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A Blueprint for an Inclusive, Global Deep-Sea Ocean Decade Field Program

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The ocean plays a crucial role in the functioning of the Earth System and in the provision of vital goods and services. The United Nations (UN) declared 2021–2030 as the UN Decade of Ocean Science for Sustainable Development. The Roadmap for the Ocean Decade aims to achieve six critical societal outcomes (SOs) by 2030, through the pursuit of four objectives (Os). It specifically recognizes the scarcity of biological data for deep-sea biomes, and challenges the global scientific community to conduct research to advance understanding of deep-sea ecosystems to inform sustainable management. In this paper, we map four key scientific questions identified by the academic community to the Ocean Decade SOs: (i) What is the diversity of life in the deep ocean? (ii) How are populations and habitats connected? (iii) What is the role of living organisms in ecosystem function and service provision? and (iv) How do species, communities, and ecosystems respond to disturbance? We then consider the design of a global-scale program to address these questions by reviewing key drivers of ecological pattern and process. We recommend using the following criteria to stratify a global survey design: biogeographic region, depth, horizontal distance, substrate type, high and low climate hazard, fished/unfished, near/far from sources of pollution, licensed/protected from industry activities. We consider both spatial and temporal surveys, and emphasize new biological data collection that prioritizes southern and polar latitudes, deeper (> 2000 m) depths, and midwater environments. We provide guidance on observational, experimental, and monitoring needs for different benthic and pelagic ecosystems. We then review recent efforts to standardize biological data and specimen collection and archiving, making "sampling design to knowledge application" recommendations in the context of a new global program. We also review and comment on needs, and recommend actions, to develop capacity in deep-sea research; and the role of inclusivity - from accessing indigenous and local knowledge to the sharing of technologies - as part of such a global program. We discuss the concept of a new global deep-sea biological research program *'Challenger 150,'* highlighting what it could deliver for the Ocean Decade and UN Sustainable Development Goal 14.

Keywords: deep sea, blue economy, Ocean Decade, Biodivercity, essential ocean variables

INTRODUCTION

Researchers have long recognized the ecological, economic and social importance of the natural capital of the global ocean to humanity (Costanza, 1999; Baker et al., 2020). However, ample evidence shows that, over time, the ocean has suffered increased stress from resource extraction, pollution, and climate change (Díaz et al., 2019; IPCC, 2019; Rogers et al., 2020a), including in the deep sea (Glover and Smith, 2003; Ramirez-Llodra et al., 2011; Sweetman et al., 2017). In 2015, the United Nations (UN) General Assembly set out 17 Sustainable Development Goals (SDGs) as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030. SDG 14 specifically relates to marine biodiversity and its sustainable use, whereas other SDGs, for example SDG 2 on food

security, SDG 8 on economic growth, SDG 12 on sustainable consumption, and SDG 13 on climate, amongst others, also apply to ocean health. Sustainable use of the marine environment also features in other UN policy commitments, including the Convention on Biological Diversity's Aichi Targets. Most recently the UN General Assembly proclaimed the UN Decade of Ocean Science for Sustainable Development (A/RES/72/73), hereinafter referred to as the Ocean Decade. The Ocean Decade will span a 10-year period commencing 1 January 2021, coordinated by UNESCO's Intergovernmental Oceanographic Commission (IOC). In preparation, the IOC issued a Roadmap (revised June 2018), that emphasized the need to drastically improve the current conditions of the world's ocean through science-based solutions and increased cooperation. To this end, the Revised Roadmap outlined six critical societal outcomes (SOs) that should

be achieved through actions taken under the Decade (**Figure 1**) and identified the links between the strategic objectives of the Ocean Decade and the SDGs (United Nations, 2018). The Ocean Decade Draft Implementation Plan, published in March 2020, and revised in May 2020, presents the Objectives (Os) (**Figure 1**) for the Ocean Decade. It provides a framework within which to develop and deliver Ocean Decade Actions, defined in a scale hierarchy as programs, projects, activities, or contributions.

The revised Roadmap for the Ocean Decade recognizes the deep sea as a frontier environment. In order to deliver the Ocean Decade SOs and Os, it specifically calls on the scientific community to conduct research that advances understanding of deep-sea ecosystems, and their functions and services to human society. The Roadmap identifies an aspiration of the Ocean Decade to expand sustained and systematic ocean observations to all ocean basins and depths, to enable characterization of Essential Ocean Variables (EOVs-physical, biogeochemical and biological) and detect natural and human-induced changes. The deep sea (> 200 m) encompasses the largest living space on Earth, and accounts for more than 95% of the habitable volume (Danovaro et al., 2017). It supports diverse species and habitats, with the continental slope supporting higher diversity than the continental shelf (Rex and Etter, 2010; Muthumbi et al., 2011). According to some estimates, bathyal and abyssal diversity are amongst the highest on the planet (Grassle and Maciolek, 1992; Mora et al., 2011). The combination of geological, physical, and geochemical attributes of the deep seafloor and water column creates a mosaic of complex habitats with unique characteristics (Ramirez-Llodra et al., 2010). While we have only sampled or visually investigated a very small proportion of the deep ocean to date (0.01% with remote instruments Ramirez-Llodra et al., 2010), our current state of knowledge links society's well-being to the health of the deep sea through a wide range of ecosystem services (see Armstrong et al., 2012; Thurber et al., 2014; Baker et al., 2020 for a review). The remoteness of deep-sea ecosystems has historically led to a presumption that they are homogeneous and impervious to human activities; however, these diverse ecosystems increasingly face large-scale and cumulative impacts from multiple human activities with global influence (Ramirez-Llodra et al., 2011). Finding solutions to these risks challenges the scientific community, industry, national and international authorities and organizations to work collaboratively toward sustainable use and conservation of deep-sea ecosystems. Technological development, investment in research by both industry and philanthropic organizations, and an overall recognition of the significance of the deep-sea in broader Earth systems has driven rapid expansion in our investigation and understanding of deep-sea ecosystems over the last 20 years. However, fundamental questions remain in deep-sea biology and ecology that must be addressed in order to achieve the Ocean Decade SOs and Os. These questions have persisted despite almost 150 years of deep-sea research, and will continue to persist in the absence of a coordinated strategically targeted global effort to change the *status quo*.

In this paper, we review research needs of the Ocean Decade in the context of the design of a new 10 year deep-sea biology research program under the Ocean Decade. This paper aims to serve as the blueprint for global deep-sea research efforts for the next 10 years and likely beyond.

KEY SCIENTIFIC QUESTIONS MAPPED TO THE OCEAN DECADE SOCIETAL OBJECTIVES

Various fora and groups have reviewed and documented critical outstanding research questions in deep-sea research, including the European Marine Board (Rogers et al., 2015) and Census of Marine Life deep-sea field projects [e.g., Chemosynthetic ecosystems (German et al., 2011); Seamounts (Clark et al., 2012)]. Most recently, the Deep-Ocean Stewardship Initiative (DOSI) specifically convened the Decade of Deep-Ocean Science working group (DOSI-DDOS WG) to promote global-scale research to understand the role of deep-sea ecosystems in ocean health and resilience. DOSI, a network of over 1400 experts from 77 different countries, seeks to integrate science, technology, policy, law and economics to advise on ecosystem-based management of resource use in the deep ocean. The DOSI-DDOS WG currently consists of 67 people from 21 countries and is open to new members at all times. This group worked with the wider DOSI community during 2 events: (1) DOSI Day 2018 (09/09/2018, Monterey, United States) and (2) a meeting of the working group (October 2018, Aveiro, Portugal), to summarize science priorities and knowledge gaps pertaining to the deep ocean, and place them in the context of the SOs identified in the Revised Roadmap. Here, we report the outcome of those discussions, and identify four broad questions and their links to the Ocean Decade SOs.

What Is the Diversity of Life in the Deep Ocean?

Although knowledge on deep-sea community composition and ecosystem functioning has advanced rapidly in recent decades, we still lack fundamental ecological data for much of the deep sea (Glover et al., 2018). Poor knowledge of what lives there, how it is distributed from global to local scales, over environmental gradients (depth, temperature, oxygen, pH, primary productivity, etc.), and over time (seasonality, event-based phenomena, hydrodynamic cycles), precludes establishing effective baselines; in some cases, we still do not know what species are common or rare. Science has described many species, but many more await discovery and description, with repeated examples where presumed "common" species mask the presence of cryptic species (Vrijenhoek et al., 1994; Etter et al., 1999; Havermans et al., 2013). Baseline ecological data form the input to all biological ecosystem models and maps. Our ability to forecast how marine biodiversity will respond to environmental changes and anthropogenic-related pressures (SO3), depends on good base knowledge such as species identities, distributions, physical and chemical drivers of distribution, abundance, biomass, growth rates, etc. Fundamental ecological knowledge severely limits efforts to model and map present-day species distributions to

Objectives

O1: Increase capacity to generate, understand, manage, and use ocean knowledge
O2: Identify and generate required ocean data, information and knowledge
O3: Build comprehensive understanding of the ocean and ocean governance systems
O4: Increase the use of ocean knowledge

Societal Outcomes

SO1: A clean Ocean whereby sources of pollution are identified, quantified and reduced, and pollutants removed from the Ocean
SO2: 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
SO3: 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
SO4: A safe Ocean whereby human communities are protected from ocean hazards and where safety of operations at sea and on the coast is ensured
SO5: A sustainably harvested and productive Ocean ensuring the provision of food supply and alternative livelihoods
SO6: 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.

FIGURE 1 | Decade of Ocean Science for Sustainable Development objectives identified in the recently published revised Draft Implementation Plan, and societal outcomes published in the revised Decade Roadmap.

fill data gaps, and predict future distributions under climate change (SO2). Existing models and maps are simplistic, and of questionable accuracy due to limited, and/or poor quality input data (Davies and Guinotte, 2011; Howell et al., 2016; Morato et al., 2020).

How Are Populations and Habitats Connected?

Effective ocean management and sustainable use critically depend on identifying linkages among deep-sea ecosystems, communities, and populations. Collectively termed *connectivity* these linkages include: migration routes, ontogenetic or seasonal movement between habitats, spawning sites, larval dispersal pathways and genetic connectivity, or energy flow pathways in the form of trophic links and food webs. For example, maintaining well-connected populations, communities, and ecosystems underpins the design of effective networks of Marine Protected Areas (MPA) (Cowen and Sponaugle, 2009; Jenkins and Stevens, 2018) (SO2). Effective management of fish stocks (SO5) requires knowledge of how fish use their environment (essential fish habitats, spawning areas, migrations, larval and juvenile dispersal, food web interactions, etc.). Increasing evidence demonstrates that numerous commercially valuable fishes (e.g., tunas), marine mammals, and seabirds prey on deep-sea (mesopelagic) fishes, which form a significant component of their diet (Battaglia et al., 2013; Giménez et al., 2018; Watanuki and Thiebot, 2018). Strong connectivity promotes healthy and resilient populations (SO2), and disruptions to these 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 and other spatial protection measures. We must identify these connections to (1) help ensure that human activities do not alter them (SO2) and (2) enable us to predict the consequences of their disruption (SO3).

