

OCEANOGRAPHY

The Global Deep Sea Exploration Goals: A representative approach to visually observing the deep seafloor

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The Global Deep Sea Exploration Goals strategy is a spatially balanced, probability-based, actionable global sampling design identifying 10,000 target locations for deep-sea visual observation (≥ 200 m). This sampling approach integrates four seafloor characteristics: bathymetry, geomorphology, sediment composition, and particulate organic carbon flux, while accounting for documented historical deep-submergence deployments. It aims to correct for historical observational biases across factors such as depth zones, ocean basins, geomorphology, and maritime jurisdictions. These proposed targets will nearly double the number of unique observed seafloor locations, establishing a more geographically and environmentally representative dataset. This globally distributed sampling design also highlights critical scientific gaps in underexplored regions, guiding both exploration and capacity-building priorities. By aligning with and amplifying complementary global initiatives in mapping and sampling, this effort lays the foundation for a more inclusive, coordinated, and statistically representative approach to deep-ocean science, which is essential for informed policy and sustainable resource management.

INTRODUCTION

Humanity's understanding of the deep ocean (200 m or deeper) is limited to the small areas where research studies, surveys, sampling, and observations have been conducted, resulting in a nonuniform understanding of deep-sea environments. This sampling bias is often underappreciated and overlooked across the marine sciences (1), but is particularly pronounced in visual observations of the deep seabed (2). The deep benthos presents unique challenges due to its remote nature, which requires advanced technology for exploration and research, resulting in expensive, inefficient, and exclusive operations (2). Consequently, very little of the deep seabed has been visually observed, and most deep-sea studies are conducted by researchers in high-income countries and locations with access to deep submergence tools (2–4). A recent study estimates that only 0.001% of the deep seafloor has been visually explored over the last seven decades (2).

Increasing threats to deep-sea ecosystems encompass a range of activities, from commercial fisheries targeting deep-dwelling species (5) to various types of deep-sea mining (6). Visual observations are vital for characterizing the deep-sea ecosystem and assessing its biodiversity (7, 8), providing contextual information for collected samples (9), enabling more accurate biodiversity and abundance surveys (10), and revealing behaviors of marine organisms (11). Research and conservation efforts, including numerous discoveries across disciplines (12–14) and the establishment of marine protected areas (15, 16), also rely heavily on visual observations.

To address the biases in global deep-sea understanding and the severe gaps in deep-sea visual data, a more representative global visual sampling of the deep benthos is urgently needed. Such an effort will enable the development of a more accurate and comprehensive understanding of deep ocean biogeography worldwide (1, 3, 17–19). Global strategies are uniquely effective at course-correcting bias in large, global datasets (20). A globally inclusive approach will not only improve the accuracy of scientific outputs but also ensure that decisions

about the deep ocean are informed by a more diverse, equitable, and representative community of explorers and stakeholders (21, 22).

This study describes the methods used to create the Global Deep Sea Exploration Goals, a proposed deep-sea, probability-based, statistical observation sampling plan encompassing 10,000 locations worldwide, resulting in a representative visual sample of the global deep seafloor (Fig. 1).

RESULTS

A sampling design for representative visual observation of the global deep seafloor

We used a probability-based sampling method (see Materials and Methods) to create an efficient sampling design for 10,000 target visual observation locations on the global deep seafloor (Fig. 1). We selected four global-coverage seafloor characteristics to drive our spatially balanced sampling design: seafloor bathymetry, geomorphology, sediment composition, and particulate organic carbon (POC) flux to the seafloor. These characteristics address key physical, chemical, geological, and biological properties of the deep seafloor using variables that are stable on decadal timescales. We also accounted for 43,681 deep submergence deployments that took place from 1958 to 2024 in 11,267 unique locations (table S1).

Our sampling design is representative of deep-seafloor areas across several key geographical and environmental dimensions. Observing these target locations, as a whole, will provide an initial visual characterization of the unexplored seafloor that more closely aligns with the distribution of enduring deep-seafloor geological, environmental, and geographical properties, compared to historical deep-sea observations. Specifically, the sampling design and the underlying sampling space from which it is generated address biases in historical seafloor observation deployments that overrepresent specific seafloor depth zones, geomorphological features, seafloor composition, and other environmental characteristics (tables S2 to S5 and figs. S1 to S4). Furthermore, the spatially balanced sampling approach prioritizes geographical spread across the entire global deep seafloor, leading to patterns of future activities across different ocean basins, jurisdictional areas,

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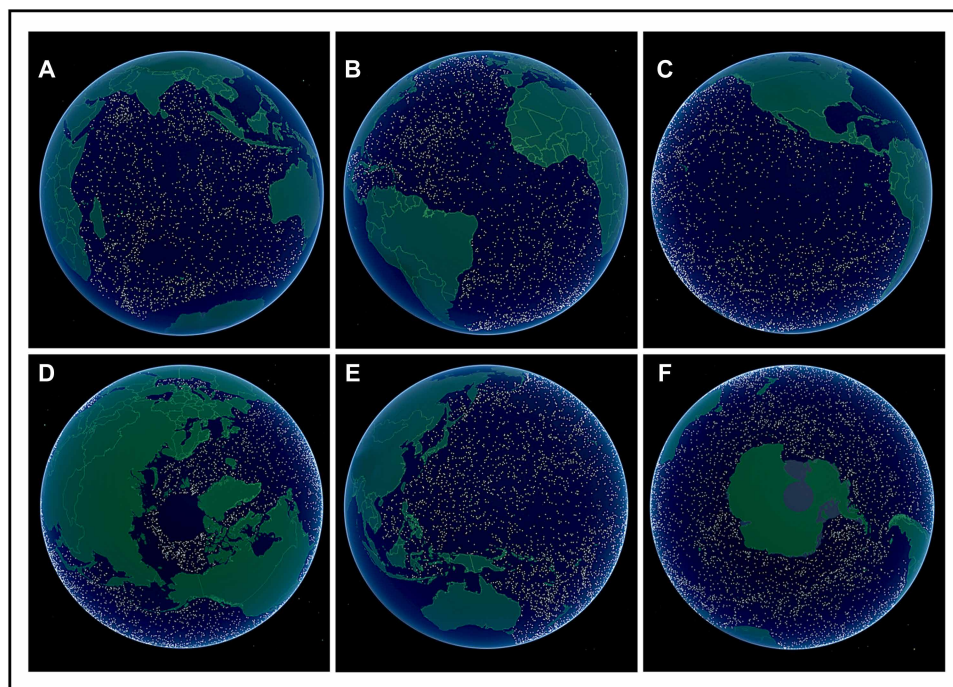


Fig. 1. 10,000 Global Deep Sea Exploration Goal target locations. The Global Deep Sea Exploration Goal locations are visualized on six views of a three-dimensional surface of Earth: (A) Arctic Ocean, (B) Atlantic Ocean, (C) Indian Ocean, (D) Western Pacific Ocean, (E) Eastern Pacific Ocean, and (F) Southern Ocean. Maps rendered with ArcGIS software (53).

and geographical subregions, which are lacking in historical observation coverage.

The Global Deep Sea Exploration Goal sampling design of 10,000 target visual observation locations improves upon historical deep seafloor observations in the following ways:

- 1) Nearly doubles the number of unique seafloor observation locations worldwide.
- 2) Aligns more closely with the distribution of key seafloor characteristics, particularly depth and geomorphology.
- 3) Leads to adjustments to past geographical biases, including ocean basins, maritime jurisdictions, and nearshore clustering.
- 4) Provides a concrete, actionable roadmap for strategic deep-sea visual exploration.

