should be treated as 3-D elements (e.g., cubes), each with its own conservation features, costs and threats (Box 1a). The vertical definition of those 3-D planning units can be either set to specific depths (as shown in Figure 3, for depths of 0-250 m, 250-1,700 m, and below 1,700 m); depth ranges related to sea bottom (e.g., the deepest vertical zone ranging between 100 m below the seafloor and 200 m above the seafloor); or depth ranges can be vertically set differentially for different planning units, based on the 3-D ecoregions as defined for each place. An example for an explicit 3-D approach (albeit for fisheries modelling) is in the Atlantis simulation framework, where the model was spatially resolved and vertically structured, with several layers defined within the water column (Fulton *et al.* 2005), in contrast with more simplified marine ecosystem models where a single water column, epibenthic and sediment layers are used (Fulton *et al.* 2004).

The growing interest in deep ocean oil exploitation and mining (Kark *et al.* 2015; Wedding *et al.* 2015; Cordes

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et al. 2016) and additional threats to deep-sea areas due to direct human activities and climate change (Sutherland *et al.* 2012; Mora *et al.* 2013; Sweetman *et al.* 2017), is of great concern given that beyond the territorial waters the sovereignty of countries is limited, and thus there are far fewer limits and regulations on activities. The International Seabed Authority has been formed to regulate deep-seabed mining and to ensure some kind of environmental protection in the ocean's deep offshore areas (Lodge 2011). However, challenges remain with regard to policy and management implications and on how to monitor and enforce regulations and laws in remote deep offshore areas.

Halpern *et al.* (2008) led one of the first global mapping efforts of human impact on the world's oceans addressing a variety of anthropogenic drivers, including fishing, commercial and recreational shipping, ocean and land based pollution, biological invasions, ocean acidification and changes in sea surface temperatures. They provide a 2-D global map of cumulative human impact on oceans. Marine conservation can benefit by extending this map and analyses to 3-D to quantify the vertical extent and intensity of the human threats and pressures along both the coast to high seas and sea-level to deep-sea gradients.

A 3-D approach is also needed for a better estimation of the volume of the oceans affected by human activities in addition to the area of marine ecoregions affected (Box 1f). This again can allow for explicit consideration of the vertical structure and flow of anthropogenic impacts along the water column. As demonstrated by Mora *et al.* (2013), projected changes in ocean biogeochemistry differ between the surface and the seafloor. Some threats to marine ecosystems and biodiversity propagate along the depth gradient up or down or both ways. For example, while many oil spills originate at the upper water surface due to tanker oil release (e.g., the 1989 Exxon-Valdez incident), modelling enables us to estimate the vertical dispersal of oil. For example, in the 2009 Montara oil spill (Timor Sea), oil contamination was mostly in the upper 25 m of the sea, yet was modelled to extend down to 100 m deep (Young *et al.* 2011). As oil and gas operations venture into the deeper sea, accidents may start at the seafloor (Kark *et al.* 2015). One of the most notorious examples was the Deepwater Horizon oil spill in 2010. Originating at a depth of 1,600 m, this led to continuous oil discharge over three months in the Gulf of Mexico, substantially impacting marine fauna, coastal areas and the fishing industry (Norse & Amos 2010; White *et al.* 2012). With most of the world's gas reservoirs classified as unconventional based either on deposit characteristics or depth (Holz *et al.* 2015), and with major reservoirs of natural gas hydrates in deep sea regions (Chong *et al.* 2016), human impacts on the deep seas are expected to increase. In addition to oil and natural gas activities reaching deeper areas, the impacts of global warming on marine ecosystems go beyond an increase in sea surface temperatures, and include shifts in circulation, vertical stratification of water, oxygen content, nutrient inputs and other effects, all projected to have significant biological effects on marine biodiversity from the sea surface to the deep-sea (Doney *et al.* 2012; Sutherland *et al.* 2012; Mora *et al.* 2013; Sweetman *et al.* 2017). While global warming in the oceans originate from the surface, increases in deep-sea temperatures have also been recorded (Yasuhara & Danovaro 2016; Danovaro *et al.* 2001, 2004), and marine species are predicted to shift their latitudinal range and depth ranges (Cheung *et al.* 2009). Due to depletion of fish stocks on continental shelves, industrial fisheries are moving toward the deep-sea. Both deep-sea fishing devices (targeting the water column) and bottom-contact fisheries have major impacts on deep-sea biodiversity (Pusceddu *et al.* 2014), and abandoned fishing gear was recently found to be the most abundant type of litter in the southwestern Indian Ocean floor (Hardesty *et al.* 2015). While plastic debris originates at the sea-surface (Goldstein *et al.* 2013), it extends to the open oceans (Cózar *et al.* 2014), it is the most common debris type, which marine wildlife encounters (Hardesty *et al.* 2015) and microplastic pollution has been found in deep-sea sediments (Van Cauwenberghe *et al.* 2013). Thus, human impacts extend from coastal and shallow areas to offshore and deep-sea areas.

Given the increase of human pressures in the oceans, it is necessary to consider conservation costs when approaching conservation questions. Several approaches can be taken for estimating costs (opportunity, management and restoration) in systematic conservation planning. Opportunity costs refer to the forgone benefits from alternative marine uses (Ban *et al.* 2011). Such benefits can be relatively straightforward to estimate for different vertical layers in the ocean, e.g., based on the revenues from fishing at different depths (Morato *et al.* 2006). There are several approaches for estimating management costs for MPAs (Ban *et al.* 2011), and these can be extended to consider the effect of depth (Figure 3E). For example, surveillance costs differ whether they are done by airborne sensors (for corals and shallow areas), boats, via remote underwater video stations or by remotely operated underwater vehicles (ROVs). Restoration costs in the deep-sea may be two to three orders of magnitude greater per hectare than in shallow marine ecosystems (Sutherland *et al.* 2012; van Dover *et al.* 2014; Barbier *et al.* 2014). Therefore, human threats and the costs required to achieve conservation targets should be quantified for each of the different vertical layers of the ocean (Box 1f).