What Is the Role of Living Organisms in Ecosystem Function and Service Provision?

Sustainable development goal 14 widely recognizes the services provided by the ocean. Within the Decade Roadmap, SO5 focuses entirely on the provision of food supply and alternative livelihoods as key services provided by the ocean. We are at an early stage in understanding the role of the deep sea in provision of services (Armstrong et al., 2012; Thurber et al., 2014; Folkersen et al., 2018; Baker et al., 2020), with scant details on mechanisms of delivery. What are the key species/habitats involved in carbon sequestration? Are some groups more important than others? For example, we know sponges may play an important role in global Si cycling (Maldonado et al., 2019), as well as a sink for inorganic nitrogen, surpassing that of marine sediments at equivalent depths (Hoffmann et al., 2009). Does redundancy exist within the system, i.e., do more than one group of organisms perform the same functions associated with service delivery? The answer largely depends on the shape of the relationship between biodiversity and ecosystem functions (the so-called biodiversity-ecosystem functions curve; Danovaro et al., 2008). To ensure the ongoing provision of those services (SO2), and to understand better marine system processes such as biogeochemical cycling, we must identify the functional groups present, their role in ecosystem function, and how that function relates to delivery of services. Quantifying the variability, in space and time, of these processes on a global scale will enable us to predict changes to function and ecosystem service provision as a result of anthropogenic activities (SO3).

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 the knowledge required to manage marine ecosystem use effectively and deliver SO1 (a clean ocean), SO2 (a healthy and resilient ocean), SO3 (a predicted ocean), and SO5 (a sustainably harvested and productive ocean). Sustainable development requires knowledge of baseline environmental data and species tolerance thresholds to disturbance, as well as measurements and predictions of realistic natural disturbance regimes in order to place biological observations in context. Moreover, effective management of deep-ocean use in the future will hinge upon understanding impacts of multiple and cumulative stressors. Limited case studies from past and ongoing disturbances provide some information (e.g., Ashford et al., 2018; Vieira et al., 2020), but even fewer manipulative experiments address the mechanisms behind the responses at different temporal and / or spatial scales (Jones et al., 2017). This gap represents a key area for research development and one of the most important categories of information required for effective management efforts and stewardship of the global ocean. Related to this we must understand the potential for restoration of impacted deep-sea ecosystems with challenges largely associated with observation technologies (Van Dover et al., 2013; Levin et al., 2019), as well as with social, political, and economic interactions

with science (Ehrlich and Pringle, 2008) and estimated costs (Van Dover et al., 2013).

These four broad questions lie at the heart of our ability to sustainably manage ocean use. The truly global challenge of addressing them requires a coordinated international and inclusive effort. As we approach the start of the Ocean Decade, the task before the scientific community is clear. We are charged with contributing knowledge to enable the Ocean Decade to achieve the stated SOs and Os. Our ability to plan for sustainable human use of the oceans, and adapt to environmental change lies in our ability to accurately predict possible outcomes and their socio-economic consequences. However, accurate forecasting requires at its base, ecological knowledge of species and habitats that, for the deep sea, is scant, highly spatially biased, with very few temporal data A new, globally coordinated program can address priority research questions that inform the development of a more holistic, non-sectoral, and equitable approach to sustainable use of deep-sea ecosystems. This program requires a coordinated, stepwise, and modular design. Next, we consider the design criteria in light of the identified research questions, and review current understanding of the role of key variables in shaping ecological pattern and process.

KEY ENVIRONMENTAL DRIVERS OF ECOLOGICAL PATTERN AND PROCESS

To address the SOs identified under the Ocean Decade we must quantify biodiversity and characterize species ecological niches, including their relationship to important climate-related variables. Until recently, the Inter-governmental Panel on Climate Change (IPCC) assessments had largely ignored climate change at the deep seafloor. However, the Special Report on Ocean and Cryosphere in a Changing Climate (SROCC) refers to clear regional and depth-related differences in projected temperature, POC flux, pH, and oxygen at the seafloor (Bindoff et al., 2019) under RCP 8.5 and 2.6 projections. To facilitate greater inclusion of the deep sea in IPCC assessment efforts we must stratify our sampling across these Essential Ocean Variables (EOVs) in order to quantify biological responses. Current and projected deep-ocean climate velocities exceed those at the surface, with consequences for the pelagic environment and consequently the benthos (Brito-Morales et al., 2020). Range mismatches among species across depths, could compromise vertical connectivity in the deep ocean (Brito-Morales et al., 2020).

Stratification by Latitude as a Proxy for Climate Related Variables

Ocean temperature above the permanent thermocline decreases with increasing latitude with sea-ice present in polar regions. POC export has a more complex relationship with latitude, but peaks at mid-latitudes (40–60 degrees) north and south of the Equator, with minima at ∼20 degrees (Lutz et al., 2007). POC export relates to POC flux to the seafloor, which in turn shapes benthic community composition (Billett et al., 2010). Both temperature and POC flux are implicated in driving global

patterns of species diversity, but relationships between drivers and responses are still uncertain (Worm and Tittensor, 2018). The latitudinal diversity gradient (LDG) in species richness is one of the most well-established ecological paradigms for many terrestrial, freshwater, and coastal systems (Hillebrand, 2004), but with equivocal support for LDGs in the deep sea. Originally described by Humboldt and Bonpland (1807), the pattern predicts highest species diversity at the equator, with decreasing diversity toward the poles. The diverse proposed processes underlying LDGs include wide spatial variation in biological interactions, evolutionary processes, energy availability, climatic variability, physical heterogeneity and patchiness, and neutral processes (Pianka, 1966; Rohde, 1992).

Evidence suggests latitudinal gradients of diversity in benthic deep-sea fauna, although this conclusion rests on much lower sampling effort compared to other ecosystems. Rex et al. (1993, 2000) reported LDGs in the North Atlantic for gastropods, bivalves, and isopods. Patterns in the South Atlantic were weak and only present in some taxa (Brandt et al., 2005). This weaker South Atlantic pattern could relate to either lower sampling effort or strong regional effects on diversity, e.g., terrigenous carbon inputs in the Amazon Basin (Rex et al., 1997). Elevated Antarctic deep-sea biodiversity could also weaken the South Atlantic LDG if deep-sea biodiversity mirrors the high diversity of the Antarctic continental shelf (Clarke, 2008). Gage et al. (2004) found poleward declines in the diversity of deep-sea cumaceans for the entire Atlantic but only on the eastern corridor, supporting earlier observations of regional and basin effects. However, polychaetes in the Arctic Ocean illustrate that LDGs may occur even with a basin (Bodil et al., 2011). Among the benthic meiofauna, deep-sea foraminiferans show latitudinal gradients in the North and South Atlantic (Culver and Buzas, 2000) related to seasonality in pelagic production (Corliss et al., 2009). Nematodes peak in diversity at mid-latitudes in the North Atlantic (Mokievsky and Azovsky, 2002). More recent research demonstrates the complexity and variability of LDGs in the deep sea. Woolley et al. (2016) reported that both the patterns and underlying drivers of ophiuroid diversity clines can vary with depth, transitioning from diversity patterns driven by temperature at shallower depths to productivity at deeper depths. This pattern, along with an earlier body of evidence (Gooday et al., 1990; Lambshead et al., 2002; Rosa et al., 2008; Smith et al., 2008; Corliss et al., 2009; Tittensor et al., 2011; McClain et al., 2012a), points to the importance of organic matter availability in driving large scale patterns of diversity in the deep oceans.

In polar latitudes, where the effects of climate change are being expressed more rapidly, changes in surface primary production as a result of decreasing sea-ice cover will likely influence carbon supply to the deep sea (Rogers et al., 2020b). In the Arctic, declining summer sea-ice cover with additional strong and complex multiyear sea ice effects (CAFF, 2017), has resulted in a 30 percent increase in surface primary production (Arrigo et al., 2008; Arrigo and van Dijken, 2015). Regional patterns of change in the duration of sea ice as well as the collapse of ice shelves characterize Antarctica. In the Atlantic sector, including the Antarctic Peninsula, the present rapid decrease in sea ice coverage and duration follows a 40-year increasing trend

(Parkinson, 2019; Vernet et al., 2019). Collapse of ice shelves in the Weddell Sea has exposed new areas of the ocean for primary production. Changes in surface primary production, including the size (AMAP, 2017; CAFF, 2017) and functional types (Orkney et al., 2020) of phytoplankton cells, will alter pelagic food webs as well as POC export and flux to the seabed, subsequently affecting benthic communities (Gutt et al., 2011).

Although surface pH tends to increase with latitude, at the deep seafloor, Highest pH values occur in the North Atlantic, and lowest values in the North Pacific (Sweetman et al., 2017). Intense research in shallow water marine ecosystems over the last decade has examined biological responses to ocean pH stemming from the predicted decrease in pH under climate change scenarios termed 'ocean acidification.' Ocean acidification results from the absorption of atmospheric CO_2 by the ocean. This facet of global climate change significantly affects calcifying organisms by requiring them to utilize larger proportions of their energy budget to offset calcium carbonate dissolution (Muller and Nisbet, 2014). In surface waters, this change can alter phytoplankton community composition, potentially altering primary productivity (Dutkiewicz et al., 2015). These surface level changes will impact pelagic food webs and POC flux to deep-sea communities. In addition, the saturation state of carbonate decreases with depth, and therefore calcifying organisms in much of the deep ocean already face energetic challenges. Although deep-sea corals show remarkable capacity to maintain calcification in waters undersaturated in carbonate (Thresher et al., 2011; Gómez et al., 2018), further declines in pH will further challenge their calcification and growth, potentially leading to dissolution of existing deep-water coral reefs.

Highest sea surface oxygen concentrations occur in polar regions and lowest concentrations in equatorial regions. At the seafloor, oxygen patterns resemble those for pH, with highest dissolved oxygen concentrations in the North Atlantic, and lowest concentrations in the North Pacific (Sweetman et al., 2017). Oxygen strongly influences benthic fauna density, biodiversity, species distributions, taxonomic composition, food web structure, biogeochemical cycling, body size and species-level population and physiological rates (Levin and Gooday, 2003; Muthumbi et al., 2004; Laffoley and Baxter, 2019; Wishner et al., 2020). In the deep sea, the strongest influence of oxygen occurs at bathyal depths (200–1200 m) within oxygen minimum zones, but particularly in the prevalent extreme OMZs in the North and Eastern Pacific Ocean, Northern Indian Ocean, and off west Africa (Helly and Levin, 2004) as well as the Western Indian Ocean (Muthumbi et al., 2004). Many of these low oxygen areas are expanding under climate change (Stramma et al., 2008; Breitburg et al., 2018; Levin, 2018). The North and East Pacific and Southern Ocean have experienced the greatest oxygen losses over the last half century (Levin, 2018; Bindoff et al., 2019).

