Deep-Sea Research in the Decade of Ocean Science
Mapping the role of the deep ocean in human society

1. The deep-sea realm: challenges of remote, poorly known ecosystems in the framework of sustainable oceans

The composition and functioning of the deep sea, comprising the largest living space on Earth, is still poorly understood, with a minimal proportion of the deep oceans sampled and investigated to date. However, with our current state of knowledge, we know that society's well-being is linked to the health of the deep sea through a wide range of ecosystem services as diverse as climate regulation to food security. To most of society, the deep sea is still thought of as a remote, featureless, lifeless and inaccessible space. However the combination of the geological, physical and geochemical attributes of the deep seafloor and water column create a series of complex habitats with unique characteristics that, together, fuel a healthy planet. Each of these habitats supports faunal communities with specific physiological and behavioural adaptations to high pressure, darkness, low temperatures (or steep temperature gradients in the case of hydrothermal vents), food limitation (particularly at abyssal plains) and in some cases isolation (e.g. seamounts, vents, seeps, trenches). In many ways, the function and physiology of the deep is fundamentally different from shallow and terrestrial habitats. In addition, deep-sea biodiversity at bathyal and abyssal depths is amongst the highest on the planet and the potential for novel discovery is enormous; these discoveries range from novel genetic resources to uncovering the roles of deep-sea habitats in ocean ecosystems. When addressing issues of biodiversity, the ecosystem functions and services supported by such biodiversity, and the potential impacts of - and resilience to - human activities in the deep sea, one of the major challenges we face is our limited knowledge of very basic baseline information.

Deep-sea ecosystems have been relatively protected from human activities by virtue of their remoteness, but increasingly face large-scale and cumulative impacts from multiple human activities. Technological developments now enable exploitation of fisheries resources, hydrocarbons and minerals below 2000 m depth. In addition, marine litter slowly sinks, degrades and accumulates on the seafloor and ocean acidification and climate change bring additional pressures on a global scale. Finding solutions to these challenges provides a new imperative for the scientific community, industry, authorities and national and international organizations to work collaboratively with a goal of sustainable use and conservation of deep-sea ecosystems. However, for many regions and habitats, baseline information is still lacking. Sound scientific knowledge is essential and urgently needed to develop a sustainable management strategy for the deep ocean, which should define baseline conditions and include science-based conservation goals, with clearly defined targets and indicators. These scientific data are essential for ongoing international processes, such as the development of an International Legally Binding Instrument under UNCLOS on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ process). Technological development and depletion of land-based and coastal resources is stimulating industrial activities in ever-deeper waters, with consequences that are largely unknown, and where remediation/restoration activities often economically non-viable. Thus, the time to act is now, to ensure that the goals and targets of UN Sustainable Development Goals (SDGs), in particularly SDG 14 (Life Below Water) and SDG13 (Climate Action) can be met, safeguarding and promoting healthy oceans for future generations.

2. UN Decade of Ocean Science for Sustainable Development

In keeping with SDG 14 and recognising the cross-cutting role of ocean science in achieving the goals and targets there-under, the UN General Assembly on 5 December 2019 decided to proclaim the UN Decade of Ocean Science for Sustainable Development (A/RES/72/73). The Decade will subsist for the 10-year period beginning on 1 January 2021 with the Intergovernmental Oceanographic Commission (IOC) at the helm of the herculean effort. In preparation, the IOC issued a Roadmap (revised June 2018) wherein the need to drastically improve the current conditions of the world's oceans through science-based solutions and increased cooperation was emphasized. To this end, the Revised Roadmap outlined six critical societal outcomes, and a further seven priority areas for research and development to arrive at the said societal outcomes, which the Decade seeks to accomplish by 2030.

In its response to the announcement of the Decade, the Deep-Ocean Stewardship Initiative (DOSI) specifically convened the Decade of Deep-Ocean Science working group (DOSI-DDOSWG) to promote research effort on a global scale to understand the role of the deep-sea ecosystems in ocean health and resilience. We propose a 10-year research programme to be developed based on science priorities identified by the DOSI community during 2 events: 1) DOSI Day 2018 (09/09/2018, Monterey, USA) and 2) a meeting of the working group (October 2018, Aveiro, Portugal). Here, we outline our four agreed science priorities and knowledge gaps pertaining to the deep ocean, and place them in the context of the societal outcomes (SO) identified in the Revised Roadmap.