Doubling visual observation locations and addressing nearshore bias

Using historical records of deep submergence deployments, we calculated that 43,681 deep-sea dives observed 11,267 unique 314 km² seafloor locations from 1958 to 2024 (2). The selection of 10,000 target locations increases the number of unique deep-seafloor locations observed by 189%, nearly doubling the number of previously observed locations (Fig. 2).

Creating a representative sample of ocean areas

Four global-coverage seafloor characteristics factored into the target areas identified by our spatially balanced sampling design: bathymetry, geomorphology, sediment composition, and Particulate Organic Carbon (POC) flux to the seafloor. Described in detail in Materials and Methods, our approach generates a normalized sampling space

that represents the proportion of seafloor characterized by different values of each of these four characteristic variables.

Bathymetric zones

Historically, deep-seafloor observations have disproportionately targeted depths between 1000 and 2000 m and deeper than 6000 m, relative to the areas they occupy (Fig. 3A). The abyssal zone has been less visually observed compared to other zones; notably, the under-sampled abyssal depth zone occupies 48.2% of the global deep sea.

The distribution of target locations across seafloor depth zones (Fig. 3A) adjusts the historical biases of observed deep-sea areas with depths between 1000 and 2000 m and areas deeper than 6000 m. The abyssal zone, between 4000 and 6000 m, has the lowest historical sampling density (six locations per million square kilometers) and the highest percent increase in the number of observations (455%) in our proposed locations. The upper bathyal zone has the highest historical sampling density of 143 locations per million square kilometers and only a 28% increase in the number of target locations (Fig. 3B).

Geomorphology

Geomorphology was included as a variable due to its influence on ecological diversity and geological processes (23). Historical deep-sea exploration disproportionately targeted geomorphological features such as escarpments, canyons, and seamounts/guyots. In contrast, geomorphological features typically located farther offshore, particularly abyssal areas, shelves, and rises, have been consistently underrepresented in past observational efforts relative to their global seafloor coverage (2) (Fig. 4A).

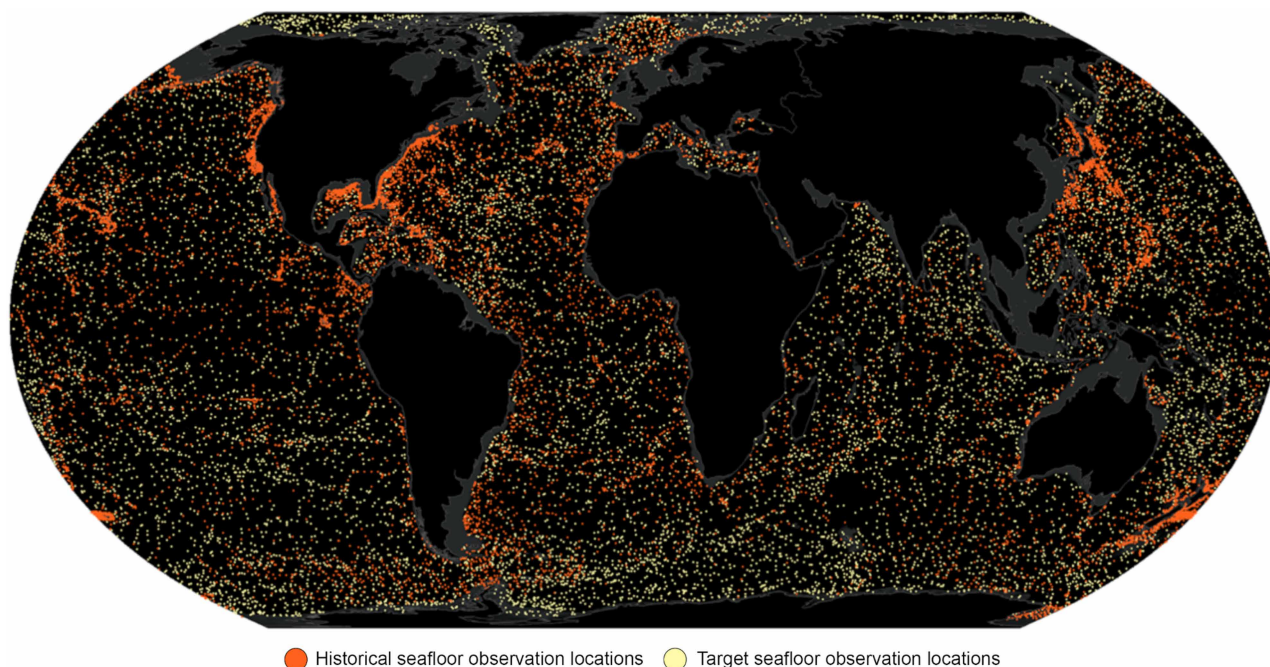


Fig. 2. Historical and target deep-seafloor observation locations. A total of 11,267 unique historical seafloor observation locations (orange) are primarily concentrated within 200 nm of the coastlines of high-income countries. Our 10,000 proposed target seafloor observation locations (yellow) spatially balance global deep-seafloor visual observations worldwide and nearly double the number of visually explored unique locations.

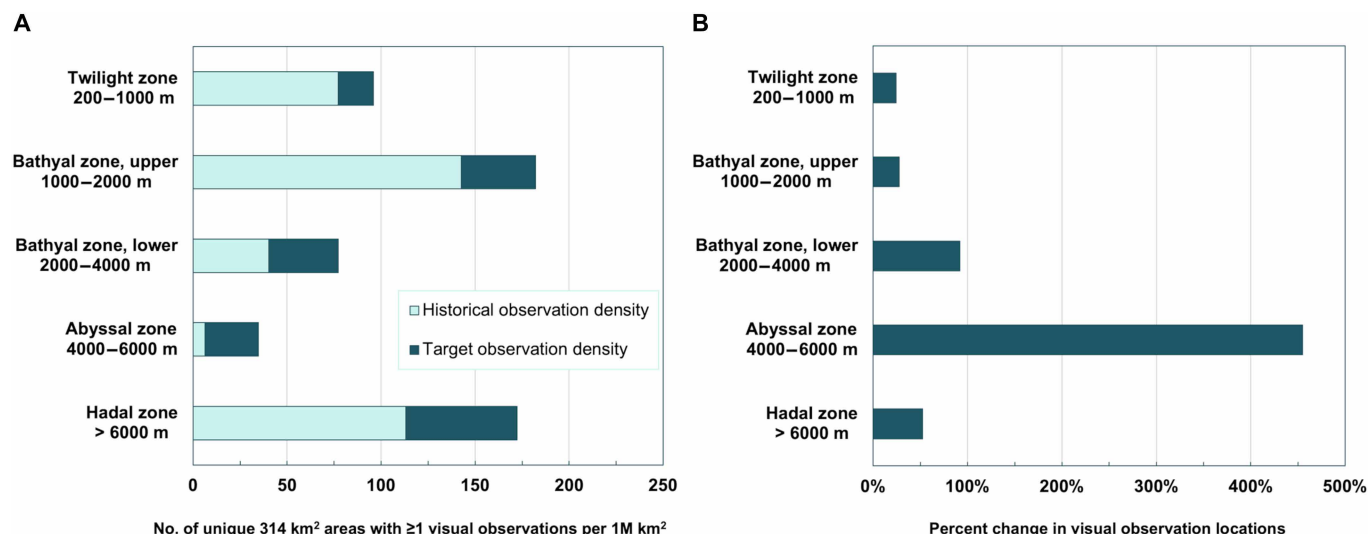


Fig. 3. Impacts of proposed target locations on visual observation densities: Bathymetric zones. (A) Past (light) and proposed (dark) sampling densities per million square kilometers by depth zone show the highest historical sampling density in the upper bathyal zone, between 1000 and 2000 m, and the lowest in abyssal zones between 4000 and 6000 m. For reference, one million square kilometers is approximately the area of Egypt (67). (B) The number of observations in abyssal zones increases by 455% with the addition of the proposed target locations, while the observations in the upper bathyal zone increase by 28%, compared to historical observation rates.