Although stratification in relation to latitude captures a range of current environmental variability, it does not capture evolutionary scale processes that have shaped faunal patterns of diversity and distribution. Many studies have considered regionalization of the marine environment into biogeographic zones. Watling et al. (2013) provides a detailed review of the history of deep-sea benthic biogeography as part of their

development and refinement of a Global Open Ocean and Deep Sea (GOODS) classification (UNESCO, 2009; Watling et al., 2013). The GOODS classification was initially developed in 2009 in an expert consultation workshop for use in high seas management, initially basing proposed units on regions and provinces recommended by Menzies et al. (1973); Zezina (1973)Zezina (1997), and Vinogradova (1979) for bathyal and abyssal regions. However, boundaries were modified with recent data, published and unpublished observations, or re-analyses of existing data. Watling et al. (2013) further developed the classification, using physical and chemical proxies considered good predictors of benthic population distribution, to delineate 14 lower bathyal and 14 abyssal provinces. The fully classification also incorporated hadal provinces defined by Beliaev (1989).

Although the GOODS classification provides a convenient system by which to stratify benthic survey and monitoring, it does not consider the pelagic environment. Surface ocean properties from the basis of most pelagic biogeographic schemes (e.g., Longhurst, 1998; Spalding et al., 2012). However, in order to characterize the mesopelagic realm (200 — 1000 m), Sutton et al. (2017) collated expert opinion on physical and chemical oceanographic conditions, and biological expertise to define 33 mesopelagic ecoregions within four biomes (polar, westerly winds, trade wind, distant neritic). Their ecoregions reflected broad-scale patterns in the daytime distributions of mesopelagic fauna, with water mass structure, surface productivity, oxygen minimum zones and temperature extremes included as variables of particular importance. These ecoregions closely parallel those identified by Watling et al. (2013) in their classification of deep bathyal and abyssal biogeography. However, Sutton et al. (2017) note that their classification omits temporal variability in conditions, which plays a central role in the fluid and dynamic pelagic realm, and, like much of the deep pelagic biome, contains extensive data gaps (Webb et al., 2010). Using back scatter data, Proud et al. (2018) examined the global distribution of biomass (as backscatter intensity) within the deep scattering layer and identified 22 provinces, that correlated with overlying primary productivity and temperature at the depth of the deep scattering layer. No study to date has attempted to classify the bathypelagic realm, likely reflecting the lack of available data.

We propose a global program uses the revised GOODS classification (Watling et al., 2013) and mesopelagic ecoregions from Sutton et al. (2017), to stratify respectively benthic and pelagic deep-sea survey and monitoring, ensuring overall stratification by latitude.

Stratification at the Regional Level (e.g., Within Biogeographic Class)
Stratification by Depth
While latitude/biogeography can serve as a proxy for many key environmental variables, vertical gradients with depth arguably represent the strongest gradient of environmental change in the global ocean. Physical and chemical oceanographic drivers, and biogeochemical and biological responses all vary with depth. Key variables that correlate with depth (not always monotonically), and play a significant role in determining species

distributions and community composition, include temperature (Haedrich et al., 1975), pressure (Somero et al., 1983), oxygen (Gallo and Levin, 2016), sediment type (Day and Pearcy, 1968), water mass structure (Howell et al., 2002), pH and aragonite saturation (Guinotte et al., 2006), and food supply (Rowe and Menzies, 1969), amongst others. Fauna undergo a non-repeating sequential change in composition with depth, with the combination of environmental variables that correlate with depth defining species depth ranges, as well as the fundamental ecological niche occupied by the species. Changes in environmental variables over depth also influence many ecological measures including diversity, abundance, and biomass. Stratifying sampling by each of these key environmental variables would be challenging. As with latitude/biogeography, depth itself serves as an easily measurable, widely accepted proxy for environmental variation. We therefore outline guidance on stratification of sampling by depth.

Although experts generally accept 200 m as the start depth for the deep sea, little evidence supports the existence of a benthic faunal boundary at this depth. Geomorphological rather than biological criteria define the transition between the deep circalittoral and deep sea, which occurs at the shelf edge break, typically taken as 200 m. Coral reef biologists recently described a new rariphotic zone extending from 150 to 300 m with community members predominantly related to shallow-water families (Baldwin et al., 2018). Carney (2005) summarized patterns of deep-sea benthic faunal zonation with depth and concluded that transition zones typically occur at 300 - 500 m (the shelf-slope zone of transition), ~1000 m (upper slope zone of transition), and 2000 —3000 m (lower slope zone of transition). Researchers typically classify the pelagic ocean by downwelling solar light levels where: the epipelagic zone (0 — 200 m), receives sufficient solar light for photosynthesis; the mesopelagic zone (200 — 1000 m), receives sufficient solar light for vision; the bathypelagic zone (> 1000 m) receives light coming only from biological sources (Sutton, 2013).

We propose a global program uses the following indicative depth horizons as a general guide for a target range for all biogeographic regions in order to achieve an unbiased global dataset: 150 — 300, 300 — 500 then every 500 m to the deepest point of the oceans at ~10 km. We chose these horizons to capture the scales of known faunal transitions over the depth gradient. These depth-delineated horizons should serve both pelagic and benthic known faunal zonation patterns. We do not dictate the density of sampling (fine or coarse) at any individual site.

Stratification by Horizontal Distance

The degree of faunal turnover (β-diversity) or its converse (similarity) between pairs of communities links closely to the spatial or environmental differences between them. The presence or absence of a species at one location, and similarity to another location, can reflect the geographic distance between them (i.e., the distance-decay relationship), acknowledging interplay with dispersal ability of the species, ocean currents, and availability of suitable habitat. Animal migrations can occur on scales of 1000s of kilometers. Larval dispersal of brooding

invertebrates span scales on the order of meters to 10s of meters, whereas broadcast spawners disperse 10s to 1000s of kilometers depending on ocean currents and planktonic larval duration (McClain and Hardy, 2010; Hilário et al., 2015). Dispersal of adult stages can vary from centimeters to 1000s of kilometers, depending on size, swimming ability (e.g., crawling isopods versus migrating fish) and current patterns. Alternatively, these biogeographic and community patterns can reflect habitat heterogeneity (Cordes et al., 2010), niche-based processes such as environmental filtering, i.e., how species specific niche requirements map out on the environmental landscape, and the long-term consequences of interspecies interactions (e.g., Quattrini et al., 2017; Ashford et al., 2018).

At large geographical scales, the deep sea varies considerably in species diversity over latitude and depth (Rex and Etter, 2010). Few studies address regional to oceanic patterns of deep-sea β-diversity for megafauna. In general, specialist assume that even at larger scales, matching environment and species' niche requirements (i.e., environmental filtering) primarily drives patterns in biogeography and biodiversity (reviewed in McClain and Hardy, 2010). Some studies downplay the importance of dispersal limitation because the planktonic larval phases of many deep-sea invertebrates theoretically allow long-distance dispersal and potentially large biogeographic ranges (reviewed in McClain and Hardy, 2010), although empirical evidence suggests limited realized connectivity of 100s rather than 1000s of kms (Baco et al., 2016). Yet few studies have evaluated these concepts.

Most research on deep-sea β-diversity has focused on benthic macrofauna or meiofauna. McClain et al. (2012b) explored patterns of β-diversity in taxonomic, phylogenetic, and functional diversity across the Atlantic Ocean, using the bivalve data set of Allen (2008). Strong environmental filtering and dispersal limitation both drove turnover in taxonomic, functional, and phylogenetic composition. Blake and Grassle (1994) detected faunal changes both across and along isobaths in the southern region of the ACSAR program, NW Atlantic off North and South Carolina (United States). Depth explained most faunal variation, but with pronounced horizontal variation in the bathyal region. For meiofauna, Danovaro et al. (2009) found significant differences in assemblages across a longitudinal gradient for the entire ocean for abyssal but not bathyal sites in the Mediterranean Sea. Bianchelli et al. (2013) subsequently found evidence that energy availability was an important driver of the structure of deep-sea nematode assemblages. Food quantity drove patterns at larger scales, and the quality and bioavailability of food determined small-to-local scale patterns. However, other studies of nematodes found that productivity played a subordinate role to sedimentary characteristics (Vanreusel et al., 2010). In contrast Leduc et al. (2012) found distances between sites, both horizontally and vertically, explained the greatest proportion of variance in β-diversity of nematodes on the upper New Zealand continental slope.

The high level of coexistence of species in the deep sea represents one of the most intriguing paradoxes in ecology. Species richness in some deep-sea localities can exceed 300 species of macrofauna within a square meter (Grassle, 1989; Etter and Mullineaux, 2001). Sampling often yields

species-accumulation curves that rarely reach an asymptote (reviewed in Etter and Mullineaux, 2001; Snelgrove and Smith, 2002), a pattern frequently interpreted as evidence of high turnover of local species. Empirical studies on the role of environmental patchiness in explaining these findings is mixed (Jumars, 1975, 1976; Thistle, 1979; Jumars and Eckman, 1983; Lamont et al., 1995; reviewed in Rex and Etter, 2010; McClain et al., 2011).

Although latitude/biogeography and depth provide useful frameworks for understanding ecological processes at a global scale, comprehensive understanding requires studies that describe and quantify ecological patterns at finer spatial scales. To enable us to begin to identify the scales of faunal turnover and connectivity, we propose that regional modules of a global sampling program stratify by horizontal distance at resolutions of 1 m, 10 m, 100 m, 1 km, 10 km, 100 km. Not all spatial scales will be appropriate for all size fractions or faunal components and this stratification should serve as a guide to interpret as appropriate to the specific study system.

Stratification by Anthropogenic Pressure

SO's 1, 2, 3 and 5 all require an enhanced understanding of human impacts on deep-sea ecosystems, in order to guide marine spatial planning and the sustainable exploitation of resources while safeguarding deep-sea life (Manea et al., 2020). Therefore, a comprehensive global study should stratify sampling by single and multiple anthropogenic pressures.

A design approach that stratifies by latitude will enable us to understand how species might respond to climate change. However, the degree of climate hazard (change relative to natural variability), and the time of emergence of climate change in the deep sea vary spatially (FAO, 2018; Bindoff et al., 2019; Levin et al., 2020). Some sites will experience climate change sooner than others. We propose targeting some early and some late emergence (e.g., potential climate refugia) sites. To effectively distinguish climate impacts requires selection of sites otherwise un-impacted, or minimally impacted by other anthropogenic pressures (e.g., not fished, low levels of pollution). This strategy implies inference from some prior knowledge on the intensity of human impacts at a given site from proxy data.