The six Societal Outcomes (SO) of the Decade of Ocean Science for Sustainable Development

1. A clean Ocean whereby sources of pollution are identified, quantified and reduced, and pollutants removed from the Ocean
2. A healthy and resilient Ocean whereby marine ecosystems are mapped and protected, multiple impacts (including climate change) are measured and reduced, and provision of ocean ecosystem services is maintained
3. A predicted Ocean whereby society has the capacity to understand current and future ocean conditions, forecast their change and impact on human wellbeing and livelihoods
4. A safe Ocean whereby human communities are protected from ocean hazards and where safety of operations at sea and on the coast is ensured
5. A sustainably harvested and productive Ocean ensuring the provision of food supply and alternative livelihoods
6. A transparent and accessible Ocean whereby all nations, stakeholders and citizens have access to Ocean data and information, technologies, and have the capacities to inform their decisions.

The seven Research & Development (R&D) Priority Areas

1. Comprehensive map (digital atlas) of the oceans
2. A comprehensive ocean observing system
3. A quantitative understanding of ocean ecosystems and their functioning as the basis for their management and adaptation
4. Data and information portal
5. Ocean dimension in an integrated multihazard warning system
6. Ocean in earth-system observation, research and prediction, with engagement of social and human sciences and economic valuation
7. Capacity building and accelerated technology transfer, training and education, ocean literacy.

From the *Revised Roadmap for the UN Decade of Ocean Science for Sustainable Development*

i. What is the diversity of life in the deep ocean?

We lack fundamental ecological data for much of the deep sea. While many species have been described, there are many more awaiting discovery and description. Poor knowledge of what lives in the deep sea, how it is distributed from global to local 'patch' scales, as well as over environmental gradients (depth, temperature, alkalinity, etc), prevents us from establishing baseline information of what is common and what is rare. These ecological data are necessary to allow predictions of how biodiversity will respond to environmental change and other anthropogenic pressures (SO3), for example, how species ranges may shift in response to climate change, ocean acidification and deoxygenation. Baseline data are also required for species distribution and habitat suitability models that map where species, habitats, and vulnerable marine ecosystems may occur, enabling the identification of biodiversity hotspots (SO2).

ii. How are populations & habitats connected?

At present, we have little information on the linkages between deep-sea habitats and populations, including migration routes, ontogenetic or seasonal movement between habitats, larval dispersal pathways and genetic connectivity, or energy flow pathways in the form of trophic links and food webs. Understanding these linkages, collectively termed connectivity, is critical to effective ocean management and sustainable use. For example the design of effective networks of Marine Protected Areas (MPA) is underpinned by establishing well-connected populations, communities and ecosystems (SO2). To manage fish stocks, we need to know how fish use their environment (essential fish habitats, spawning migrations, larval and juvenile dispersal, food web interaction, etc) (SO5). There is increasing evidence that a number of commercially-valuable fishes (e.g. tunas), marine mammals, and seabirds prey on deep-sea (mesopelagic) fishes, which form an important part of their diets. Strong connectivity promotes healthy and resilient populations and disruptions to their connections, for example through changes in ocean circulation patterns or plumes from mining activities, can impact population persistence and recovery after disturbance, as well as the effectiveness of MPAs. We must understand those connections in order to 1) ensure they are maintained (SO2) and 2) enable us to predict the consequences of their disruption (SO3).

iii. What is the role of living organisms in ecosystem function & service provision?

The goods and services provided by the ocean are widely recognised through SDG 14. Within the Decade roadmap, SO5 is focused entirely on the provision of food supply and alternative livelihoods as key services provided by the oceans. We are at an early stage in our understanding of the role of the deep sea in provision of those wider goods and services. For example, what are the key species/habitats involved in carbon sequestration? Are some groups more important than others? Is there redundancy in the system i.e. is there more than one group of organisms performing the functions that lead to the delivery of the service? To ensure the ongoing provision of those services (SO2), we need to identify the functional groups present, their role in ecosystem function, and how that function relates to delivery of goods and services. Quantifying the scale and variability of these processes on a global scale can allow us to predict changes to function and service provision as a result of anthropogenic activities (SO3).

iv. How do species, communities and ecosystems respond to disturbance?

This question addresses both natural and anthropogenic disturbance (e.g. pollution, mining, fisheries, climate change, etc) and gets to the heart of what we need to know to be able to effectively manage the marine ecosystem and deliver SO1, SO2, SO3 and SO5. Knowledge of the baseline environmental data and species tolerance thresholds to disturbance is essential. Moreover, understanding how the interactions and synergies play out between climate stressors and direct disturbance will be essential to effective management of the deep ocean in the future. There are a limited number of case studies from past and ongoing disturbances that provide some information, and even fewer laboratory experiments to address the mechanisms behind the responses. This is a key area for intellectual development and one of the most important categories of information required for effective management and stewardship of our oceans.

