

OCEANOGRAPHY

How little we've seen: A visual coverage estimate of the deep seafloor

Katherine L. C. Bell^{1*}, Kristen N. Johannes^{1,2}, Brian R. C. Kennedy^{1,3}, Susan E. Poulton¹

Despite the importance of visual observation in the ocean, we have imaged a minuscule fraction of the deep seafloor. Sixty-six percent of the entire planet is deep ocean (≥ 200 m), and our data show that we have visually observed less than 0.001%, a total area approximately a tenth of the size of Belgium. Data gathered from approximately 44,000 deep-sea dives indicate that we have also seen an incredibly biased sample. Sixty-five percent of all in situ visual seafloor observations in our dataset were within 200 nm of only three countries: the United States, Japan, and New Zealand. Ninety-seven percent of all dives we compiled have been conducted by just five countries: the United States, Japan, New Zealand, France, and Germany. This small and biased sample is problematic when attempting to characterize, understand, and manage a global ocean.

INTRODUCTION

Importance of the deep ocean

The deep ocean (200 m or deeper) covers 66% of Earth (1), encompasses the largest ecosystem on our planet, provides critical services and resources to humankind, and is the least explored and understood biome on Earth (2). The deep ocean is a haven for diverse ecosystems and processes that provide critical benefits to the planet and humans, ranging from oxygen generation and climate regulation to food and pharmaceuticals. The deep ocean and the deep seabed are intrinsically linked, thus the benefits of the deep ocean and the deep benthos are interconnected. Phytoplankton, fed by upwelling of cold, nutrient-rich deep waters, produce an estimated 80% of the world's oxygen (3). From the sinking of marine snow to the great whale conveyor belt (4), the deep ocean plays a key role in carbon sequestration and climate regulation, and the value of carbon transported and stored in the deep sea is estimated to have a social impact cost of USD 159B per year (5). The ocean supplies 200 million tons of fish and seafood annually, feeding approximately 20% of the world's population and employing 60 million people worldwide (6). Numerous pharmaceuticals, including treatments for HIV, breast cancer, and COVID-19, are based on chemical compounds from marine sponges (7–10); in the past 50 years, researchers have discovered thousands of compounds in marine organisms such as sponges, sea hares, sea squirts, and bacteria, with the potential for medical use for their anticancer, antibacterial, antifungal, anti-inflammatory, and antiviral properties (9–11). As exploration increases in the deep ocean, so does the potential for discoveries that will continue to benefit humanity.

Despite the many benefits it provides, humans have been affecting the deep ocean for centuries. These impacts have been well documented and broadly grouped into three main categories: disposal of litter and chemical pollution, exploitation of biological and geological resources, and climate change and ocean acidification (2, 12). Researchers predict that the negative impacts on deep-sea ecosystems will nearly double as exploitation and climate change increase (12).

For example, the ocean has absorbed 90% of the excess heat and 30% of the CO₂ released into the atmosphere by human activities (13). These heat and CO₂ increases result in warming (14), deoxygenation (15, 16), and acidification (17), causing increased stratification (18), changing circulation patterns (19), and inhospitable environments for deep-sea life (17). These changing oceanographic patterns, in turn, affect biodiversity, habitability, and productivity globally across all ocean depths (17, 20). While climate change is already affecting the deep ocean, deep-sea mining and marine carbon dioxide removal (mCDR) also have the potential to cause irreparable damage, as evidenced by numerous studies (20–22), highlighting the need for precaution in the absence of adequate science (23–25).

While human activity threatens the deep ocean, we have barely scratched the surface when exploring and characterizing the deep seabed (26). We are only beginning to understand the unique role the deep benthos plays in this ecosystem. From the discovery of new benthic fauna (27) to understanding how deep seafloor geology interacts with its surroundings (28) and subsurface biology (29), accelerating exploration and understanding of this vital ecosystem are essential.

Visual observations are critical

Visual imaging is one of the most critical methods for studying the deep seafloor, advancing all areas of oceanographic science (30–33). It allows researchers to provide situational context to collected samples (34), observe behaviors and interactions of marine life (35), conduct more accurate biodiversity and abundance surveys (36), simultaneously gather biological and geological data and assessments (37, 38), and groundtruth acoustic and other remote sensing data [e.g., (39)]. Visual observations are a critical component of “seafloor exploration.” Here, we define “explored seafloor” as those locations where visual observations, seabed mapping, sampling, and environmental data collection exist (40, 41). Notable discoveries made using visual observations include the first hydrothermal vents found on the Galápagos Rift in 1977 (42), the alkaline Lost City hydrothermal vent field on the Mid-Atlantic Ridge (43), the impact of the Deepwater Horizon oil spill on coral regrowth in benthic communities in the Gulf of Mexico (44), and the well-preserved shipwrecks in the anoxic waters of the Black Sea (45).

¹Ocean Discovery League, Saunderstown, RI 02874, USA. ²Integrative Oceanography Division, Scripps Institution of Oceanography, University of California San Diego, San Diego, CA 92037, USA. ³Biology Department, Boston University, Boston, MA 02215 USA.