Global overfishing of coastal fish stocks and the need to feed a growing human population have led capture fisheries to target stocks inhabiting progressively deeper waters (e.g., Watson and Morato, 2013) and Areas Beyond National Jurisdiction (ABNJ) (e.g., Merrie et al., 2014) since the 1950s. In general, life-history traits such as slow growth, late maturation, and low fecundity (e.g., Drazen and Haedrich, 2012) increase the vulnerability of deep-sea fishes to fishing pressures. Long-lived species that form dense, local aggregations, such as orange roughy and oreos, are particularly vulnerable to rapid overexploitation, but approximately equal population reductions occur in all species whose ranges fall within the fished depth range (Bailey et al., 2009). The economic returns from demersal fishing decrease, and ecological costs increase with depth below c. 600 m in the NE Atlantic (Clark et al., 2016a). Restrictive measures to support sustainability of deep-water fisheries and to protect benthic ecosystems are now in place in EU Atlantic

waters, including a depth ban on bottom trawl fishing below 800 m (Regulation (EU) 2016/2336). Recent papers suggesting exceptionally high mesopelagic fish biomass (Kaartvedt et al., 2012; Irigoien et al., 2014) have helped drive a resurgence of interest in targeting mesopelagic fishes as a source of protein for fishmeal. Acknowledging that deep-living pelagic fauna represent a largely unexploited marine resource, any future use must carefully balance benefits against both the considerable lack of knowledge about the ecology and ecosystem function of the deep pelagic realm (Webb et al., 2010), the high value of mesopelagic fauna in carbon transport and sequestration and their role in oceanic food webs (Colaço et al., 2013; Trueman et al., 2014). In addition to impacts on fish stocks, fishing, and specifically use of bottom contact gear, can cause significant adverse change or serious harm to benthic habitats and species (Rogers and Gianni, 2010), reducing structural and functional diversity and altering biogeochemical cycles (Puig et al., 2012; Ramalho et al., 2018; Vieira et al., 2019). Little information exists on resistance to, and rates of recovery from, the physical damage associated with bottom contact gear for many species. However, available data indicate limited resilience and thus high vulnerability in some species. At regional levels, Regional Fisheries Management Organizations (RFMOs) and national monitoring programs can provide satellite-derived data on marine vessel movements. These data enable a reasonably accurate assessment of the spatial distribution of fishing pressure (e.g., NAFO data input to benthic studies in the NW Atlantic; Ashford et al., 2018, 2019).

Litter and contaminants from different sources now infiltrate the deep sea, and have been identified in sediments and in biota (e.g., Ramirez-Llodra et al., 2010; Pham et al., 2014; Woodall et al., 2015; Courtene-Jones et al., 2020). These contaminants include debris of different types and sizes, such as plastics (ranging in size from nano- to macro-) or fishing gear, and other particulate or dissolved chemicals such as hydrocarbons, metals, and legacy and emergent persistent organic pollutants (POPs) (e.g., Pham et al., 2014; Woodall et al., 2014; Taylor et al., 2016; Jamieson et al., 2017). Nevertheless, we lack information on how these materials spread, whether a gradient of contamination decreases away from terrestrial sources, or how, and for how long, they move into the deep sea. High resolution ocean circulation models (van Gennip et al., 2019), indicate a ∼2 year transit time of the litter produced in the western coast of South America, including debris produced by the industrial fishery operating in the high seas off Chile and Peru, to the center of the South Pacific Gyre. However, we lack any reliable estimate of the portion of this debris reaching the deep sea and the time it takes. Importantly, how do pollutants accumulate in sediments and biota, and how do they impact fauna? Some initial studies reported microplastics in megafauna from the Rockall Trough dating back to the mid-1970s (Courtene-Jones et al., 2017) and we now know these contaminants spread to the deepest ocean trenches (Jamieson et al., 2019). Environmental risk assessment, for instance, requires knowledge of baseline levels for concentrations of contaminants, in order to develop sediment quality guidelines and to assess baseline levels of biomarkers of stress in organisms, against which to measure

effects of disturbance. Stratification of sampling over a gradient of contamination adds significant challenges; ocean circulation and topography can concentrate litter (e.g., canyons, gyres), whereas bioaccumulation can concentrate pollutants. Distance from pollution sources, such as land, river mouths, or major shipping lanes offers one potential proxy.

Other forms of anthropogenic activities are more spatially constrained. Licensing requirements limit deep-seabed mining and oil and gas activities to specific locations best studied through dedicated regional monitoring programs. A global program could provide a baseline against which to monitor, and therefore should ensure inclusion of sampling locations within areas licensed for oil and gas extraction, or contracted for seabed mining exploration, as well as comparable areas (e.g., potential reference sites) that are protected from various forms of anthropogenic impact where possible.

We propose a global program replicates the following treatments in regional designs where possible: high and low climate hazard under early/late time of climate change emergence, fished/un-fished, near/far from pollution sources, licensed/protected from industry activities.

Other Considerations

Substrate type, an essential ocean variable, shapes benthic biological community composition. Historically, we largely based our knowledge of deep-sea benthic ecosystems on data obtained using trawls and sledges from soft-sediment seafloors. However, over the last 40 years, advances in technology coupled with decreases in cost, have supported growth in the use of video and still image-based tools for semi-quantitative sampling of previously inaccessible hard substrate habitats. The resulting new findings challenge the prevailing view of deep-sea ecosystems (Danovaro et al., 2014). The global design must factor in substrate type. However, lack of knowledge on seafloor composition constrains *a priori* stratification by substrate type. Collecting acoustic survey data (multibeam/sidescan sonar) prior to any biological work, undertaking topographic and acoustic backscatter classification, and stratifying biological surveys by remotely sensed bottom type (Brown et al., 2011; Riehl et al., 2020) provides a useful approximation. Alternatively, published models of seafloor lithology may be useful (Diesing, 2020). However, these models likely lack the resolution required for realizing stratification by substrate type in survey design.

Global bathymetry data, such as the General Bathymetric Chart of the Oceans, offers another approach to stratification, based on topography. This simplified form of geomorphological classification analyses terrain derived variables such as slope, rugosity, bathymetric position index, to differentiate terrain types. Bottom slope provides a particularly useful proxy for multiple ecologically relevant variables (McArthur et al., 2010). Existing geomorphological classifications (e.g., Harris et al., 2014) may provide a useful standardized means by which to consider the global stratification of sampling. However, such classification may not produce ecologically meaningful geomorphological classes, and thus should not form the basis of stratification efforts. Nevertheless, a global program should strive to include different ecosystem types, an issue addressed further in section 6.

We propose that a global program should stratify sampling by substrate type and / or topography, including bottom slope, within regional designs.

TEMPORAL SURVEY AND MONITORING NEEDS

Effective assessment of human impacts requires long-term monitoring (time series) of both impacted and control sites. In addition, to determine the functional significance of organisms and their role in the delivery of goods and services to humankind critically requires temporal sampling and experimentation. Although our blueprint focuses on setting spatial design criteria for a global survey program, the design must include sites prioritized for monitoring and temporal surveys.

Within each biogeographic region experts should identify and include potential monitoring sites in the design. Levin et al. (2019) and the DOOS initiative provide an inventory of current sustained deep-ocean observing activities, and propose a series of potential region-specific, interdisciplinary projects to demonstrate the feasibility of sustained deep-ocean observing, relevant technologies, and the impact and utilization of deep-ocean observations. These proposed locations include the Clarion-Clipperton Zone, Azores Archipelago, Northeast Pacific: Cascadia Margin to the Juan de Fuca Ridge, Western Pacific, and Ocean Trenches: Izu-Ogasawara Trench and Mariana Trench. Researchers selected these sites on the basis of strategic advantages and existing infrastructure, and they represent excellent choices for demonstration projects, but we must now identify further sites for all biogeographic regions (e.g., Indian Ocean) and take the first steps toward establishment of a globally comprehensive network of sites for sustained observations. Following Levin et al. (2019), we propose a global program use the following criteria in site selection: access to different strata outlined in the global design, availability of existing observing infrastructure, opportunity and ease of installing and maintaining new infrastructure.

PRIORITY AREAS FOR NEW BIOLOGICAL AND ECOLOGICAL DATA COLLECTION

The strong spatial bias in our knowledge of the marine environment largely drives the need for a globally coordinated and inclusive program. Latitudinally, the most undersampled regions include equatorial and polar areas as well as southerly latitudes (Menegotto and Rangel, 2018). Researchers have prioritized the data poor south Atlantic, south and central Pacific and Indian Oceans for research (Clark et al., 2012; Saeedi et al., 2019). Globally, sampling effort decreases with depth. For example as of 2019 10.4% of the Ocean Biodiversity Information System (OBIS) records were from > 200 m, with only 1.5% of time series data (> 5 years) falling below 200 m. Only 158,000 records fell between 500 and 10,900 m. At the conclusion of the Census of Marine Life, Clark et al. (2010) highlighted the lack

of data available on deeper sections of seamounts (> 2000 m depth). Recently, Taylor and Roterman (2017) identified only nine published papers that dealt with population genetics below 3500 m depth. The bathypelagic environment is the least studied, and largest component of the deep oceans by volume (Webb et al., 2010). The BioTIME initiative reports similar spatial bias in time series data with most studies occurring in Europe, North America and Australia (Dornelas et al., 2018), with large data gaps in the Pacific, South Atlantic and Indian Oceans. As ice cover in the Arctic continues to decline, this ocean basin will experience increasing anthropogenic influence and deep-sea research efforts should also prioritize this key region. There is a clear and well documented need to prioritize research effort in southern and polar latitudes, deeper depths, and midwater environments.

SPECIAL CONSIDERATIONS FOR DIFFERENT ECOSYSTEM TYPES

The global design detailed above sets out a strategy that is independent of any perceived ecosystem type, and thus moves away from the traditional silos in which many deep-sea researchers find themselves. However, the global design should preferentially ensure inclusion of different ecosystem types. Here, Harris et al.'s (2014) global geomorphological classification scheme may provide a useful standard against which to classify a given study site. However, from an ecological perspective some of Harris et al. (2014) classes easily group into single ecosystem types that correspond to established research areas with the deep-sea biological research community. Some of these ecosystem types require additional design considerations to facilitate a more complete representation of these specific systems with respect to addressing the Ocean Decade SOs. We identify different ecosystem types, the equivalent Harris et al. (2014) class(es) and further variables by which to stratify individual or regional project level designs (**Table 1**).