3. A 10-year scientific program

Our Aim: to map the role of the deep ocean in human society

SO2 in the Decade Roadmap recognises that 'supplementing and completing the science base with holistic mapping of the ocean, in all its dimensions, will be needed for an adaptive management approach towards good ocean stewardship' (R&D priority 1). By the end of the Decade, we aim to be able to reliably map and model: 1) the distribution of key benthic and pelagic habitats and species (including diversity, biomass) (SO2), 2) the connectivity of populations, including dispersal/migration pathways, and realised gene, energy and nutrient flows from the ocean surface to the seafloor (SO2, SO5), 3) the delivery of ecosystem goods and services by deep-sea species and habitats (SO2, SO3, SO5), and 4) the impact of human activities in the deep ocean, including mining, energy extraction, fishing, waste disposal, climate change, and their cumulative effects. This mapping will sit alongside the physical mapping of the seabed proposed under Seabed 2030.

We anticipate this will be achieved by a series of research projects focused on different deep-sea systems similar to the former Census of Marine Life programme 2000-2010 (www.coml.org). However, this programme will differ from, but build on, what was achieved under the Census, by adopting of a single global modular experimental design. This design will include the use of standardised methods across all projects, a single agreed-upon method of open access archiving and storage of data and samples (R&D priority 4), and coordinated quality control measures to ensure all data are cross compatible. This level of integration between large research projects is difficult to achieve, but it is exactly what is required in order to deliver the single greatest advance in our understanding of the ecology of the oceans since the Challenger Expedition almost 150 years ago.

We also anticipate that this programme will contribute to R&D priority 2 – a comprehensive ocean observing system, in several ways. For the deep sea it will 1) inform our choice of the best biological indicators of change and how best to monitor them, 2) identify a global network of sites that are appropriate for monitoring change including both water column and seafloor, 3) inform the choice of technology to be used such that it is available and practical for all nations, 4) produce coordinated observations using selected focal sites and methods for deep-sea biology. This will link to the Deep Ocean Observing Strategy and its Biology and Ecosystems Essential Ocean Variables panel.

The programme will address R&D priority 3 – a quantitative understanding of ocean ecosystems and their functioning as the basis for their management and adaptation. Use of new technology is critical for making the step-change in collection of biological data required to address the questions identified above. A recent international discussion meeting, hosted by the Royal Society of London, UK "Beyond Challenger - a new age of deep-sea science and exploration", identified new imaging technologies, use of artificial intelligence (AI) and computer vison (CV), as well as eDNA sensors as tools playing a central role in a Decade of Ocean Science deep-sea programme. Some key findings were that efforts of both the deep-sea ecology and technology communities are needed to deliver these new technologies on-line during the Decade. For example, the use of eDNA techniques as a means of rapid survey requires that the faunal community has been DNA bar-coded, and observed sequences are reliable indicators of the presence of living organisms within a given distance and within a given time window. Very few deep-sea species have been DNA bar-coded. Use of AI and CV to identify animals from images and video data requires standardised datasets on which to train AI and CV algorithms. At present there is no standard image reference guide to deep-sea species (although international efforts to develop one are in progress). A key component of the first half of a deep-sea programme will be to focus efforts on enabling new technologies.

Societal Outcomes (SO) of the Decade of Ocean Science for Sustainable Development						Research & Development (R&D) Priority Areas						
1	2	3	4	5	6	1	2	3	4	5	6	7

Table 1. Societal outcomes and research and development priority areas addressed by the 10- year scientific programme.

4. Why is international collaboration essential?

Deep-sea research, exploration, and exploitation is heavily dominated by developed nations. This is reflected in availability of samples, bias in available data, and overall knowledge of deep-sea ecosystems. The least studied parts of the deep sea are often within the EEZs of developing nations and / or the High Seas / the Area, away from the continental slopes. In addition, deep-sea research is currently conducted piecemeal, in a poorly coordinated fashion. Individual projects tackle small aspects of larger questions, and do not integrate approaches or findings to ensure that the whole is bigger than the sum of the parts. The projects are frequently constrained by available budgets, time, and the logistics of sampling in the deep sea. There are often trade-offs made in experimental design or resolution of data against greater temporal / spatial coverage or to provide data to satisfy multiple competing aims. While we have significantly advanced our knowledge of the deep-sea in the near 150 years since the Challenger Expedition, a new approach is called for to enable us to make the great leaps in knowledge needed to better manage our oceans.