*Corresponding author. Email: croff@alum.mit.edu

Today, there are numerous types of deep submergence vehicles (DSVs) used for gathering visual observations from the deep seafloor, including human-occupied vehicles (HOVs), remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), tethered tow cameras, and benthic landers, each with its operational benefits and challenges (46). After an expedition, researchers can later use the imagery captured for many purposes that could not be defined at the moment or within the scope of a single research hypothesis or priority (47, 48). Visual imaging is also an effective engagement tool to build connections and custodianship with communities around issues facing the ocean (49, 50).

Researchers have previously attempted to estimate the percentage of individual deep-sea habitats visually observed in the past century (2, 51). The distribution of and access to the records of this work are spread across multiple institutions or individual principal investigators, making it impractical to aggregate and analyze these data quickly. This lack of global perspective creates challenges in understanding the deep ocean holistically, including the ability to make informed, science-based management decisions. It inhibits the deep-sea community from developing an integrated global exploration strategy beyond the research interests of individual scientists or institutions.

Here, we present the most comprehensive global estimate of deep-sea benthic observation coverage to date. Our goal is to provide all stakeholders with baseline data they can use to strategically plan future expeditions and dive locations.

RESULTS

Estimates of global deep seafloor visual coverage

To quantify the visually explored deep seafloor, defined here as the area of seafloor imaged by a vehicle with optical imaging capabilities, we aggregated 43,681 records of deep submergence activities (depth ≥ 200 m) conducted in 120 Exclusive Economic Zones (EEZs) and the high seas. Thirty-four institutions in 14 countries and territories carried out these expeditions (Fig. 1). While this is the largest deep submergence dataset yet compiled, we acknowledge the limitations due to a lack of data availability (see Methods).

We then used two independent methods to estimate the amount of deep seafloor observed globally over the past seven decades (see Methods). Using the dive-based method, we estimate a maximum visual seabed coverage of 2130 km². Using the time-based method, we estimate visual seabed coverage of 3823 km².

Of Earth's total surface area (510 million km²), the seafloor makes up 360 million km² (approximately 71%). Of this ocean area, approximately 93% is deep seafloor (≥ 200 m), yielding 66% of the Earth's total surface area (~ 335.7 million km²) (1, 52, 53). In the framework of this global context, our exploration coverage estimates show that deep-sea visual tools have only observed 0.0006 to 0.001% of the deep seafloor since 1958.

A biased sample of the deep seafloor

There is also a growing disparity in dive activities between the high seas and EEZs (Fig. 2A). In 67 years of deep sea dives, only 19.1% of