THE NEED FOR STANDARDIZATION IN OBSERVATIONS AND METHODOLOGIES

Increasing evidence in recent years illustrate that inconsistencies in sampling of different habitats and regions have challenged efforts to bring datasets together and provide a global picture. Several deep-sea field projects under the Census of Marine Life (2001–2010) noted this issue when collating and collectively analyzing their data. The highly variable array of sampling equipment and survey approaches constrained analyses. Effective broad-scale analyses of ecological patterns and processes, and human impacts requires standardized comparable data (Clark et al., 2016b). The high diversity of life forms, from microscopic bacteria to large cetaceans, require different sampling approaches and methods depending on the composition and abundance of the biological communities and environmental characteristics of their habitat. Although national goals often drive scientific objectives and specific survey design, we identified consistent sampling across national and international programs as a priority

to advance our knowledge of deep-sea ecosystems. The guidance on "best-practice" sampling of deep-sea environments (Clark et al., 2016b) complemented other deep-sea texts (e.g., Danovaro et al., 2010, 2020; Eleftheriou, 2013) and initiatives such as the Global Ocean Observing System (GOOS) and the Deep Ocean Observation Strategy (DOOS) in trying to improve global-scale science.

Building on the efforts of GOOS (Miloslavich et al., 2018a), DOOS has proposed essential ocean variables (EOVs) for the deep ocean (Levin et al., 2019). Many of the GOOS variables identified by the Bio/Eco panel occur only in shallow water (e.g., mangrove, seagrass, algal cover, turtles). DOOS has identified a suite of physical, biogeochemical, and biological/ecological variables that are sufficiently mature (technologically ready), suitable for sustained, and, in some cases automated, observing; but this prioritization omits many critical kinds of information. Danovaro et al. (2020) identified, through expert elicitation, a set of essential ecological variables necessary to address (1) biodiversity; (2) ecosystem functions; (3) impacts and risk assessment; (4) climate change, adaptation and evolution; and (5) ecosystem conservation at the deep seafloor.

The need for a consistent approach to data collection and close collaboration between marine scientists from different countries and disciplines to advance knowledge of the ocean also catalyzed the development of the General Ocean Survey and Sampling Iterative Protocol (GOSSIP) (Woodall et al., 2018). Focusing on 20 biological, chemical, physical, and socioeconomic parameters the detailed GOSSIP framework supports consistency in future marine data collections. It highlights standardized collection methods and discusses their relevant limitations and caveats to help researchers apply (or at least understand) best practice techniques for generating globally comparable marine data. Although concerned with mesophotic, deep-pelagic, and bathyal biological communities, application of this protocol more widely offers a good starting point for research efforts under the Ocean Decade. In addition, the International Oceanographic Data and Information Exchange of the IOC has developed the Ocean Best Practices System (OBPS) including an open access, permanent, digital repository of community best practices in ocean-related sciences and applications (Pearlman et al., 2019). This repository contains highly detailed standard operating procedures and operational field manuals for a range of survey and sampling equipment and techniques, and may provide additional detail and points of reference for specific gear types and procedures, including quality assurance and archiving of data.

Although standardized observations and methodologies require further work, we recommend that a global program adapt Woodall et al. (2018); Levin et al. (2019), and Danovaro et al. (2020), relevant archived best practice documents in the OBPS (Pearlman et al., 2019) as a basis for further development of standardized approaches to deep-sea biological survey and monitoring. Danovaro et al.'s (2020) and **Table 1** provides a summary of actions required for deep-sea monitoring of the most important essential ecological variables. Woodall et al.'s (2018) and **Table 1** summarizes key measurements and methods to obtain such measurements in a robust, standardized,

TABLE 1 | Ecosystem-specific considerations.

Ecosystem type	Stratification variable	Importance of stratification variable	Recommendation
Topographic rises including Seamounts, guyots, ridges, abyssal hills, abyssal mountains, mid ocean ridge.	Position on topographic rise, e.g., summit, flanks, base, aspect.	Oceanographic conditions differ substantially between summit, flanks and base related to terrain slope and the wider geomorphological nature of the feature (Rogers, 1994).	Ensure sampling of summit, flanks, and base.
	Aspect	Can reflect different oceanographic conditions.	Aspect (e.g., up-current versus down-current; ridge axis versus flanks either side) should be factored in.
Canyons – shelf incising and blind.	Shelf-incising vs slope-confined (blind) canyons (sensu Huang et al., 2014)	Contrasted organic resource supply in intensity and frequency, hard substrates/soft bottom habitats, both in relation to canyon hydrodynamics (Fernandez-Arcaya et al., 2017)	Sampling of different geomorphological units within canyons. Huang et al. (2014) provide a classification system for canyons that may be a useful means of standardizing definitions of canyon types.
	Active vs inactive canyons (sensu Bernhardt et al., 2015)		
	Large volume vs small volume canyons (Sensu Huang et al., 2014)		
	Canyon head (shelf incision) and mouth (deposition lobes on abyssal plain)		
Trenches	Latitude/Depth	Major influence of productivity and deep water mass influence, on trench biogeography and community structure, connectivity aspects included (Jamieson et al., 2010)	Can be captured with latitude – based stratification guidance and by considering trenches' distance from the continents and from each-others
	Overlying Productivity	Fundamental source of nutrient supply	
	Hard vs soft substrates	Unexpected habitat heterogeneity with diverse topographical features within the trenches (e.g., ridges, cold seeps, sedimentary ponds)	Sampling of different geomorphological units within the trenches, along bathymetric transects, and along trenches axis to ensure capture of all topographic features and associated communities through the sampling effort
	Trench topography (e.g., flanks, bottom)	Different organic resources supply in both intensity and frequency mainly depending on trench hydrodynamics (deep-sea currents), and earthquakes and volcanic eruptions (gravity-driven landslides phenomena). Different level of natural disturbance within the trench system (Jamieson et al., 2010).	
Abyssal Plains	Nodule cover	Nodule mining	Stratify across nodule cover
	Topographic setting	Abyssal plains often feature numerous, but small, abyssal hills and troughs as part of the ecosystem	Sample in both topographically complex versus simple settings. Could use the global design substrate-based stratification guidance in this context.
	Distance to bathyal depths	Will permit testing of bathyal/source - abyssal/sink hypothesis	Use the global design distance-based stratification guidance in this context.
	Productivity in space and in time	Productivity derived from surface, terrestrial inputs, organic falls, etc., determines interannual carbon flow variations	Cover areas with different productivity regimes (e.g., oligotrophic vs. eutrophic). May be considered as part of the global design latitudinal based stratification guidance in this context.
Slopes	Island vs Continental;	Terrestrial influence (manifested on continental margins, and to a lesser extent on islands) modifies slope communities (Levin et al., 2001)	Ensure inclusion of continental and island slopes.
	Upwelling regime	Upwelling regimes affect oxygenation and food supply to the slope, modifying densities, diversity, lifestyles, body size and ecosystem function (Rogers, 2000)	Include Eastern boundary upwelling areas and western boundary current regions in N. and S. hemisphere
Seeps	On vs off seep	Seeps are unique chemosynthetic ecosystems (Levin et al., 2016a)	Stratify by on vs off seep
	Hard vs Soft substrates	Different communities develop in seep sediments than on authigenic carbonates (Levin et al., 2016b)	Sample seeps dominated by hard and soft substrates. Could use the global design substrate-based stratification guidance in this context.

Continued

TABLE 1 | Continued.

Ecosystem type	Stratification variable	Importance of stratification variable	Recommendation
	Depth	Strong depth zonation for seep megafaunal taxa (mussels, tubeworms, clams) (Rodrigues et al., 2013; Levin et al., 2016a)	Follow guidance in main design.
Hydrothermal vents	Vent biogeography	They have their own biogeographic provinces (about 11 after Rogers et al., 2012) linked to spreading rate, ocean basin and connectivity.	Stratify by vent biogeography rather than GOODS biogeography.
	Active / inactive hydrothermal systems	Seafloor Massive Sulfide mining may target inactive hydrothermal deposits, but known deposits so far are in proximity to active vent fields (exploration leases include active areas) (Van Dover et al., 2018; Van Dover, 2019)	Sample the continuum from active vents out to "dormant" sites.
	Mid Ocean Ridges vs Back Arc Basins, volcano flanks, seamount summits and serpentine-hosted systems (including Lost city type)	Geological diversity and natural instability (eruption, seismicity) are predominant drivers of vent biodiversity (Ramirez-Llodra et al., 2007)	Sample on different geological settings with contrasted environmental properties (acidic to alkaline pH, metal-rich or depleted, different energy sources for chemosynthesis H_2/CH_4/H_2S/FeII and others to be discovered)
	Proximity to the nearest vent field	Peripheral non-vent fauna benefit from local primary production has received less attention, despite its importance for regional biogeography and regarding ecosystem services (Van Dover, 2019)	Stratify by distance to nearest vent field
	Axis / off axis vent deposits on Mid Ocean Ridges	Relates to geological age (Beaulieu et al., 2015)	Stratify by on axis/off axis
Ice-covered ocean	Seasonal sea ice, cover by multiyear ice, or ice shelf	Ice cover determines the quantity and quality of primary production reaching the deep-sea floor. Permanent/ ice age old ice shelf may cover very rarely studied /undiscovered ecosystems (Beaulieu et al., 2015; Boetius et al., 2015).	Stratify according to ice cover.

Ecosystem types conform to geomorphological classes presented in Harris et al. (2014) where applicable.

and affordable approach. Levin et al.'s (2019) and **Table 2** provides a list of biological and ecosystems Essential Ocean Variables, including new EOVs proposed by the Deep Ocean Observing Strategy (DOOS). Here, we align these three study recommendations on what to measure and how (**Table 2**) to provide advance understanding of deep-sea ecosystems and form a basis for further discussion on this topic under a global program.

Physical Specimen Sampling Needs

Importantly many of the measures identified in **Table 2** require the collection of physical specimens. Biodiversity measures (KSQi) require physical specimens for biomass measurements, and for morphological and genetic analysis (DNA barcoding) to confirm organism identification and resolve taxonomy and phylogeny unambiguously. Connectivity studies (KSQii) specifically population connectivity require physical specimens for microsatellite, AFLP, or NGS studies, as well as reproductive studies such as fecundity, reproductive mode and timing of spawning. Trophic studies require samples for stomach content, fatty acid, pigment, stable isotopes, and potentially eDNA analyses. Further questions around ecosystem function (KSQiii) require physical specimens to quantify physiological processes and ecosystem services such as carbon sequestration, and to determine biological traits such as growth rates, longevity, age and size at first maturity, population size structure, and length/weight relationships. Earlier efforts to develop a functional traits database for vent species

highlighted how few life-history traits could be assembled for all species (Chapman et al., 2019). Impact and risk assessment measures (KSQiv) require physical specimens for analyses of contamination such as microplastics, particulate or dissolved metals, hydrocarbon exposure, and legacy and emergent persistent organic pollutants. We propose that targeted physical specimen sampling form an important part of a global program. Coordinated and targeted physical specimen sampling efforts, and development of processing pipelines that include access to experts and effective archiving require further consideration.