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Existing and future 3-D conservation schemes, plans and research

Once conservation features have been mapped, conservation targets defined, and conservation costs estimated (all in three dimensions), systematic conservation planning can then be performed in 3-D. Here we provide examples that demonstrate the applicability of a 3-D approach, where conservation actions are prioritized based on endemism, the 3-D distribution and status of biodiversity features, as well as on management costs and human threats (Ban & Klein 2009) in 3-D. Such an approach will enable vertical zoning of allowed human activities and of protected areas (Box 1g; Figure 3).

Some examples of existing vertical zonation in marine conservation can be found, such as the Tasmanian Seamounts Marine Reserve of Australia. This reserve, which was declared in 1999, includes a vertical zoning of a strict nature reserve (IUCN Category Ia) from a depth of 100 to 500 m below the seabed so as to forbid mining), and a management zone in the upper 500 m of the water column, where commercial pelagic fisheries are allowed by permit (nontrawling; Probert *et al.* 2007). In New Zealand, the fishing industry has led an initiative that resulted in the formation of benthic protection areas in November 2007. These areas, where trawling of the seabed is prohibited cover 1.1 million km^2 (approximately 30% of New Zealand's EEZ; Helson *et al.* 2010). The criteria for designating this area aimed to select benthic protection areas in New Zealand which are large, with simple boundaries, relatively unfished, and representing the marine environment classification (Helson *et al.* 2010). Additional examples of successful benthic protection areas that exclude the use of mobile fishing gear that is impacting the seabed, include those of Alaska (nearly 1.5 million km^2) and the Florida Tortugas Ecological Reserve (520 km^2; Spear & Cannon 2012). Williams *et al.* (2016) recently provided a case study from a new deep-water marine reserve off eastern Australia, where biodiversity conservation and line fishing can coexist in a deep-water marine reserve of seamounts, based on vertical and diurnal zoning of management actions. This work is an example of the need for dynamic ocean management, whereby accounting for temporal and spatial mobility of species (horizontally and vertically) can provide benefits and greater efficiency in marine management (Lewison *et al.* 2015; Maxwell *et al.* 2015).

Within the Mediterranean Sea, the agreement of the General Fisheries Commission for the Mediterranean (GFCM) recommended the establishment of Fisheries Restricted Areas (FRAs) to protect deep-sea sensitive habitats; in addition, the GFCM recommended prohibiting towed dredges and trawlers at depths beyond 1,000 m, a recommendation which was adapted by the European Union (Micheli *et al.* 2013). It has been suggested that in certain cases, vertical zoning can be established such that recreational pelagic fishing can be allowed in MPAs, which are mainly focused on benthic conservation (Grober-Dunsmore *et al.* 2008). Moreover, benthic protection areas should be extended beyond the restriction of fisheries activities, to also include nonfishing activities, such as mineral and energy exploration and exploitation (Spear & Cannon 2012).

The above examples demonstrate that in several cases vertical zones of the water column have been given different management schemes due to depth-related stratification of physical, biological, chemical, and biodiversity patterns, and due to vertical differentiation in human pressures and uses. However, as far as we are aware, the above examples of vertical zonation did not apply the principles of systematic conservation planning. In the past, protected areas were mostly designated based on scenery values and where there were few competing interests, and hence the bias in the location of terrestrial protected areas towards remote and rugged regions (Joppa & Pfaff 2009). The same logic applies to marine conservation planning. If we aim to optimize the allocation of resources and achieve more conservation targets, the third dimension should be explicitly added into marine systematic conservation planning.

Designating, implementing and enforcing 3-D conservation zones may increase the complexity of management actions (Figure 3F). However, it has been demonstrated that managers and fishers can implement complex dynamic spatial zoning (in space and in time) with success (Hobday *et al.* 2010), and therefore adding vertical zoning is achievable in our view. Automatic Identification Systems (AIS) for monitoring shipping traffic using satellites (Eriksen *et al.* 2006), is now a reality with such services offered for example by exactEarth® (http://www.exactearth.com/). In addition, available technologies now allow a sounder and larger scale monitoring of marine ecosystems than was possible previously (Danovaro *et al.* 2017), which will enhance future implementation of complex management actions and make feasible what has been precluded or was too expensive in the past.

Future directions

Including the third dimension in conservation planning (as demonstrated in Box 1) might assist in a more realistic treatment of marine biodiversity, and it has been estimated that by better managing and conserving marine biodiversity, marine ecosystem services will be better maintained (Palumbi *et al.* 2008). Future research should

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be directed to explore the diversity of deep-sea pelagic regions, which are the least explored yet, and their trophic and life cycle links with deep and shallow seafloor biodiversity. Three-dimensional marine conservation planning and prioritization should explicitly address vertical variability in biodiversity, threats and conservation costs along the water column. Vertical zonation of management actions along the water column is expected to better define, plan and achieve conservation targets, at lower costs, while avoiding spatial biases and allowing multiple uses in the face of emerging human uses of the oceans. Applying conservation actions in 3-D will obviously increase the complexity and difficulty of managing and protecting these systems. Advances in software and in the availability of data facilitate the visualization and analysis of 3-D data. Three-dimensional management actions in the future will benefit from advances in software, AISs, and from remote underwater operated vehicles (Danovaro *et al.* 2017), thus enabling systematic conservation planning in 3-D to become a reality.

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