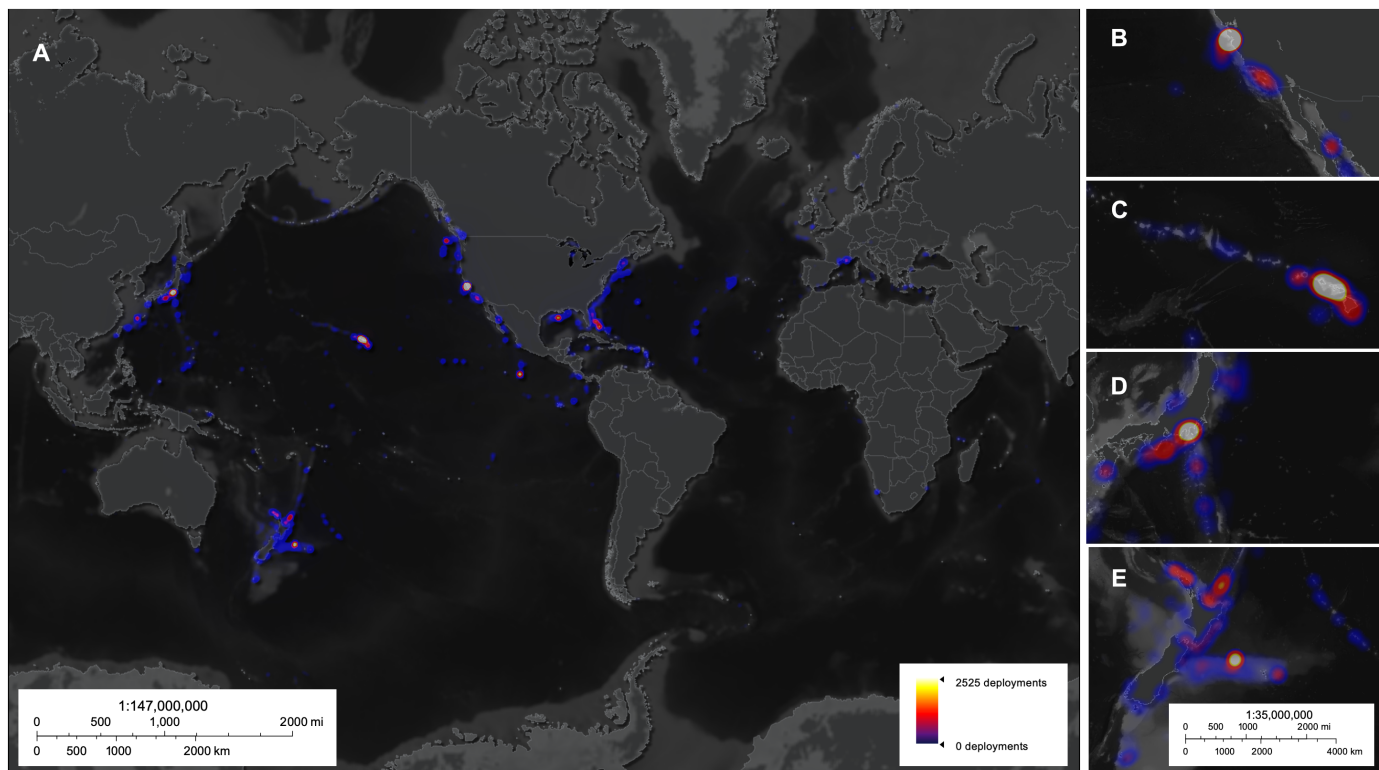


Fig. 1. Deep-sea dive activity, 1958–2024. (A) Deep-sea dive activity has been concentrated in a small number of locations, particularly (B) Monterey Bay, USA; (C) Hawaii, USA; (D) Suruga and Sagami Bays, Japan; and (E) New Zealand. The heatmap represents the number of dive activities per 250 km², not the area observed. The actual area observed on the seabed is too small to represent on a map at this scale. Map source data: GEBCO bathymetry (47) (<https://creativecommons.org/licenses/by/4.0/>), rendered in ArcGIS software.

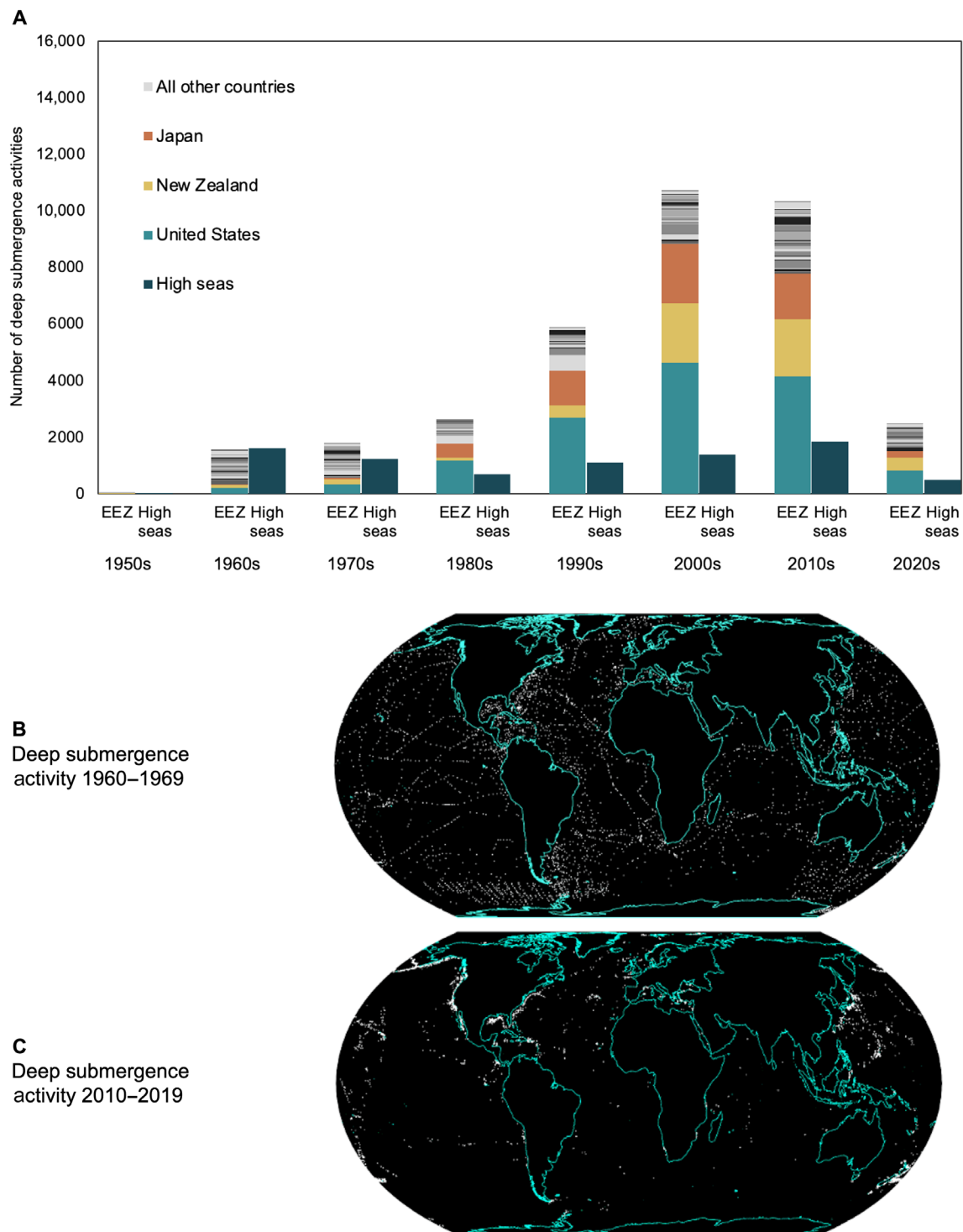


Fig. 2. Geographic dive trends by decade, 1950s–2020s. (A) Since the 1980s, there has been a shift from global, exploratory deep submergence activity in the 1960s and 1970s to a focus on modern-day EEZs or areas that are now within national jurisdiction. (B) In the 1960s, 51.2% of all dive activities took place in what is now the high seas; (C) in the 2010s, that fraction dropped to 14.9% of all dive activities, and dives were mostly concentrated within the EEZs of the United States, Japan, and New Zealand.

all dives occurred on the high seas, the area beyond national jurisdiction that encompasses 58% of the ocean (52, 54). In the 1960s and 1970s, before the formation of EEZs through the adoption of the 1982 United Nations Convention on the Law of the Sea (55), 46.0% of all dives were conducted on what is now the high seas. Since the 1980s, there has been a global shift toward working within EEZs, with only 14.7% of all dives from the 1980s to the present taking place on the high seas. Comparing the first complete decade with dive records (the 1960s) and the last full decade (the 2010s), we found that 51.2% of all dives conducted in the 1960s took place on what is now the high seas (Fig. 2B); in the 2010s, only 14.9% of dives took place in areas beyond national jurisdiction (Fig. 2C).