DATA AND SPECIMEN ARCHIVING

In addition to the fundamental need for standardization of measures, collection and processing methods, data accessibility following collection also remains a challenge. O1 and SO6 (**Figure 1**) consider a transformative increase in ocean knowledge that include data and specimen archiving as part of the desire to expand, innovate and integrate knowledge in global systems (O2). We expect that this information will enhance understanding and prediction of the global oceans (O3) as part of the interconnected system and the need to develop a decision support system (O4). Critical elements include data storage, and ensuring it follows both the Findable, Accessible, Interoperable, and Reusable (FAIR) principle and the principles of Collective benefit, Authority to control, Responsibility and Ethics (CARE). These principles

TABLE 2 | Woodall et al. (2018); Levin et al. (2019), and Danovaro et al. (2020) recommendations for what to measure and how, aligned for equivalency, and supplemented by additional considerations.

Scientific Area as defined in Danovaro et al. (2020)	Primary Components as defined in Woodall et al. (2018)	Essential ecological variables as defined in Danovaro et al. (2020)	Detail of priority measurements recommended by all three papers and supplemented with new parameters.	Data acquired inform which Societal Outcomes (SOs) and key scientific questions (KSQ's) (see Section 2).
Biodiversity: Water column components	Biological parameters: Pelagic	Macro and meso zooplankton	Provided in Woodall et al. (2018) under the following headings in **Table 1**. (1) Size structure and species composition of mesozooplankton, pelagic micronekton, and pelagic nekton (fish abundance and distribution – Levin et al., 2019) (2) Acoustic sensing of water column biomass (3) Size structure and abundance of gelatinous zooplankton (4) Microbial community (5) Census of associated biota Levin et al. (2019) add zooplankton biomass and diversity We add genetic/genomic diversity.	SOs: 2, 3 KSQs: i
Biodiversity: Sediments components	Biological parameters: Benthic	Macro- and megafauna	Provided in Woodall et al. (2018) under the following headings in **Table 1**. (6) Deepwater hyperbenthos (7) Mesophotic hyperbenthos (8) Epibenthos [including hard coral cover and composition and benthic invertebrate abundance and distribution (Levin et al., 2019)] (9) Infauna including benthic invertebrate abundance and distribution (Levin et al., 2019) Levin et al. (2019) also add microbial biomass and diversity. We add genetic/genomic diversity.	SOs: 2, 3 KSQs: i
Not covered	Environmental drivers	Not covered	Provided in Woodall et al. (2018) under the following headings in **Table 1** (10) Bathymetry and Seafloor morphology (11) Seafloor composition (substrate type) (12) Current velocity (13) Temperature, salinity, pressure (derived density) (CTD) (14) Nitrate/nitrite (NO3, NO2), silicate (SiO4), and phosphate (PO4) (15) Dissolved oxygen (DO) (16) pH (17) Dissolved inorganic carbon (DIC) and total alkalinity (TA) Although other programs under the Ocean Decade, for example GOOS and Seabed2030 will measure physical properties of the ocean, a deep-sea biology program should make *in situ* physical measurements to accompany biological data.	SOs: 1, 2, 3, 5 KSQs: i, ii, iii, iv
Ecosystem functions	Not covered	Trophic structure	Requires collection of physical specimens for dietary analyses.	SOs: 2, 3, 5 KSQs: ii, iii
Ecosystem functions	Not covered	Benthic faunal biomass	Guidance provided in Danovaro et al. (2020) and **Table 1**. Bio-volume estimates (for example, class size frequencies from individuals' body lengths) We add direct measurements of biomass.	SOs: 2, 3, 5 KSQs: i, iii
Impact/risk assessment	Sociocultural parameters and impacts	Habitat damage	Provided in Woodall et al. (2018) under the following headings in **Table 1**. (19) Records of litter and anthropogenic damage (20) Microplastic abundance and diversity Guidance provided in Danovaro et al. (2020), **Table 1**. The analysis of seascapes changes based on habitat mapping approaches and georeferenced photomosaic compositions Levin et al. (2019) add ocean sound No study considers other particulate or dissolved chemicals such as metals, legacy and emergent persistent organic pollutants (POPs).	SOs: 1, 2, 3, 5 KSQs: iv

Continued

TABLE 2 | Continued.

Scientific Area as defined in Danovaro et al. (2020)	Primary Components as defined in Woodall et al. (2018)	Essential ecological variables as defined in Danovaro et al. (2020)	Detail of priority measurements recommended by all three papers and supplemented with new parameters.	Data acquired inform which Societal Outcomes (SOs) and key scientific questions (KSQ's) (see Section 2).
Impact/risk assessment	Not covered	Recovery rate (as a proxy of resilience)	Time-series data required. Guidance provided in Danovaro et al. (2020), **Table 1**. Multivariate analysis time-series counts for species depicting fluctuations according to concomitant oscillations of key environmental drivers (for example, temperature and oxygen maxima and minima). We add data on growth rates, longevity, fecundity, reproduction, recruitment rates, size at first maturity (puberty), maximum body size, dispersal.	SOs: 2, 3, 5 KSQs: iv (and may draw on i, ii, iii)
Global change, adaptation and evolution	Not covered	Shifts in bathymetric distribution	Time-series biodiversity data required. See Biodiversity / Biological parameters	SOs: 2, 3, 5 KSQs: i, ii, iv
Global change, adaptation and evolution	Not covered	Local extinctions	Time-series biodiversity data required. See Biodiversity / Biological parameters	SOs: 2, 3, 5 KSQs: i, ii, iv

Woodall et al. (2018) provide further detail on how measurements should be made to ensure consistency in collections which we will not repeat here, but direct others to read.

apply not only to digital products, but also to physical specimens, which all form the foundation of repeatability in science.

The IOC, together with the Center for the Fourth Industrial Revolution: Ocean under the Ocean Data Platform[1], are developing an Ocean Data and Information System to improve significantly the availability of ocean data and information, and to enable open source products and services catered to the needs of a broad community of users, including academia and ocean managers. This, together with existing UN supported initiatives such as OBIS, will provide the means to archive data collected under a global program. However, whether this initiative includes provision for open sharing of specimens as well as data remains unclear. Participants in a global program should commit to the open sharing of specimens as well as data, including deposition of specimens with an established museum, an institution with a recognized charter that supports both the permanent storage and care of archive specimens, and access to those specimens by the scientific community. Natural history museums facilitate loans to enable the global community to utilize specimens in their care. Nonetheless, any material collected within the territorial waters of a specific nation falls under the purview of the Convention on Biological Diversity and particularly the Nagoya Protocol and its access and benefit sharing rules. A framework governing access and benefit sharing for marine genetic resources in areas beyond national jurisdiction (ABNJ) is in discussion at the UN (The International Legally Binding Instrument for the Conservation and Sustainable Use of the Biological Diversity of ABNJ; Wright et al., 2018). Both of these legal frameworks require traceability of biological specimens and any digital sequence information from the origin of the samples through subsequent uses, especially if used commercially (Rabone et al., 2019). This traceability means that a unique identifier for samples

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[1]https://www.oceandata.earth/

taken at sea may become an important requirement both for tracing the use of samples, but also for linking specimens or digital sequence information to sample locations and their associated metadata.

Rapid technological change over the coming decade will parallel accelerating species loss. Consequently, a standardized repository approach, to archive or 'bank' frozen specimens, tissue samples, and specimens fixed for morphological visualization, will enable scientists to address future questions not yet envisaged or for which technology does not yet exist (e.g., regarding functions). Museum specimens represent the pinnacle of sustainable science: material collected now will be used by future generations another 150 years in the future, just as we use the original specimens collected on the *Challenger* Expedition, the birth place of deep-sea science, 150 years ago. Guiding principles in both data and specimen archiving should include rapid accession and minimal embargo, and a commitment to collect broadly. Collection and archiving of data and specimens should not only serve the goals of an individual project, but prepare for synergistic and unpredictable future uses.

BUILDING CAPACITY AND PROMOTING KNOWLEDGE EXCHANGE IN DEEP-SEA RESEARCH

Objective 1 of the Ocean Decade (**Figure 1**) focuses on increasing capacity to generate, understand, manage, and use ocean knowledge. This objective has particular relevance for deep-sea research. While more than 70% of countries have a deep-sea environment within their EEZ, economically developed nations (sensu UN Department of Economic and Social Affairs) conduct most deep-sea research. Availability of samples, bias in available

data, and overall knowledge of deep-sea ecosystems all reflect this bias. Countries with developing economies face significant barriers to participating in deep-sea research, including access to technological capability and infrastructure, and specific expertise. Yet the least studied parts of the deep sea often occur within the EEZs of less economically developed nations. A global assessment of capacity development needs in ocean science was undertaken by the UN through a series of regional workshops between 2011 and 2013. This assessment highlighted particular needs for capacity building in deep-sea research (Ruwa et al., 2016). In 2015, the Intergovernmental Oceanographic Commission Assembly adopted its Capacity Development Strategy for 2015–2021 (IOC-UNESCO, 2016), identifying six high-level outputs to address on a long-term and sustained basis:

(1) Human resources developed
(2) Access to physical infrastructure established or improved
(3) Global, regional and sub-regional mechanisms strengthened
(4) Development of ocean research policies in support of sustainable development objectives promoted
(5) Visibility and awareness increased
(6) Sustained (long-term) resource mobilization reinforced.

A global program should aspire to contribute to the Ocean Decade O1 by committing to core principles of effective research capacity sharing and building (e.g., Hind et al., 2015):

(1) *Co-development and co-creation of contributing regional research projects.* To ensure a truly global and inclusive program, the community should consider their proposed research region, and actively seek early engagement with other region-based collaborators to facilitate co-design and development of research plans and funding applications. Particularly in the case of Small Island Developing States (SIDS), a.k.a. Large Ocean States, local/indigenous methodologies and epistemologies have great potential in ocean observations from under sampled locations as well as knowledge production. Many countries increasingly focus on applying traditional ecological knowledge to coastal and shallow marine research, but less so in deep-sea research. We propose that capacity sharing and building actions actively invest in and support diverse practitioners to pursue deep-sea research. A new generation of deep-sea scientists, from a more diverse geographic pool, would bring new perspectives and approaches to research in the open ocean. In addition, local/indigenous knowledge systems linked to the deep ocean should be given a voice and considered alongside natural science in evolving deep sea exploration targets and management.