International collaboration is the key to both broadening our knowledge of the deep sea, and to make deep-sea research more accessible to scientists from all nations. The Decade presents an opportunity to design a truly global deep-sea research programme to tackle the long-held, and as yet unanswered, questions outlined above. We envisage a coherent well-designed global modular sampling programme: each sampling module will be nested within a local / regional ocean context, and results from all modules will be combined toward the end of the decade to answer the big questions, and provide 'one giant leap' for human understanding of the oceans.

Capacity development will play a central role in this programme. The Revised Roadmap clearly states that the Implementation Plan, to be developed by 2020, will include a plan for capacity development, training and education (R&D priority 7). We envisage a programme of research that is fully inclusive, and where each sampling module is owned and operated by nations proximal to the sites of sampling (SO6). For example, a sampling module in the Indian Ocean would be owned and operated by nations bordering the Indian Ocean as part of the Global programme. The programme would make provision for academic training of students as part of a global cohort of trainees, providing peer support and knowledge sharing between nations and research groups (R&D priority 7). In addition, a well-developed programme of international public education and outreach would be essential to the project (SO6).

We envision that the proposed effort will engage the existing expertise represented within the census of marine life legacy programs INDEEP (International network for scientific investigation of deep-sea ecosystems) and DOSI (Deep-Ocean Stewardship Initiative), as well other global networks including the Challenger Society, Deep-Sea Biology Society and the Scientific Committee on Oceanic Research. It will also build on the efforts of the Global Ocean Observing System (GOOS) via the Deep Ocean Observing Strategy (DOOS). These international networks have embraced many key elements discussed above; here we offer a way forward. We anticipate key collaboration with the DOOS Essential Ocean Variable Biology and Ecosystem panel (which itself is working with the GOOS Biology and Ecosystem panel), the DOOS demonstrations projects, and with the DOSI/INDEEP/DOOS SDG 14 voluntary commitments. Critical links to the existing deep-ocean physical and biogeochemical measurement programs (e.g. ARGO, deep ARGO, BGC Argo, GoSHIP, Ocean Sites, Observatories) can be achieved through DOOS. Our activities will be designed to support the information needs of the current Biodiversity Beyond National Jurisdiction (BBNJ) deliberations.

5. What is needed to develop a new 10 year programme?

An easily digestible public message

The Census of Marine Life had a clearly defined and inclusive aim, to census all marine life. The project itself addressed many specific environmental and ecological questions, but the simple title captured the attention of the scientific community and the imagination of the public. Similarly, the Seabed 2030 project has a simple and clearly defined aim "to map the global ocean seafloor". The recently announced Earth Biogenome Project aims to sequence, catalogue and characterise the genomes of all of Earth's eukaryotic biodiversity over ten years. It is described as "a moonshot for biology" and again has a clear output. There are many examples of projects with big questions and large-scale international collaboration, with a clear and simple aim/output. For example, one of the main aims of the Large Hadron Collider facility was to find the Higgs boson, to "enable humans to comprehend their cosmic home more fully". Various space missions offer pure exploration of specific astral bodies. The European Space Agency's Mars Express programme and the NASAs Mars Exploration Programme offered exploration of Mars as the goal. A programme focused on the deep-sea for the Decade of Ocean Science will have a clear aim and deliverables that are accessible to non-scientists. Our proposed aim is to ***map the role of the deep ocean in human society*.**

A clear project plan and a road map with clear impact pathways

The development of a plan for a global programme is essential for moving forward, and this development requires an unprecedented level of international coordination. An international steering group is required to advise on all aspects of the project development. Sub-groups will then be needed to deliver the tasks required to develop the programme plan. For example a field sampling programme sub-group(s) is needed to develop the global sampling plan / modules, a communications sub-group will be required to draw up an education and public outreach plan, a technology sub-group will be required to integrate new technology into the sampling programme, including cheap / accessible technology to help democratise deep-sea science (SO6). The development of a draft field programme to tackle the questions identified in different systems (e.g. seamounts, canyons, abyssal plains etc) is a critical next step. This programme should be integrated with wider efforts under the Global Ocean Observing System (GOOS) via the Deep Ocean Observing Strategy (DOOS), and may make use of opportunities provided by a demonstration project for Deep Ocean Observing Strategy. Consultation with the international deep-sea science community, and clear opportunity for all to comment and provide feedback on plans as they develop will help promote wide engagement. It will also facilitate the development of the full programme and the mapping of impacts at global, regional and national levels. The project must have a robust data management and dissemination plan, ensuring national and/or regional ownership of samples, but global accessibility to data and a strong legacy footprint (SO6).