There is also a substantial and persistent gap in dive locations conducted within the EEZs of different countries and territories. Of the more than 35,000 dives conducted within 200 nm of coastal states, 71.1% were within the waters of only three high-income countries—the United States, Japan, and New Zealand; only 28.9% were conducted within the EEZs of 120 countries and territories (Fig. 2A). Comparing dive activities regionally, 42.0% were in Northern America, 18.8% were in Oceania, 18.3% were in Asia, 10.2% were in Latin America and the Caribbean, 8.1% were in Europe, 1.6% were in Africa, and 1.0% were in other locations (Antarctica, disputed EEZs, or joint EEZ regimes) (56). Ninety-five percent of all dives within coastal waters were within 200 nm of high-income or upper-middle-income countries and territories (57).

Operator bias in conducting deep sea dives

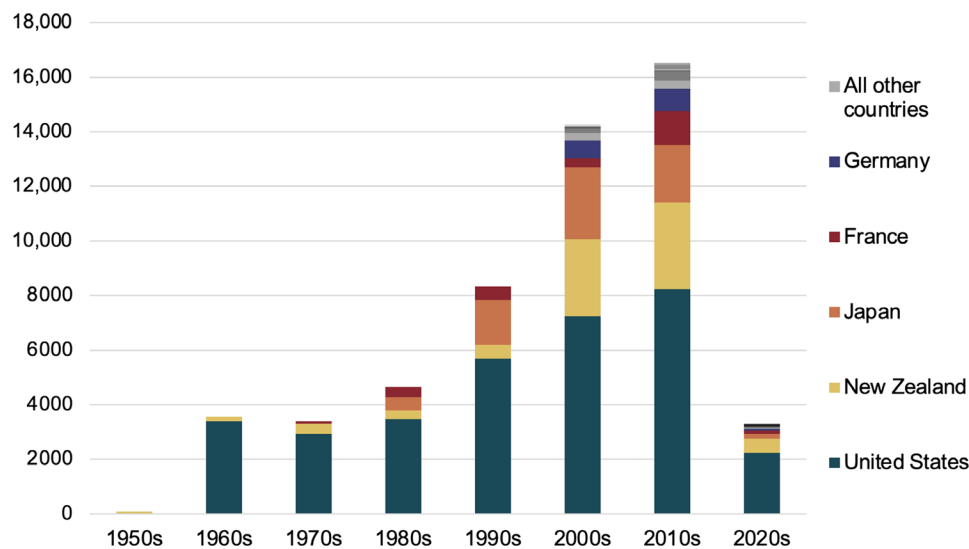
In addition to biased dive locations, there is also operator bias. Operators are defined as organizations and institutions that have the financial and physical means to conduct deep ocean seafloor observations. Of the global organizations and institutions conducting deep submergence dives, only five countries—the United States, Japan, New

Zealand, France, and Germany—led 97.2% percent of all dives (Fig. 3). All but one dive was conducted by operators in Asia, Europe, Northern America, or Oceania; one was conducted by an operator in Latin America and the Caribbean, and none were led by an operator from Africa. In addition, 99.7% of all dives were conducted by operators from high-income countries (57).

A biased view of depth zones and geomorphology

The number of dives increased approximately fourfold from the 1960s to the 2010s, while the proportion of depths reached skewed shallower over time (Fig. 4A). In the 1960s, 58.4% of all dives were deeper than 2000 m, while only 25.9% were deeper than 2000 m in the 2010s. This shift is notable because the majority of the ocean—74.9%—lies between 2000 and 6000 m below sea level, yet the majority of our observations are from depths shallower than 2000 m (Fig. 4B).

We have also observed a biased sample of geomorphological features. Research efforts across geomorphological characteristics of the seafloor have disproportionately focused on a select group of seafloor features, including canyons, escarpments, and slopes (Fig. 5A). These features are over-observed relative to the estimated area of the seafloor they occupy globally, while features including shelves, rises, and abyssal plains are undersampled in observation efforts relative to their abundance. Furthermore, the distribution of dives conducted on over-observed features such as canyons is biased toward a few highly observed individual locations (Fig. 5B). Harris *et al.* identified 9472 unique seafloor canyon features worldwide, yet only 442 were visually observed at least once (58). The most frequently observed canyon—Monterey Canyon on the Pacific coast of the United States—has been the target of 3530 deep submergence activities, 48.2% of all activities within canyons on record worldwide.



All other countries includes: Canada, United Kingdom, Taiwan, Australia, Belgium, Bermuda, Russia, China, and Montserrat.