The sampling design adjusts the distribution of previously over- and undersampled features, increasing, for example, the rate of observation for abyssal mountains by 380%, while increasing observations of historically well-sampled escarpments and canyons by only 44% and 37%, respectively. Abyssal hills and plains, while somewhat under-represented in historical observation activities, were intentionally sampled at half the rate relative to their proportional global area to maintain a feasible global sampling effort (see Materials and Methods).

Even with this adjustment, our sampling methodology maintains a similar sampling density to historical observations, increasing abyssal plains by 99% and abyssal hills by 96% (Fig. 4B).

Seafloor composition

We developed a composite seafloor composition layer to ensure representation of diverse benthic environments (see Materials and Methods). Historically, there were more than twice as many dives on seep sites

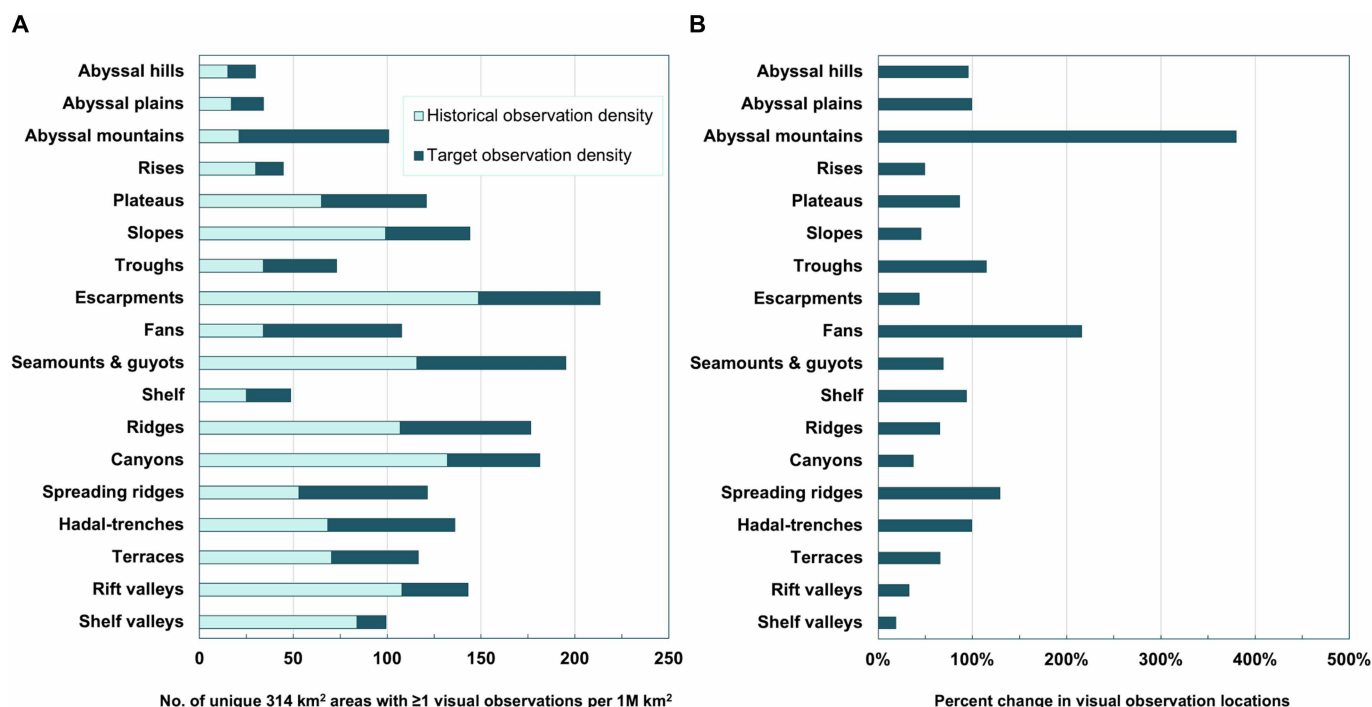


Fig. 4. Impacts of proposed target locations on visual observation densities: Geomorphology. (A) Past (light) and proposed (dark) sampling densities per million square kilometers by geomorphological feature show the highest historical sampling density on escarpments and canyons, and lowest on abyssal plains and hills. (B) With the addition of observations at the proposed target locations, the number of observations on abyssal mountains increases by 380%, while observations on canyons only increase by 37%. Note that sills and bridges are not included in the chart, even though our proposed sampling design includes four dives on sills and two dives on bridges. These features have not been visually observed previously, and any increase in the number of dives results in an infinite percent increase in observation locations.

compared to the next frequently visited seafloor types, spreading ridges, calcareous sediments, and crusts (Fig. 5A). Comparison of historical and target sampling densities shows the greatest increase on seafloors composed of radiolarian ooze (214%) and diatom ooze (143%), both historically undersampled compared to the area of seafloor they occupy (Fig. 5B). Seafloor composed of clay, crusts, and spreading ridges also rose by over 110%, while seep observations will increase by only 28%.

POC flux to the seafloor

To capture variability in nutrient availability at the seafloor, we used model-derived estimates of POC flux as a proxy for benthic productivity (see Materials and Methods). Visual sampling has historically favored high-productivity regions by approximately two times, compared to areas with lower modeled productivity rates (Fig. 6A). Our proposed approach results in increased visual sampling in regions with lower productivity, with the highest increases in areas with POC flux between 0.0 to 0.1 and 0.1 to 0.3 mmol C/m² per day, which will rise by 120 and 87%, respectively (Fig. 6B). In contrast, the highest-flux areas (>1.1 mmol C/m² per day) will have the smallest increase in visual observations of only 39%.

Adjustments to geographical biases

In addition to the global-coverage seafloor characteristics factored into our spatially balanced sampling design, the resulting distribution produced several additional outcomes, including the adjustment of historical sampling biases in ocean basins, maritime jurisdictions, and proximity to shore.

Ocean basins

Historic patterns of seafloor exploration deployments are biased toward the North Pacific and North Atlantic Oceans (Fig. 7A). Although targets are proposed for these basins, the sampling design yields a decreased rate of future exploration activities in historically over-represented basins and a corresponding increased rate in activities in underrepresented basins, relative to historical patterns, as quantified by the ratio of future target locations to historic deployment locations per million square kilometers.

For example, the North Atlantic and North Pacific Ocean basins have the highest historical visual observation sampling density among all ocean basins (73 and 52 locations per million square kilometers, respectively), while the Indian, Arctic, and Southern Oceans have the lowest (13, 17, and 21 locations per million square kilometers, respectively). Our proposed target locations increase observations by only 40% in the North Atlantic and 51% in the North Pacific, while increasing observations in the Indian Ocean by 225% and in the Southern Ocean by 247% (Fig. 7B). The Arctic Ocean observation density will increase by 327%, the highest rate of all ocean basins.