Funding

Funding a 10-year programme is challenging. The Census of Marine Life, a comparable 10-year global programme, received initial core funding from the A.P Sloan Foundation, a private philanthropic foundation. This core funding of $650 million provided the 'glue' to bring people together and enable funding to be leveraged from multiple further sources including both governmental and private sources. The Seabed 2030 programme is sponsored by 3 organisations, the Nippon Foundation, International Hydrographic Organization (IHO) and the IOC. The Nippon Foundation has pledged $2 million as seed funding, with an estimated total cost of $3 billion. Activities of the Earth Biogenome Project are currently being funded by the participating organisations as well as private foundations, governmental organisations and crowd-funding sources. Participating institutions have committed to raising funds to complete the project in 10 years. Significant funds have already been raised by taxon-based communities, national and regional projects to meet the $600 million goal necessary to complete Phase 1 of the project.

One approach to funding a new programme would be a memorandum of understanding and a global scale commitment by key institutions and nations to a common plan financed by existing programmes, in-kind staff time, philanthropic sources, etc. This would allow a launch of a programme, to which others could then be attracted. Potential candidates for philanthropic funding include REV Ocean, the Schmidt Ocean Institute, or the Monaco Foundation, amongst others.

An alternative or complementary approach will be facilitated by the modular sampling design that can be replicated in different ocean basins to collectively address global scale question(s). This design could be incorporated into proposals involving regional questions and a common research plan developed and submitted to multiple national and/or regional funders simultaneously. There are existing agreements between some nations funders for simultaneous joint submissions (for example NERC and NSF, NERC and FAPESP, FCT and FAPESP) and these could be used as a mechanism to obtain regional funding (e.g. North and South Atlantic Ocean).

Access to ship time is a major financial constraint of deep-sea research. Research vessels represent very expensive assets with high development, investment, operation, maintenance and implementation costs. Access to research vessels (both public and private) could be facilitated though an agreement between vessel operators to create a "ship time bursary" dedicated to the Decade programme. Such action would be led by the IOC and possibly coordinated by DOSI.

6. What would be the scientific benefits?

The deep sea remains the "black box" in our ability to predict how the ocean will respond to both increased anthropogenic use and the impacts of global climate change. Our current ecological knowledge and global models are primarily based on terrestrial, fresh water, and shallow marine ecosystems. The deep sea offers another, much larger testing ground for current paradigms in ecology, which will broaden our understanding of how our planet works.

The lack of primary research has hampered efforts to infer general patterns regarding the ecology of deep-sea populations. A recent review found that there are just nine scientific papers that provide population-genetic studies of invertebrates inhabiting non-chemosynthetic ecosystems in the abyssal plains (depth > 3500 m), a region that accounts for ~50% of the planet's surface. Similarly, studies of the Clarion-Clipperton Fracture Zone in the central Pacific have found up to 90% of species sampled were new to science. The benefits of improved fundamental ecological knowledge of the deep sea cannot be overstated. Integration of the deep sea into existing ecological models, and ocean system models, be they nutrient cycling, fisheries, species distribution, or other types of models, must occur if we are to make reliable and robust predictions on which to base ocean management decisions.

7. What would be the societal benefits?

Scientific knowledge acquired during the Decade will inform policy and provide tools for the sustainable use of the deep ocean and continued provision of ecosystem services, such as carbon cycling, climate regulation and food provision. For example this improved knowledge will enable us to i) make recommendations for minimizing environmental damage through living and non-living resource extraction such as deep-sea fisheries, deep-sea mining and oil and gas; ii) develop survey tools to efficiently monitor remote MPAs in ABNJ; iii) facilitate equitable access to and management of marine genetic resources, etc. A major societal benefit will be the legacy value of data that will be made freely available to future generations of scientists and stakeholders. This includes physical samples housed in museums, image and video data archived in national repositories, interpreted ecological, genetic and bioprospecting data stored in open access databases such as OBIS, Genbank etc. Further, communication of new knowledge will increase awareness that will undoubtedly translate into increased social pressure to find solutions to challenges currently (and in the future) faced by the oceans. Ultimately, these benefits will advance the sustainability of the largest part of the planet that is the deep ocean, with direct implications in the health of our planet.