Fig. 3. Dive operator trends by decade, 1950s–2020s. While the number of dive activities increased fourfold from the 1960s to the 2010s, only five countries—the United States, New Zealand, Japan, France, and Germany—conducted the vast majority. The decrease in dive operations in the 2020s is due to the disruption to marine science operations caused by the COVID-19 pandemic (79, 80), data embargoes still in effect immediately following recent data collection, and an incomplete decade (see Methods).

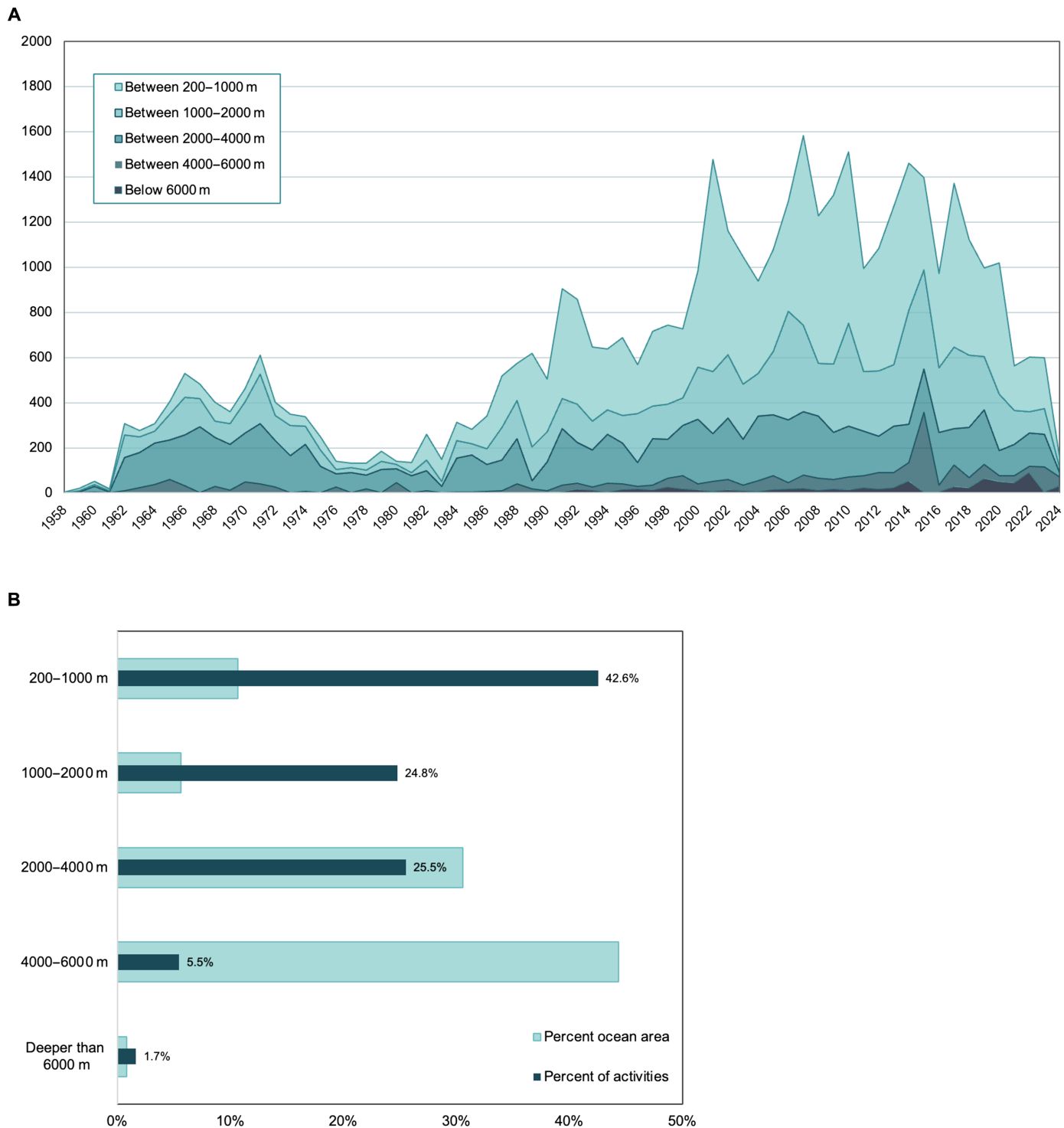


Fig. 4. Maximum depths of deep-sea dives, 1958–2024. (A) Deep-sea dive activity has increased almost fourfold since the 1960s, but the fraction of dives occurring deeper than 2000 m has decreased from 58.4 to 25.9%. **(B)** Depths shallower than 2000 m are disproportionately oversampled relative to the estimated area of the seafloor they occupy globally.