Maritime jurisdictions

From a jurisdictional perspective, both the distribution of historical deep-seafloor observations and the 10,000 target locations in the sampling design can be divided between the high seas and areas within exclusive economic zones (EEZs). The high seas occupy 65% of the global deep-seafloor area, while EEZs are controlled by 170 different coastal nations and territories, which collectively occupy 35%. Historically, only 20.0% of deep-seafloor observations lie within the

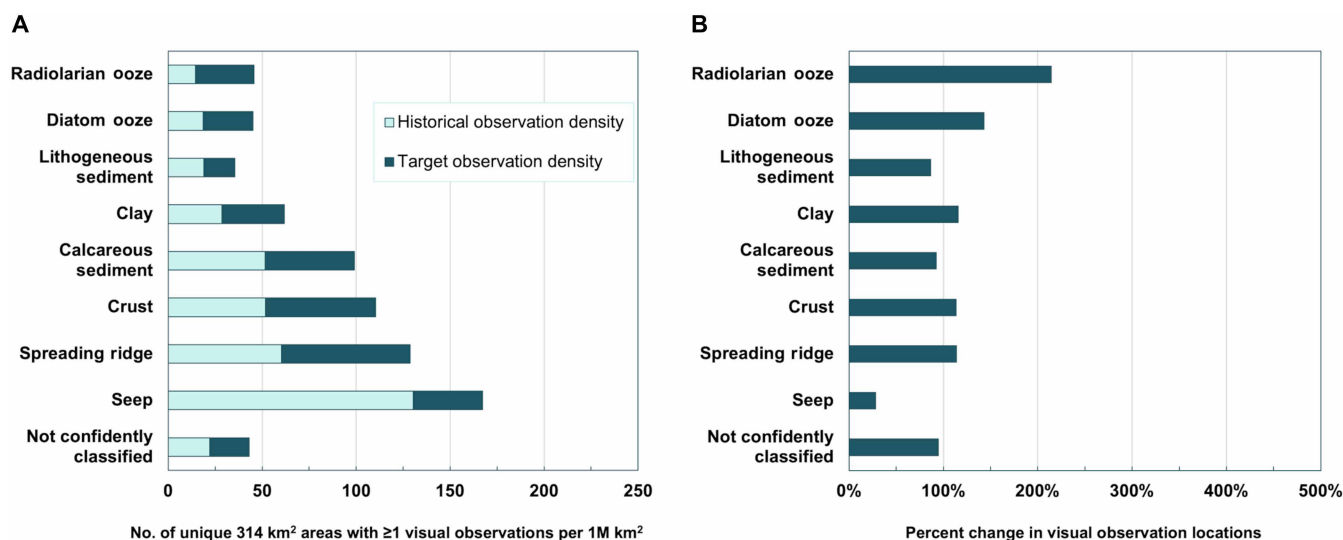


Fig. 5. Impacts of proposed target locations on visual observation densities: Seafloor composition. (A) Past (light) and proposed (dark) sampling densities per million square kilometers by geomorphological feature show the highest historical sampling density on seafloors composed of seeps and spreading ridges. (B) With the addition of observations at the proposed target locations, the number of observations on radiolarian oozes, for example, increase by 214%, while observations on seeps only increase by 28%.

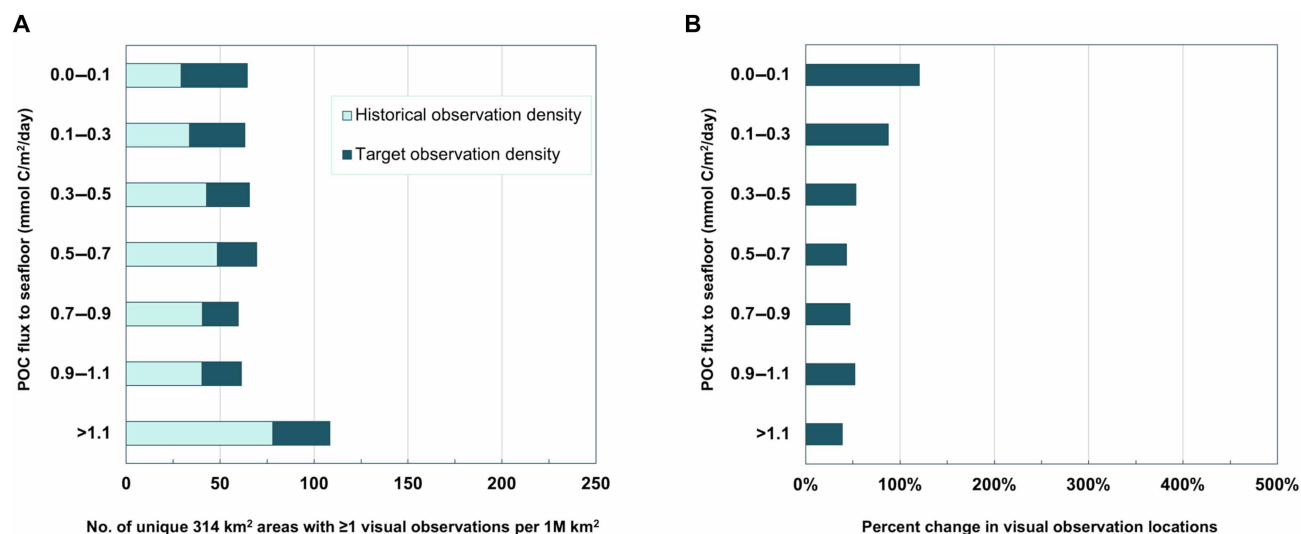


Fig. 6. Impacts of proposed target locations on visual observation densities: POC flux to seafloor. (A) Past (light) and proposed (dark) sampling densities per million square kilometers by geomorphological feature show the highest historical sampling density on areas with the highest POC flux to seafloor (>1.1 mmol C/m² per day). (B) With the addition of observations at the proposed target locations, the number of observations in areas with more than 1.1 mmol C/m² per day will increase by only 39%, while areas with 0.0 to 0.1 mmol C/m² per day will increase by 120%.

high seas, with the remaining 80.0% located in areas of national jurisdiction (2). By using a spatially balanced sampling approach, the sampling design of 10,000 future target locations yields 5684 targets in the high seas (56.8%) and 4316 targets within EEZs (43.2%).

At a finer scale, historical seafloor observation activities have been disproportionately concentrated, relative to seafloor area, within EEZs in a limited number of geographical subregions (Fig. 8A) (21), including 234 historical observations per million square kilometers in Eastern Asia and 231 in the Caribbean. In contrast, some subregions have seen nearly 20 times lower observation densities, notably, 16 historical observations per million square kilometers in Eastern Africa, 14 in Melanesia, and 11 in the high seas.

The sampling design results in lower rates of future observations for geographical areas with higher historical sampling densities and higher rates of future observations for subregions that have been historically undersampled, including high seas areas, relative to their seafloor area (Fig. 8B).

Nearshore clustering

Our proposed method also results in the expansion of the geographical distribution of seafloor observations beyond coastal regions (Fig. 2). This reduces nearshore clustering and observation clusters in close proximity to high-income countries, compared to historical deep-sea-floor observations.