(2) *Investment in training for scientists from economically developing countries.* Previous studies have identified the crucial need to develop human capacity for oceanographic research in economically developing countries, as well as examples of activities that can achieve this objective (Morrison et al., 2013; Miloslavich et al., 2018b). Research projects contributing to a global program should, where possible, include a budget for full participation of regional partners in ship-board training activities, as well as knowledge-exchange and networking activities, e.g., conference and meeting attendance (Stefanoudis et al., 2020). Projects should also consider small investments in local research infrastructure that may enable long-term data collection (see new technologies section below), allowing local researchers to continue producing data beyond specific projects (Hind et al., 2015).

(3) *Sharing research products.* Projects should assign time and resources for co-analysis of data and dissemination of research outcomes with regional partners. We also strongly recommend open access publication of research, a small but valuable step in international engagement under a global program.

THE POTENTIAL ROLE OF NEW TECHNOLOGY

Technological development forms the nexus in our ability to identify and generate ocean data, information and knowledge (**Figure 1**, O2). Access to technology is one of the barriers to broadening participation in deep-sea research ((**Figure 1**, O1). The revised Roadmap for the Ocean Decade outlines the potential role for new technologies in helping researchers better measure biodiversity, functions of deep-sea ecosystems and cumulative impacts of ocean stressors, and define the carrying capacity of ocean ecosystems to sustain human impacts and economic development. Anticipated developments over the decade largely grouped into three areas: improved access to the oceans, in terms of exploration (spatial coverage), variability (temporal monitoring) and costs (low cost technology); improved extraction of information from observations including automated data processing; and democratization of the sharing of both data and knowledge obtained.

Data Acquisition

Historically, access to the deep ocean has been both expensive and sparse, reliant upon access to large ocean-going ships and deep submergence research assets (both human occupied and robotic) operated by relatively few nations and often in regions far away from the largest of Earth's ocean basins. Moving beyond satellite-based remote sensing, other fields of ocean research have advanced the use of new technologies that enable larger-scale coverage for global-scale ocean investigations. For example, recently developed biogeochemical (BGC) ARGO floats extend the capabilities of the ARGO array to measure important parameters in the deep ocean including pH, oxygen, chlorophyll, nitrate, suspended particles and downwelling irradiance. Simultaneously, the development of autonomous surface vessels such as the sail drone have enabled completion of demonstration projects that couple persistent presence at the ocean surface with remote sensing satellite data to guide vehicles (equipped with suitable instrument payloads) to ground-truth observations from remote sensing data. Under the Ocean Decade, judicious use of deep gliders and long-range AUVs, reporting back to shore-based scientists via autonomous surface

vessels, could begin to conduct first-pass exploration of remote portions of the deep ocean floor (German et al., 2012). Even this modest contribution could immediately begin to improve the efficiency and efficacy with which the science community can deploy the most expensive assets among the international research community (global-class research ships and deep diving submersible assets).

Although recent technological advances leave no part of the world's deep ocean out of reach, the capacity to deploy those assets remains limited worldwide. The extreme expense associated with buying, operating and maintaining large-scale oceanographic infrastructure, including ships and deep - submergence facilities pushes them out of the reach of most developing countries. However, satellite-enabled telepresence has enabled many thousands of individuals across the planet to join in discoveries and investigations in the deep ocean in real time but only if they have internet access. Partnerships between research institutes, universities, museums, and aquaria that can offer free access to the video, annotation, and scientists themselves during an expedition could augment this access. However, broader participation in this discovery field clearly requires the development of low-cost and smaller technologies to apply to deep-sea research (Phillips et al., 2019).

Data Extraction

Extraction of information from acquired data also offers ripe opportunity for technological advancement over the Decade. Miniaturization and increasingly lower power requirements for *in situ* sensors for multiple environmental parameters enable installation on an increasing number of platforms obviating the need for laborious analyses and increasing coverage in the oceans, both in terms of spatial coverage and temporal monitoring. In parallel, non-invasive identification of species through genetic samples via environmental DNA (eDNA) sequencing provides an important, portable, and non-invasive technique enabled by emerging sequencing technology (Mariani et al., 2019). The approach offers an exciting opportunity to quickly analyze the diversity of fauna present within any given environment, although lack of an effective reference library to identify sequences by comparisons constrains application of the approach to the deep-sea biota (Howell et al., 2019). Many deep-sea eukaryotic species have never been sequenced before, or may be species new to science, and eDNA therefore cannot yet offer definitive identification. An emphasis on well-curated physical specimens entrusted to museums and the principles of open data sharing will overcome this bottleneck to identifying many deep-sea species.

In parallel, the increasing volumes of image and video data we anticipate scientists will acquire over the decade, not just from conventional methods but from expanded use of ship-free deep-ocean robotic assets will require a comparable ramp-up in the throughput of image analysis, and highlight a need for software solutions to improve pipeline processing and automatic analysis. Howell et al. (2019) identify the requirement for manual image analysis as a significant bottleneck in image-based marine ecological survey and monitoring, and that artificial intelligence (AI) and computer vision (CV) offer a potential means by which

to both accelerate and standardize the interpretation of ecological image-based data (Piechaud et al., 2019). However, significant barriers to further development of these methods remain, including the lack of a standard morphospecies reference image catalog against which to base identifications and annotations. Such a catalog is in development for deep-sea fauna (Howell et al., 2019), and other potentially useful classification schemes already exist (Althaus et al., 2015). The deep-sea research community should prioritize agreement on a standard approach in order to expedite the use of AI and CV.

Technological advance will form a significant aspect of the Ocean Decade, and a global program should seek to contribute to, and benefit from, these developments in progressing toward the achieving the SOs.
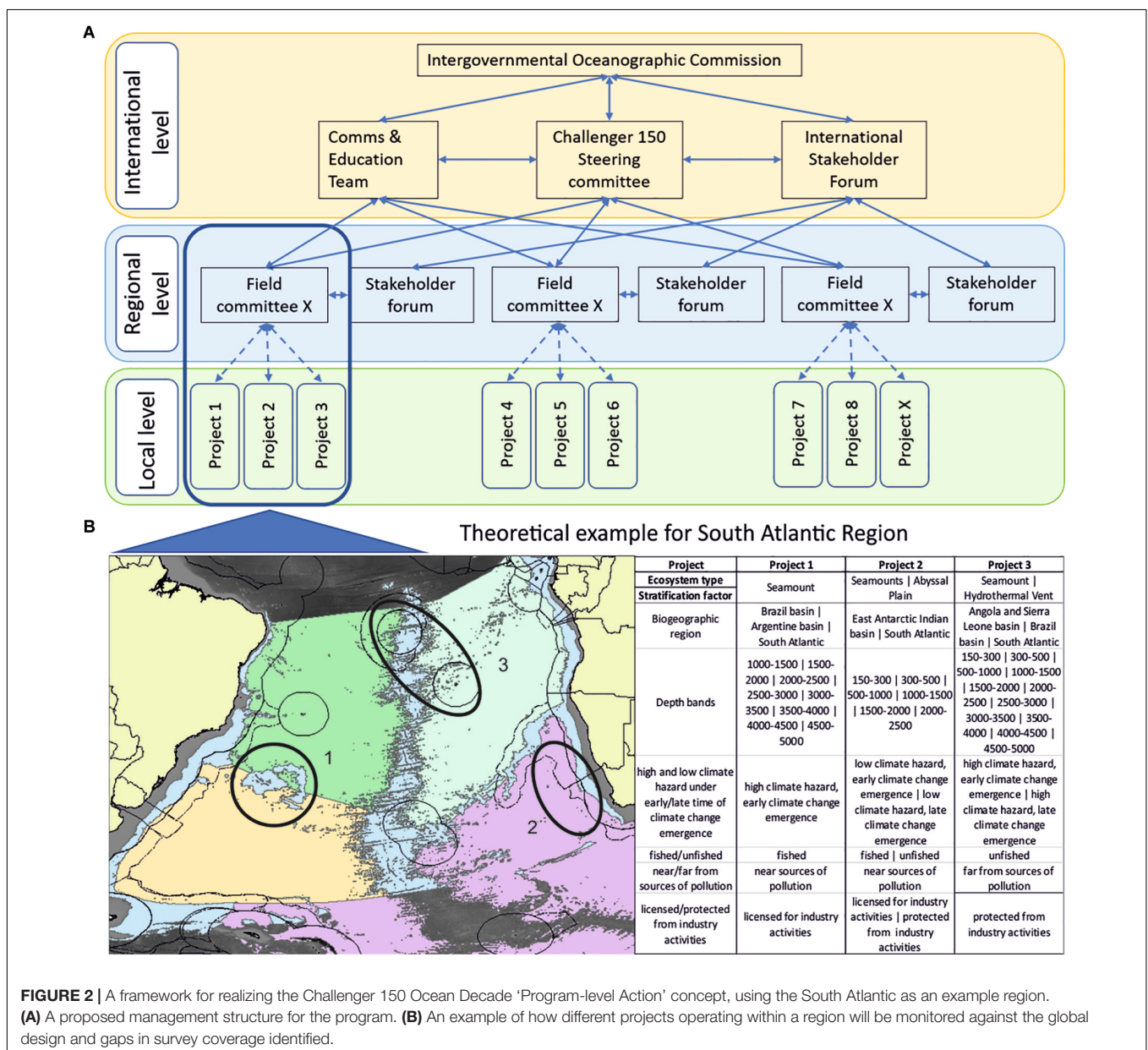
DISCUSSION

In this paper, we have reviewed research needs of the Ocean Decade in the context of the design of a new 10 year deep-sea biology research program. This paper offers a blueprint for the further development of a global program as an official 'Action' of the Ocean Decade that we name here *Challenger 150*. Scientists and the public alike associate the name "Challenger" with exploration of new frontiers. One hundred and fifty years ago '*HMS Challenger*' spent 4 years circumnavigating the globe, mapping the seafloor, recording the global ocean temperature, and providing us with a first panoramic view of life in the deep sea. Rightly scientists now attribute the birth of deep-sea biology and oceanography to *HMS Challenger*. The NASA space program later used the same name, first for the Apollo 17 Lunar Module that landed on the Moon in 1972, and later forthe space shuttle *Challenger* that flew the first American woman, African-American, Dutchman and Canadian into space. Today the name describes the deepest point of the ocean, the bottom of the Mariana Trench where, in January 1960 Jacques Piccard and Don Walsh made the first human descent to the Challenger Deep in the bathyscaphe Trieste. More recently, in March 2012 film director James Cameron made the first solo descent in the deep-submergence vehicle *Deepsea Challenger*. We use the name Challenger here to invoke the same spirit of exploration embodied by the previous Challengers, and to recognize the importance of that first global deep-sea biological dataset that, for some parts of the ocean, remain the only data available. However, we fully acknowledge that past exploration involved colonialism and exclusion. We advocate that in keeping with the Ocean Decade objectives *Challenger 150* should forge a new inclusive, representative and equitable face for an historic name.