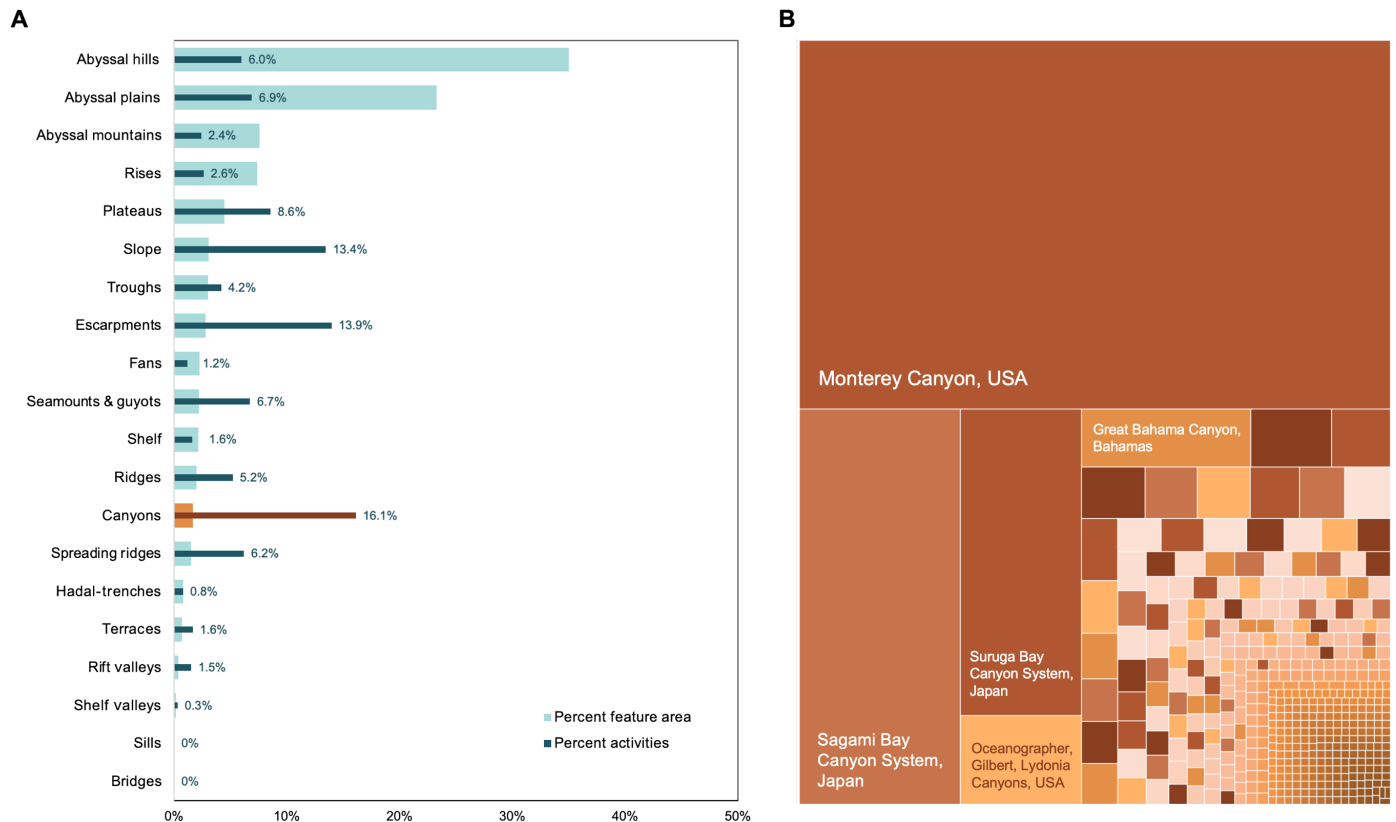


Fig. 5. Deep submergence activity compared to the area of geomorphological features, 1958–2024. (A) The distribution of deep submergence activities across seafloor geomorphological features (dark bars) is not representative of the total seafloor area occupied by each feature (light bars). Abyssal features are undersampled, while features such as canyons (orange bars) appear to be oversampled as a category relative to their seafloor area. (B) Individual boxes in the treemap reflect each of the 443 identified canyons that have been observed by deep submergence activities in our record; the area of each box reflects the relative frequency of activities devoted to that canyon. Five individual canyon systems have been the focus of 75.1% of canyon activity, while 9029 of the identified canyons remain unexplored (58).

Toward a diversity of operators

While only five countries conducted 97.2% of all dives, there has been a notable increase in the diversity of operators conducting deep-sea dives in the last quarter century (Fig. 6). In the 1960s, four institutions in two countries conducted 3136 deep submergence dives using six unique platforms. In the 2010s, 27 institutions in 13 countries conducted 12,348 deep submergence dives using 79 unique platforms. From the 1960s to the 1980s, the number of countries and institutions conducting deep-sea exploration and research approximately doubled, and from the 1980s to the 2000s, they more than doubled (2.5 times increase of countries, 2.7 times increase of institutions).

DISCUSSION

As the research presented here demonstrates, we have visual records of a minuscule percentage of the deep seafloor, an ecosystem encompassing 66% of the surface of planet Earth. Our maximum estimate of 3823 km², or 0.001% of the deep seafloor, geographically compares to roughly the smallest US state, Rhode Island (2678 km²) (59), or only a tenth of the size of Belgium (30,688 km²) (60).

The primary limitation of our data was access to classified, commercial, and embargoed dive records (see Methods). It should also be noted that these estimates may substantially underrepresent the explored seafloor, as oil and gas and telecommunication companies have

records that are not public and there are scientific DSV deployment records that are either incomplete or the authors were unable to locate. Acknowledging the incompleteness of the records used in this study, the estimate presented here, even if off by a full order of magnitude, less than one-hundredth of 1% of the seafloor has any visual records. Understanding the limitations of the dataset presented here, it is the largest aggregation of these types of records ever collected and provides valuable insights into the state of ocean exploration and the trends of deep seafloor science across space and time.