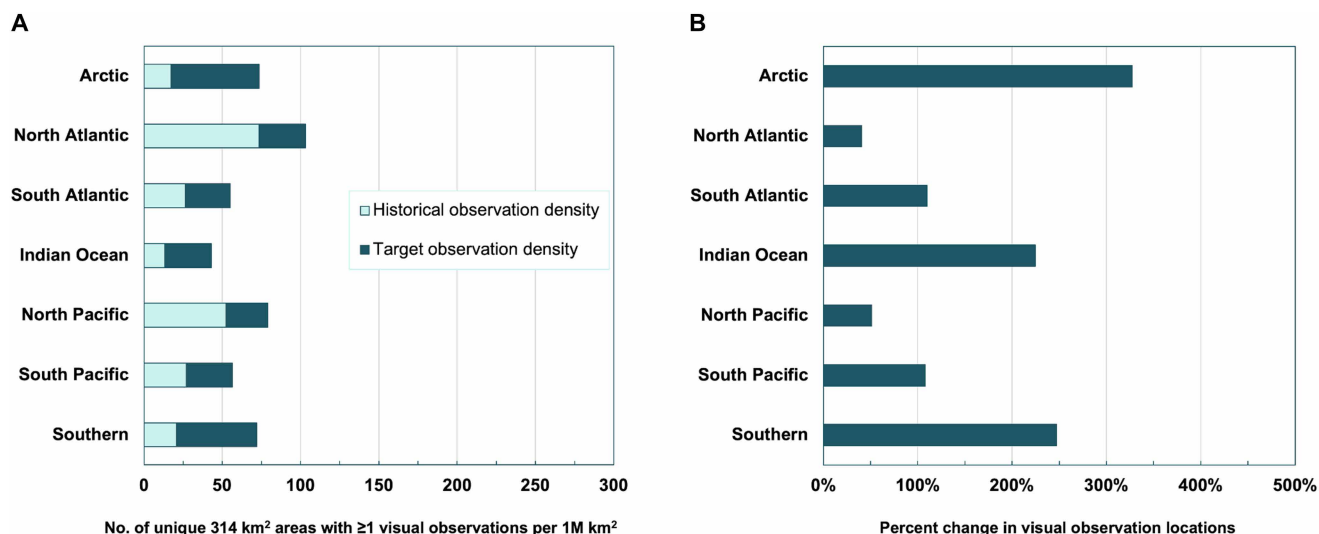


Fig. 7. Impacts of proposed target locations on visual observation densities: Ocean basins. (A) Historical (light) and target (dark) sampling densities per million square kilometers in each ocean basin show the highest historical sampling density in the North Atlantic and North Pacific Oceans, and lowest in the Indian and Southern Oceans. (B) With the addition of the proposed target locations, the number of observations in the Arctic Ocean will increase by more than 300%, compared to past observation records. In the Southern and Indian Ocean basins, they will increase by more than 200%. The South Atlantic and South Pacific will maintain a similar observation density to the past, while the observation densities in the North Atlantic and North Pacific Ocean basins will increase by only 40 to 50% compared to historical rates.

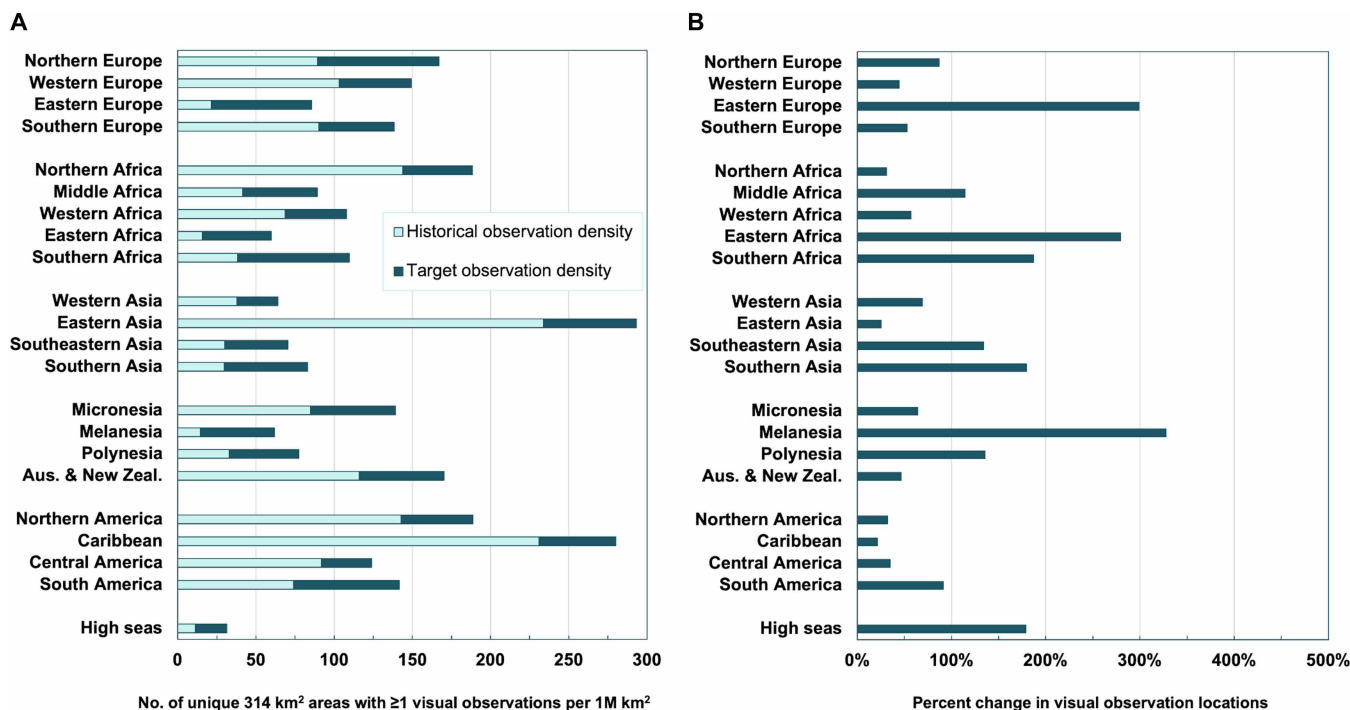


Fig. 8. Impacts of proposed target locations on visual observation densities: Maritime jurisdictions. (A) Past (light) and proposed (dark) sampling densities per million square kilometers by subregion show the highest historical sampling density in Eastern Asia and the Caribbean, and lowest in Melanesia and Eastern Africa, and Eastern Europe. (B) In general, the percent change of observations in each subregion inversely correlates with historical sampling densities. The number of observations in the EEZs of Melanesia, Eastern Africa, and Eastern Europe, for example, will more than double or triple, while the sampling density in the Caribbean and Eastern Asia will only increase by approximately one-fifth to one-quarter, compared to historic observation rates.

We compared the distribution of distances from the nearest shore for both historical deep submergence deployments and the target seafloor visual observation locations to the distribution of all deep-sea-floor areas (Fig. 9). The density of past deployments is concentrated in nearshore areas, with 85.26% historical deployments within 370.4 km (200 nm) of the nearest shore, deviating reliably from the distribution of all ocean areas (Kolmogorov-Smirnov test, $D = 0.527$, $P < 0.01$) (Fig. 9A). The proposed sampling design for future observation locations, though still reliably different from the distribution of global seafloor areas, more closely matches the global distribution of ocean areas' distances to shore (Kolmogorov-Smirnov test, $D = 0.061$, $P < 40.01$) (Fig. 9B).

DISCUSSION

Gaps in deep-sea knowledge

Although the deep seafloor (≥ 200 m) comprises 66% of the Earth's surface (24), our scientific understanding of this ecosystem remains

limited to the small areas that have been mapped, sampled, or visually observed, resulting in a highly uneven and incomplete view (2, 17). This reflects a long-standing bias in both the location of gathered data and the approaches used to collect it. Past seafloor exploration is biased in its proximity to countries and geographical subregions with the highest presence of and access to deep submergence tools and other research infrastructure (22). Deep-sea exploration has also historically been shaped by expensive, technologically intensive methods largely inaccessible to researchers outside high-income nations, leading to concentrated efforts in a handful of well-resourced regions and leaving 99.999% of the seafloor unseen (2–4).