We present *Challenger 150* as a concept for an Ocean Decade 'Program-level Action' as defined in the draft Implementation Plan. It would serve as a community-led collaborative endeavor in the stepwise development of a coherent, well-designed, deep-sea global survey and monitoring program. The concept would be realized through individual research projects committing to align with the blueprint presented here, and in so doing, becoming a piece in a larger global jigsaw puzzle. Such a program would require an unprecedented level of communication and

coordination between research projects over the course of the Ocean Decade, and thus the program would require an effective management structure established to coordinate with, and support the community to follow the outlined design criteria regionally, annually reviewing progress toward the overall global design and Ocean Decade SOs and Os (**Figure 2**). We envisage a process where-by individual projects, supported by a diverse range of funders, will formally align with the Challenger 150 program and the recommendations within this text. Lead PIs of projects from the same region, together with other relevant regional researchers will form a regional field committee (**Figure 2A**) to coordinate and monitor fieldwork efforts at that scale, and to support regional teams to develop new projects to fill survey gaps over the course of the Ocean Decade

(**Figure 2B**). They will also interact with a regionally relevant stakeholder pool to ensure field projects complement research occurring within other disciplines, and remain aligned with end-user needs. Development of these regionally relevant stakeholder forums will draw upon existing regionally relevant bodies, for example the Second International Indian Ocean Expedition in the Indian Ocean, or the Benguela Current Commission in the South East Atlantic. Representative membership of each regional field committee will sit on the Challenger 150 steering committee to ensure coordination of field projects at a global scale, and monitor progress against the program aims and global survey design. The steering committee will report on progress to the IOC. They will also interact with a global stakeholder pool specific to the program, or possibly at the

FIGURE 2 | A framework for realizing the Challenger 150 Ocean Decade 'Program-level Action' concept, using the South Atlantic as an example region. **(A)** A proposed management structure for the program. **(B)** An example of how different projects operating within a region will be monitored against the global design and gaps in survey coverage identified.

level of the IOC, where a global stakeholder pool may interact with multiple Ocean Decade programs. A communications and education team will coordinate activities between projects, and liaise with the IOC's communications and education team, to ensure joined up efforts between different Ocean Decade programs. Participating research projects would be required to commit to use of new knowledge, as it accumulates, to address the Ocean Decade SOs and Os. By the end of the Ocean Decade the data from all projects could be combined to provide 'one giant decadal leap' for human knowledge of the deep ocean. Through this approach, contributing projects could potentially make a major contribution to both the Ocean

Decade (**Table 3**) and SDG14, that simply could not be achieved working in isolation.

The revised Roadmap for the Ocean Decade calls upon the scientific community to think beyond business as usual and aspire for real change in the level of knowledge of the ocean in support of sustainable development. The implementation plan foresees a funding resource base that is multi-actor in nature, broad and flexible, taking a variety of forms. As we stand on the brink of the Ocean Decade, the *Challenger 150* concept seeks to coordinate global research efforts in deep-sea ecology and oceanography for the express purpose of contributing to the delivery of the Ocean Decade SOs. However, success depends

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TABLE 3 | What an inclusive global program could deliver against each of the relevant Ocean Decade societal outcomes and by inference SDG14.

Societal Outcome	Deliverable	Comments
1	A comprehensive knowledge of the distribution, abundance and diversity of contaminants in our ocean including litter, microplastics, dissolved metals, hydrocarbons, legacy and emergent persistent organic pollutants.	These data can be used to identify sources and pathways of pollution, and inform action to reduce the level of contaminants entering the Ocean.
2	New mapping data including bathymetry, environmental data, species and habitat distributions, ecosystem functions, and human impacts. Knowledge of the individual and cumulative effects of different anthropogenic pressures including climate change. An established global network of sites where we can monitor climate change. New knowledge of the roles of deep-sea species and habitats in delivering ecosystem goods and services.	These deliverables can be used to inform decision-making, through the integration of updated biological and ecological knowledge within marine spatial planning processes to guide a sustainable blue economy. This could include use of ecosystem-based management approaches, including the establishment and designation of area-based management tools (e.g., Ross and Howell, 2013). Both the spatial footprint and cumulative impacts of anthropogenic and climate-derived pressures on species, habitats, ecosystem functions, services and goods will be better measured. These measurements will (1) inform policy decisions that reduce human impacts and/or ensure ecosystem services are maintained; and (2) support estimates of the natural capital the deep sea provides to societies and their wellbeing, and so help reveal different trade-offs faced in different use scenarios, informing policy decisions on ocean management.
3	New data on species and habitat densities, distributions, ranges, environmental drivers and tolerances. An established global network of sites through which we can measure and monitor change. New data on abundance, diversity, biomass, size structure, fecundity, growth rates, dispersal, longevity, nutrient uptake, respiration rates, and diets of species. New data quantifying human impacts on abundance, biomass, diversity, and community composition. New knowledge of the roles of deep-sea species and habitats in delivering ecosystem goods and services.	These data, together with those collected under other Ocean Decade programs (e.g., Seabed 2030, physical oceanographic programs) will facilitate the use of various modeling approaches to predict current and future conditions, for example current patterns of, and shifts in, the distribution of species and communities (Howell et al., 2016; Brito-Morales et al., 2020; Morato et al., 2020) under climate change, changes in fishing effort, onset of mining activities, etc. The establishment of appropriate monitoring sites will provide temporal data with which to train temporal models, forecast into the future with greater confidence, and disentangle climate-related change from changes caused by other human activities. Coupled with new knowledge of the role of species and habitats in delivering ecosystem goods and services, this will support further predictions of what modeled changes mean for human wellbeing and livelihoods.
5	New data on the abundance, density, biomass, size structure, fecundity, growth rates, dispersal, longevity, connectivity, respiration rates, diets, and habitat preferences of species including commercially harvested species.	As with SO3 these new data will facilitate the use of modeling approaches to predict ecological responses to fishing pressure (Howell et al., 2009; Heymans et al., 2011), as well as cumulative pressures to support policy decisions around sustainable harvesting. Coupled with socio-economic research these data can be used to inform scenario modeling around provision of food supply and livelihoods.
6	New data and specimens appropriately archived and openly accessible A larger number of nations actively engaged in deep-sea research Improved deep-sea ocean literacy	The global nature of the research described herein will take place in a wide variety of state-controlled waters as well as areas beyond national jurisdiction (ABNJ, or The Area). New consortia formed to address each biogeographic region, composed of/or at least including researchers and students from respective regions, will help to train a new generation of deep-sea scientists as part of a global community. The data generated will be included in the UN designated open-access databases as a product of the Ocean Decade, to support Ocean management and decision-making around the world. Physical specimens will be archived and accessible in relevant regional natural history museums.

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upon the nations and their research communities mobilizing and obtaining funding to support such efforts. Ship time represents a significant cost, and the only realistic option for some nations will be to seek public-private or philanthropic partnerships such as the REV Ocean, Schmidt Ocean Institute, Ocean Exploration Trust, Nekton Foundation, OceanX, The International Seakeepers Society, and industry to provide access to appropriate platforms. Industry could play a particularly important role to play in less economically developed countries. The IOC and REV Ocean have already agreed on several areas of collaboration under the Ocean Decade, including use of the REV Ocean vessel, offering a real opportunity to advance the *Challenger 150* concept in the identified priority areas for new biological data collection. For other nations who can access large infrastructure, national, regional and bilateral funding mechanisms may be more appropriate or accessible as a means to fund contributing projects.

Although data collection represents a challenge, data processing, interpretation, archiving and storage represent a significant and on-going cost that at present can only be met by multiple applications for funding from national research budgets or philanthropic mechanisms. Regardless of where scientists apply for funding, alignment of projects with the blueprint outlined here as part of a community led, globally coordinated 10 year program brings greater opportunity for both efficiency and impact. Therefore projects aligned with the *Challenger 150* concept may appear more attractive to funders thus offering benefits to the wider community.

The Ocean Decade begins on the 1st January 2021 and already the deep-sea research community has begun to sow the first seeds of coordination between projects to contribute to a global program via the Deep Ocean Stewardship Initiative's (DOSI) Decade of Ocean Science working group and the Scientific Committee on Oceanic Research (SCOR) working group 159. We hope that the blueprint provided in this paper helps the wider deep-sea community to engage with the *Challenger 150* concept as a shared endeavor; to forge regional and inclusive consortia, co-develop research plans and funding bids aligned with the blueprint, and help achieve the SOs and Os of the Ocean Decade.

Summary of Recommendations
We Propose a Global Program

(1) uses the revised GOODS classification (Watling et al., 2013) and Sutton et al. (2017) mesopelagic ecoregions to stratify respectively benthic and pelagic deep-sea survey and monitoring, ensuring an overall stratification by latitude.

(2) uses the following indicative depth horizons as a general guide for a target range for all biogeographic regions to achieve an unbiased dataset: 150 — 300, 300 — 500 then every 500 m to the deepest point of the oceans at 10 km.

(3) uses the following indicative horizontal distances as a general guide for component projects to stratify sampling by: 1 m, 10 m, 100 m, 1 km, 10 km, 100 km.

(4) uses the following replicated treatments in regional designs where possible: high and low climate hazard

under early/late time of climate change emergence, fished/unfished, near/far from sources of pollution, licensed/protected from industry activities.

(5) stratifies sampling by substrate type and / or topography, including slope, within regional designs.

(6) uses the following criteria in selection of sites for potential monitoring: access to different strata outlined in the global design, availability of existing observing infrastructure, opportunity for and ease of installing and maintaining new infrastructure.

(7) prioritizes research effort in southern and polar latitudes, deeper depths, and midwater environments.

(8) considers additional ecosystem-specific stratification in addition to those of the main design (**Table 1**).

(9) uses **Table 2**, and the papers cited within, to provide guidance on what to measure and how in order that the data can be used to help deliver the SOs; and visit the OBPS digital repository at oceanbestpractices.org for more specific guidance.

(10) ensures that targeted physical specimen sampling form an important part of the program.

(11) follows the following guiding principles in both data and specimen archiving: rapid accession and minimal embargo, a commitment to collect broadly, FAIR, CARE.

(12) commits to and provide for the deposition of specimens with an established regionally relevant museum.

(13) commits to core principles of effective research capacity sharing and building, including engagement with local and indigenous communities.

(14) seeks to contribute to, and benefit from, technological developments in progressing toward the achieving the SOs.

AUTHOR CONTRIBUTIONS

KH and AH conceived the idea and convened the working group. KH, AH, AM, LL, ER-L, MB, PVRS, JX, HW, MC, EE, CG, SR, PE, and LM helped to conceive the manuscript and outline structure. All authors contributed ideas, text, and edits.

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