Equally as concerning as the small sample size is the inequitable nature of the observations collected. Over-observing of EEZs, hyperfocus on certain types of geomorphologies, and research and seafloor dives conducted by only a few countries and operators result in limited observations that have influenced the general perception of the nature of the benthic environment (Fig. 6).

As a result, the oceanographic community has based much of its characterization of the benthic ecosystem of the deep ocean on this incredibly small and biased sample. To provide an example for comparison, the entire land area of Earth is 148,940,000 km² (61). If the scientific community were to make all assumptions about terrestrial ecosystems from observations of 0.001% of that total area, it would equate to an assessment area of 1489 km² (575 mi²), smaller than the land area of Houston, Texas, at 1669 km² (641 mi²) (62).

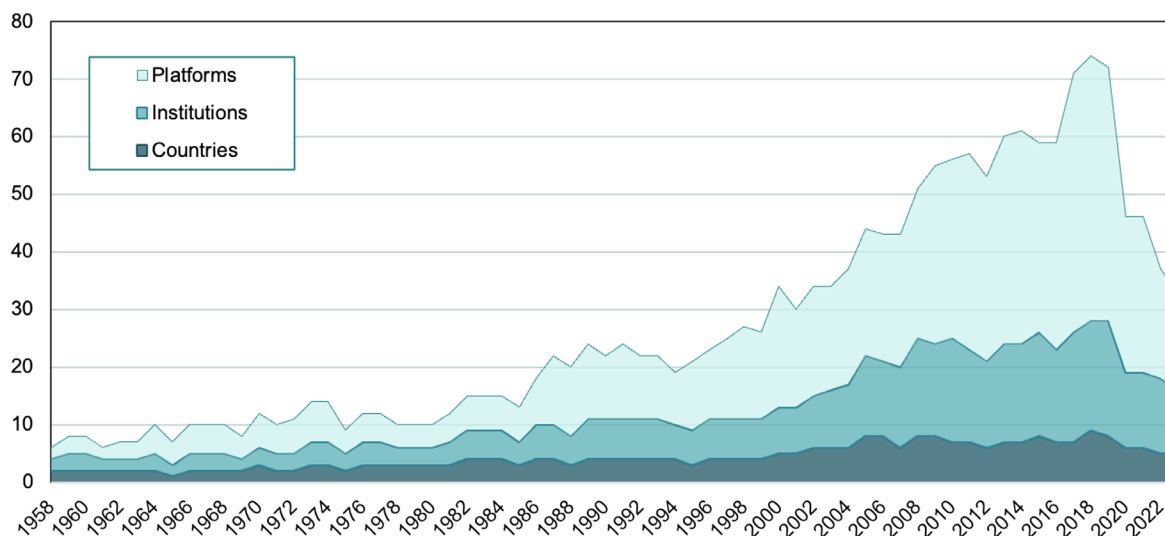


Fig. 6. Number of operating countries, institutions, and platforms, 1958–2024. The number of deep submergence platforms and the diversity of institutions and countries operating deep-sea submergence vehicles have increased from the 1960s to 2010s, the first and last decades with complete dive records. The drop in countries, institutions, and platforms in the current decade is due to the decrease in available records since 2020 (see Methods).

Attempting to extrapolate global understanding from limited and biased samples has proven problematic in many disciplines, from health care (63) to sustainability and climate change research (64, 65). For example, US clinical trials, whose results could have global implications, markedly underrepresent racial and ethnic minorities. Even with legal efforts put in place to require equity in US clinical health research, minority groups account for less than one-tenth of trial participants while composing more than one-third of the American population (66). Similarly, as climate model development increasingly uses artificial intelligence to process large datasets, gaps in climate change data can produce biased and potentially dangerous results for lower-income countries with less access to climate and weather datasets (67). Small and incomplete datasets are one of the three causes of bias in machine intelligence systems and can have a large-scale impact on the reliability and accuracy of these systems (68). Data equity in all fields is needed to ensure we base global assumptions on representative samples.

The visual observations summarized in this research play a critical role in characterizing this ecosystem and quantifying the biodiversity found there (33). Before an increase in the ability to visually explore the seafloor, the oceanographic community often extrapolated inaccurate global assumptions from minimal data. In 1971, researchers published the first compilation of the limited visual observations of the deep ocean captured at that time, becoming a primary reference source for the oceanographic community. While having the most globally diverse observation set yet available, this source still characterized the density of life in the deep ocean as “extremely low” (31).

We now know the ocean’s biomass is considerably more dense and diverse (69). For example, in 1977, chemosynthesis moved from a hypothesis to an entirely new field of science only 6 years later when a deep ocean expedition documented the first hydrothermal vents (70). These vents host a variety of life that thrive without access to sunlight and use symbiotic relationships (42). This discovery is now a critical component of astrobiology research and the basis for the origin of life on Earth and other planetary bodies (71, 72).

Notably, since the discovery of abundant life on hydrothermal vents, researchers have found chemosynthetic species on hydrocarbon seeps, or cold seeps, worldwide (73). Underwater geologic features, including landslides and mudslides, also generate hydrocarbon emissions that fuel benthic life. An expedition in Grenada on the Kick ‘em Jenny seamount found that previously abyssal plains were lush with bacterial mats that were the symbiotic hosts to some of the largest mussels ever discovered (74).