Risks to the deep benthos are escalating. This ecosystem faces mounting threats from industrial extraction, including deep-sea mining, as well as the accelerating impacts of climate change (5, 6, 25). We are making critical policy and conservation decisions based on an incomplete understanding of this environment. Without a larger and more representative foundation of observations and data, these decisions risk replicating the failures seen in other fields. For instance, in

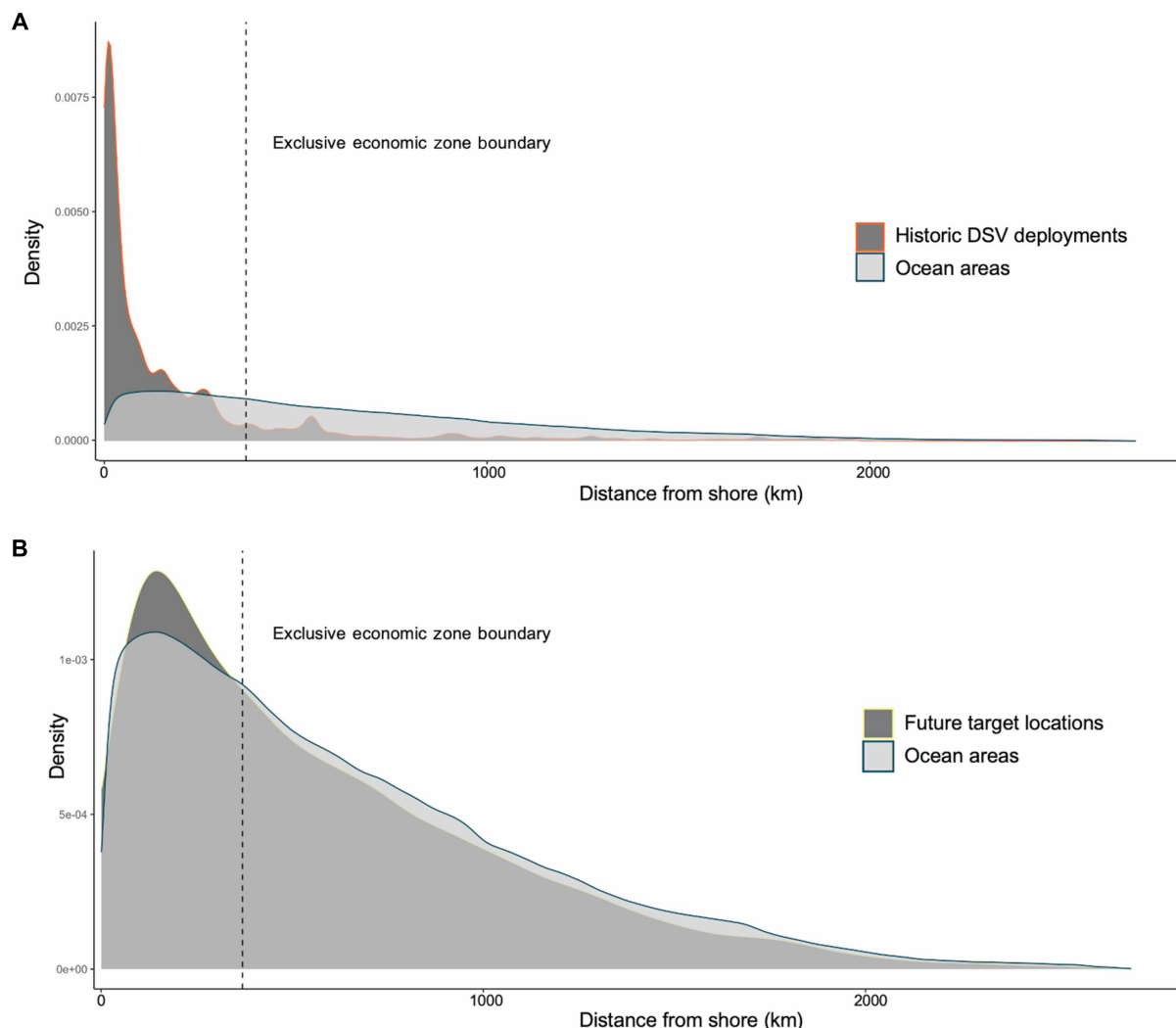


Fig. 9. Distances of historical and proposed deep-seafloor observation target locations to the nearest shore. (A) Historical deep-seafloor observation locations (orange outline) were heavily concentrated within 370.4 km (200 nm) of coastlines, compared to the density of distances from the nearest shore to all unique deep-seafloor locations (teal outline). (B) The density of distances from the nearest shore to our proposed target locations (yellow outline) more closely resembles the distribution of distance densities for all deep-seafloor areas (teal outline).

environmental management, terrestrial conservation policies based on incomplete global plant diversity data have resulted in the establishment of misplaced protected areas and the oversight of ecologically important hotspots (26).

To make better-informed decisions about the future of the deep ocean, we must urgently course-correct our exploration strategies and data collection methodologies. Fortunately, research has shown that even modest improvements in data coverage can substantially enhance scientific models and predictions. For example, studies have demonstrated that increasing observational diversity improves the accuracy of habitat suitability models and biodiversity assessments, which are critical tools for resource management and conservation planning (27). These findings highlight the importance of collecting data that are not only broader in geographic scope but also more representative of undersampled environments.

Global initiatives for ocean science

Addressing the systemic biases and gaps in deep-sea data collection will require not just technological innovation but a fundamental realignment of global strategy. Global cooperation and approaches not only generate more robust scientific outcomes but also catalyze broader public engagement, leading to additional support for the costs and timelines needed to accomplish global goals (20). Increasing global participation will also lead to previously unexplored perspectives, deeper understanding, and better science (28).

Precedents from other fields demonstrate how identifying global data gaps can catalyze responsive efforts. In terrestrial biodiversity science, the underrepresentation of tropical regions in global biodiversity research has led to considerable gaps in our understanding of Earth's species diversity. Historically, studies have been disproportionately concentrated in temperate zones, resulting in a skewed perception of global biodiversity patterns and hindering conservation efforts in tropical regions (29). Efforts like the All Taxa Biodiversity Initiative (30) and the Kunming-Montreal Global Biodiversity Framework (31) are working to strategically correct these gaps. Similarly, the Global Soil Biodiversity Initiative is a collaborative project that focuses on synthesizing and mapping current and future research on soil biodiversity to fill existing knowledge gaps (32), particularly in tropical areas (33). These examples demonstrate that when the scientific community acknowledges systemic bias and actively works to address it, the resulting insights can be more robust, equitable, and actionable.

The deep-sea science community now faces a similar inflection point. The last coordinated global effort for deep ocean visual observations dates back to the 1940s through 1970s when Heezen, Hollister, and others conducted a systematic global visual sampling of the seafloor, primarily using deep-sea cameras deployed from research vessels and contributions from scientists in several countries (34). Their approach involved lowering tethered systems, including towed deep-sea sleds equipped with cameras and lighting, to the seabed to capture photographic transects. These visual records enabled unprecedented direct observation and characterization of seafloor features, sediment types, biological communities, and geological phenomena. Imagery captured before 1980 still comprises ~14% of all documented visual observations of the deep seafloor (2).

At that time, deep-seafloor exploration efforts were more globally distributed, driven by scientific curiosity, commercial interests, international competition, and the Cold War (2, 35). However, from the 1980s to the early 2000s, focus narrowed to EEZs, driven by reductions

in oceanographic funding (35), and financial and resource-driven interests in the newly established areas of national jurisdiction. In addition, the majority of Heezen and Hollister's deployments produced black-and-white still images, which, while revolutionary at the time, do not provide the same scientific value as surveys conducted with modern imaging technology (34). Today, with advances in imaging, robotics, and data science, there is an urgent need for a new, practical, and globally coordinated strategy for modern visual exploration of the deep ocean.

Previous ocean science programs, including the World Ocean Circulation Experiment (WOCE) and the Census of Marine Life, have demonstrated the power of globally coordinated campaigns to fill knowledge gaps and produce foundational datasets. WOCE, conducted from 1990 to 2002, was a highly effective global strategy to understand ocean circulation and its role in climate by coordinating an international effort that produced an unprecedented dataset, including ocean temperature, salinity, currents, and chemical tracers, and resulted in breakthroughs in ocean modeling and improved climate predictions (36). From 2000 to 2010, the Census of Marine Life catalyzed a new era in marine biodiversity research and conservation with numerous achievements, including the discovery of more than 6000 potential new species, aggregation of 30 million species-level records, and creation of the Ocean Biogeographic Information System (OBIS) (37).

Current global initiatives, including the Argo Program, Seabed 2030, Ocean Census, and Challenger 150, are illustrating how systematically addressing data gaps can yield transformative insights into global ocean systems. For more than 25 years, the Argo Program has used a fleet of robotic drifters to measure water properties of the global ocean for oceanic, atmospheric, and climate research (38). Argo has completed more than 2 million profiles, resulting in hundreds of scientific publications and a previously unknown understanding of the ocean's role in Earth's climate system. Since 2017, Seabed 2030 has aggregated high-resolution seabed mapping data of 27% of the ocean, and aims to produce a fully mapped, high-resolution digital map of the entire ocean floor by 2030 (39, 40). Ocean Census is a global alliance dedicated to discovering at least 100,000 new marine species over the next decade through expeditions to undersurveyed ocean regions, thereby almost doubling the number of known ocean species worldwide (41). Challenger 150 is a global program created to support the goals of the UN Decade of Ocean Science for Sustainable Development, targeting areas where increased biological sampling will fill in critical gaps (42).

Today, international agreements, commercial pressures, and conservation measures are broadening the scope of deep-sea activity. Instruments such as the Agreement for the Conservation and Sustainable Use of Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement) (43) and the seabed mining negotiations of the International Seabed Authority have increased interest in seabed exploitation, climate interventions, and high seas marine protected areas, and have renewed the incentive to explore globally and strategically (44, 45).

Toward the Global Deep Sea Exploration Goals

In addition to a global approach, a statistically representative approach to deep-sea visual exploration is essential. First and foremost, visual observations of geographically distributed and currently unexplored seafloor regions are critical for generating a validated and ecologically meaningful biogeographical map of the deep seabed. Such a

map would serve as a baseline for identifying patterns of biodiversity, ecosystem function, and environmental variability across depth, region, and substrate type. Without a representative approach, we risk reinforcing existing biases, assumptions, and blind spots, perpetuating a skewed view of deep-sea life and habitat distribution.

Given the extreme sparseness of existing visual data, the model-derived nature of most global deep-seafloor attributes, and the time estimated for a completely comprehensive visual assessment of the entire deep seafloor (2), any effort to generalize findings across the global deep ocean must rely on probabilistic methods. This makes it even more critical to ensure that sampling strategies are designed to capture ecological variability rather than just areas of convenience or technological feasibility.

This approach also challenges prevailing biases in research methodologies and approaches to deep-sea exploration. With targeted locations in previously neglected ocean basins, jurisdictional areas, and geomorphological features, our strategy ensures a balanced representation of global seafloor characteristics, and aims to not replicate patterns of past bias.

Implementing the Global Deep Sea Exploration Goals

A globally unified visual observation strategy will function both as a coordinated international initiative led by committed partners and as a framework that can be opportunistically adopted by any deep-sea expedition to contribute valuable visual observations alongside their exploration objectives. This approach is intentionally designed to integrate with and amplify existing efforts, accelerating progress toward a truly representative understanding of the deep sea. Our analysis of 2023 GEBCO data shows that 26.54% of globally distributed target locations for visual observation already overlap with areas mapped using multibeam bathymetry (46). Expanding visual surveys in tandem with bathymetric mapping will greatly enhance the scientific value of both.

Several countries have established internal strategies to systematically map a defined percentage of their EEZs; similarly, nations could lead concerted efforts to visually observe all Global Deep Sea Exploration Goal target points within their territorial waters, contributing to a global dataset while advancing national scientific priorities (47). This model aligns with existing international commitments such as the Ocean Decade Alliance Seabed Mapping Initiative, a global pledge by countries and organizations to coordinate and accelerate the collection of seabed mapping data (48). A comparable pledge-based approach could be achieved for deep-sea visual observations, formalizing commitments to collect imagery alongside ongoing exploration and mapping efforts. Even minimal visual observations, such as those collected using towed camera systems or simple drop cameras, would be transformative, providing baseline information in regions where no visual data currently exist. At a minimum, each observation should include video and/or still imagery, Conductivity, Temperature, Depth (CTD) measurements, and deployment location collected within a defined radius of the target point.

Because this strategy can leverage existing planned expeditions, the incremental time and cost required to complete the Global Deep Sea Exploration Goals could be relatively modest. Individual observations can typically be integrated into ongoing operations with minimal additional ship time, while standalone drop-camera deployments can be conducted at comparatively low cost using small vessels or chartered platforms. At national scales, comprehensive coverage of Global Deep Sea Exploration Goal targets within an EEZ could be achieved over

several years by incorporating visual observations into regularly scheduled research cruises. At a global scale, broad adoption across government, academic, and industry operations suggests that a statistically representative baseline of deep-sea visual observations could be achieved within one to two decades.

Achieving this globally representative effort cannot be accomplished solely through improved sampling design and global commitments from existing exploration collaborators; it also requires a redistribution of opportunity, tools, and training. Viewed through the lens of global exploration capacity, we must increase the technical and human capacity in low-capacity regions (22) to achieve these goals. This global strategy identifies scientific gaps that point to where capacity building and new deployments are most urgently needed. The analysis reveals regions, often remote from prior exploration efforts and historically overlooked in deep-sea science, that are critical to achieving a statistically valid understanding of the deep seabed. By focusing efforts in these underrepresented areas, the global community can help close critical knowledge gaps while democratizing access to ocean science.

Transformative results for deep-sea science

The results of the Global Deep Sea Exploration Goals will be transformative on multiple fronts. Scientifically, the addition of 10,000 targeted points will effectively double the number of unique locations that have ever been visually explored, producing the most geographically balanced dataset of the deep seabed to date. This unprecedented visual record will enable previously unexplored ecological discoveries, support the identification of biogeographic patterns, and improve our understanding of biodiversity, ecosystem function, and environmental change in previously unseen regions. These data will serve as a critical foundation for refining global habitat classification schemes and enhancing the accuracy of environmental models, which in turn will guide conservation planning, resource management, and climate mitigation strategies. The effort will also contribute directly to ongoing international initiatives such as Seabed 2030 by promoting coordinated mapping and imaging across all major ocean basins.

Beyond the scientific impact, this initiative will also catalyze transformation in how deep-sea research is conducted through global cooperation, equitable capacity building, and open data sharing. It provides both the justification and framework for vessels and institutions worldwide to participate in a coordinated campaign of exploration, data collection, and stewardship. The resulting datasets will be valuable not only for standalone research but also as contributions to global repositories such as FathomNet (49), WoRMS (50), and OBIS (51), which support broad-scale analyses of marine biodiversity and ecosystem health. Just as important, this effort will help build the infrastructure and human capacity needed in regions that have historically been excluded from deep-sea research. In doing so, it will create a more inclusive and cooperative scientific community, capable of both understanding and protecting the deep ocean.

MATERIALS AND METHODS

Experimental design and efficient sampling approach

We adapted a spatially balanced sampling design process developed for terrestrial use (52), implementing a probability-based sampling design in a Geographical Information System (GIS) using ArcGIS Pro software (53). Using a spatial sampling design method allows

for specification of unequal probabilities associated with different combinations of characteristics across geographical locations on the seafloor. This yields an uneven sampling space, with individual probabilities that reflect the spatial distribution of multiple seafloor characteristics, such that higher probabilities indicate more frequently occurring characteristics. From this, it is possible to generate sampling locations that are spatially balanced, and by extension, geographically distributed, to sample the global seafloor.

Two properties characterized the sampling design process. First, we specified an inclusion probability space, built from data layers reflecting deep-seafloor characteristics of interest, wherein each location is assigned a known, nonzero probability. This ensured that all locations within the sampling area have some known chance of being selected (52). Second, we created a balanced spatial distribution of locations in the resulting sampling design, achieved by tessellating the sampling area and its associated inclusion probability space using Theissen polygons (54, 55) to optimize the spatial independence of each location.

Data sources

We chose four global-coverage seafloor characteristics to drive our spatially balanced sampling design: seafloor bathymetry, geomorphology, sediment composition, and POC flux to the seafloor. These characteristics address key physical, chemical, geological, and biological properties of the deep seafloor using variables that are stable on decadal timescales. We also took into account the locations of historical dives to ensure that the target locations would not overlap with prior visual seabed observations.

Seafloor bathymetry

We used gridded bathymetry data, accessed through the General Bathymetric Chart of the Oceans (46), to generate depth estimates across the global seafloor. We aggregated bathymetry estimates into 1000-m-depth bands and analyzed them as a raster layer with a resolution of 15 arc sec (fig. S1). Accompanying GEBCO type indicator data values were also used to quantify the proportion of target locations in the sampling design that overlapped with areas that have been mapped with multibeam bathymetry measurements (46).

Seafloor geomorphology

We used world seafloor geomorphology layers to capture the distribution of geomorphological features on the global seafloor. The layers were developed using mapping data from GRID-Arendal (23, 56) and characterized physical features on the seafloor and the global ocean zones in which they occur. The complete dataset included seventeen geomorphic features (e.g., seamounts, ridges, guyots, and rifts) and additional seafloor terrain distinctions for shelf, slope, hadal, and abyssal zones, as well as individually identified ocean basins. Geomorphological features, terrain, and zones were accessed as polygon layers and converted to a raster layer, with a resolution of 15 arc sec (fig. S2), for analysis. The original dataset was structured as a series of overlapping layers, with punctuated features layered atop seafloor terrain, which was nested within zones. In combining these layers for use in a sampling space, we flattened this structure so that a given pixel represented the value of a geomorphological feature, where available, and a terrain or zone value where features were not present (table S3).

Seafloor composition

We developed a composite layer of seafloor sediment and surface characteristics. These included model-predicted areas of lithological types, subjected to a 50% confidence threshold (57), areas of known

crust (58), predicted seep locations (59), and hydrothermal vent locations inferred from the location of mid-ocean ridges (23). Seafloor areas that were not classified with any of these characteristics were labeled as “not confidently classified.” This information was combined into a single raster layer and sampled to a resolution of 15 arc sec (fig. S3).

POC flux to seafloor

We used global model outputs from the Nucleus for European Modeling of the Ocean (NEMO)–Model of Ecosystem Dynamics, Nutrient Utilization Sequestration and Acidification (MEDUSA) simulation as a proxy for seafloor productivity, as POC flux to the seafloor (60). The simulation combines an ocean physics model from the NEMO (version 2) (61) and a benthic submodel from the MEDUSA (62). Estimates of benthic POC were displayed and analyzed as a raster layer with a resolution of 30 arc sec (fig. S4).

Global deep submergence deployments dataset

We used a global metadata set from historical deep submergence deployments to ensure that already-observed locations were not under consideration as targets in the sampling design (63). We binned these point data at a resolution of 314 km² and then generated a corresponding raster dataset for use in the spatially balanced sampling design process.

Data processing

Data processing was conducted in three parts using ArcGIS Pro software (53). First, each raster dataset was resampled to create a layer with a common 30-arc-sec resolution. After resampling, each raster layer underwent a pixel-level reclassification, assigning a partial probability value to each pixel proportional to the global area characterized by the value at that pixel. In this way, each layer was normalized to reflect the relative proportion of global seafloor area characterized by each value range in the layer, and all value ranges for the layer summed to 1. For example, if 10% of the seafloor is geomorphologically defined as slope terrain, all pixels in the geomorphology raster layer with the value “slope” were reclassified with the value 0.10. After reclassifying all four seafloor layers in this way, we used raster addition to combine the layers and renormalized the resulting layer to generate a sampling space of nonzero probability values. Last, we removed locations with previous deep submergence deployments by assigning a probability value of zero to the corresponding cells in the sampling space raster (64).

Sampling process

Once inclusion probabilities for the sampling space were computed, we used the Create Spatially Balanced Points algorithm (65) in ArcGIS Pro (53) to generate our sampling design of 10,000 target locations. This algorithm optimizes the spatial independence of sampled locations by computing Theissen polygons around candidate samples, ensuring that variance within a polygon is low (i.e., environments within each polygon are more similar), relative to variance between polygons.

Before implementing the sampling algorithm, we partitioned the global sampling space into two geomorphologically distinct areas to be sampled at different rates. Specifically, we separated contiguous abyssal plains, abyssal hills, and unclassified abyssal zone areas, from all other seafloor areas in the sampling space. Nearly half of the deep seafloor is made up of these abyssal areas and, while there is evidence to suggest that these environments are not ecologically homogenous (66), sampling abyssal areas at a rate proportional to

their occurrence would situate 50% of our proposed exploration targets in abyssal plains, redirecting research efforts from other smaller and potentially lesser-known seafloor environments. To address this and ensure representative sampling of less prevalent seabed features, we chose to sample abyssal plain environments at half their proportional rate, yielding a sampling design comprising 3750 locations in abyssal areas and 6250 in nonabyssal areas.

Validation

We selected a sample size of 10,000 target locations to make the resulting number of proposed targets practicable for guiding future deep-sea exploration planning in the coming years. To confirm that a sample size of 10,000 target locations was also sufficient to provide a representative sample of the characteristics in our sampling space, we compared the distribution of target locations against the corresponding distributions of each characteristic for 100,000 locations (figs. S5 to S8). The larger sample of locations closely matched our sample of 10,000 target locations across all four environmental characteristics.

Additional deep submergence deployment data, sourced after the sample of target locations was generated, provided an opportunity to verify that our 10,000 target locations did not overlap with known deep-sea exploration and visual observation activities, beyond those deployments that were used in the sampling process. We compared the locations of these additional 1147 points (table S1) to our sample of target locations and confirmed that the closest deployment was 4.15 km from a target location, and 99.7% were more than 10 km from the nearest target location.

Supplementary Materials

This PDF file includes:

Tables S1 to S5

Figs. S1 to S8

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