All of these sites—from the mid-ocean ridge hydrothermal vent systems to the hydrocarbon seeps—contain features now easily located by sonar and chemical sensors and, therefore, heavily targeted by expeditions. Hydrothermal vents only make up an estimated 50 km² of seafloor area (75), but the oceanographic community has targeted them for exploration heavily since their discovery. Encouraging visual exploration of other kinds of geomorphologies would likely lead to the discovery of numerous ecosystems and species.

For example, recent interest in deep sea mining has led to more expeditions using DSVs to the Clarion-Clipperton Zone (CCZ), an area in the Pacific Ocean of approximately 6 million km², harboring manganese nodules and other mineral-rich resources. Recent expeditions in the CCZ led to the discovery of hundreds of new species and the prediction that thousands more are yet to be found in this region (27). Most recently, the discovery of “dark” oxygen production by electrochemical reactions between polymetallic nodules rather than photosynthesis is challenging assumptions about how life may have formed on Earth (28). If it had not been for mineral-rich resources and the commercial interest in mineral extraction, the scientific community may not have conducted this number of expeditions in the CCZ, and neither of these discoveries might have been made. With each subsequent dive and observation, the scale of biodiversity and geology of the ocean floor are expanded and redefined.

With the continued anthropogenic pressures on this ecosystem and the slow pace of deep ocean exploration and observations, we do not have the thousands of years it would take to visually characterize the entire deep seafloor once. If there were an increase in

observing capacity to 1000 platforms operating worldwide, visually covering the seafloor at the current rate of $\sim 3 \text{ km}^2$ per year per system, it would take more than 100,000 years to visualize the seafloor once. These estimates illustrate that we need a fundamental change in how we explore and study the global deep ocean.

Given the substantial expense of gathering these data, access to the tools and resources for this work is globally limited (76, 77). As a result, only a fraction of the countries with deep ocean in their EEZ determine the research objectives for these dives. Recent trends suggest that we are moving in the right direction. We have shown that since the 2000s, there has been a notable increase in the number of dives conducted worldwide and the number of countries and institutions carrying out deep-sea exploration and research.

As technology advances and deep-sea tools become smaller, more affordable, easier to use, and more autonomous, we anticipate a proliferation of technology worldwide and a broadening of the deep-sea community, resulting in a more equitable collection of global deep-sea data. In addition to accelerating visual data collection, the deep-sea community needs to identify a targeted set of locations that, when explored, will fill in the gaps and create the first unbiased and statistically representative biogeographical characterization of the entire deep seafloor.

METHODS

Data collection

Global dive dataset

We built on datasets published in 2023 to compile a record of historical deep submergence observation activity, specifically activity that supported visual observation of the seafloor via images or video footage deeper than 200 m (53, 78). The dataset contains 43,681 records from 34 institutions in 14 countries, conducted in 120 EEZs and the high seas; each record includes point-based locations of DSVs and equipment, ROVs, AUVs, HOVs, camera sled tows, and benthic landers. Key metadata variables include point-based latitude-longitude coordinates, maximum depth, date of observation, operating institution and country, platform name, and type of equipment.

To include an individual dive record in the dataset, we minimally required latitude and longitude coordinates of where the dive occurred, the year the operator carried out the activity, the operator's institution, and the country where the operator was based. We included activities conducted by operators only at depths equal to or

below 200 m. For 82% of the dive records, the organizing institution provided the depth information in supplied cruise reports. Eighteen percent of the dive records did not include depth information; in these cases, we estimated maximum depth using General Bathymetric Chart of the Oceans (GEBCO) values at the geographic location of the activity (52).

Dive records date back as early as 1958, and we collected the data using public and internal databases, data requests, and published research findings. There are several potential sets of metadata that we are confident exist but could not access due to the nature of the observation activities. These include, but are not limited to, classified dive records from national naval and military institutions, environmental assessment records from commercial mining, oil and gas exploration activities, and archaeological sites. In addition, because of data embargoes immediately following data collection and operational disruptions due to the COVID-19 pandemic (79, 80), we do not have complete dive records for some of the more recent expeditions.

Bathymetry and geomorphology

We used gridded bathymetry data from GEBCO to generate depth estimates across the entire global ocean (52). We analyzed bathymetry estimates as a raster layer with a 15-arc sec resolution.

We used a set of World Seafloor Geomorphology geographic information system layers developed with mapping data from GRID-Arendal (81) and made accessible through the Esri Living Atlas collection (82). These layers characterize physical features on the seafloor and the global ocean zones in which they occur. The dataset includes 25 geomorphic features (e.g., seamounts, ridges, guyots, and rifts) and terrain types, and maps their spatial distribution across the global seafloor. We simplified our descriptive analyses by collapsing several related feature categories. For example, we combined distinct "trough" and "glacial trough" features into the single category of "trough." The dataset also includes an identification system for 9472 spatially individual submarine canyons, which we used in our analysis of dives conducted on geomorphological features. Table S1 lists a complete list of original geomorphology categories and our groupings.

Method 1: Dive-based visual seafloor coverage calculation

For method 1, we estimated total visual seafloor coverage by calculating an average minimum and maximum for each type of DSV based on actual vehicle tracks over the seafloor. First, we estimated the linear dive track coverage of each DSV type: HOV, ROV, camera tow, and lander (Table 1):

Table 1. Reference vehicle systems used to calculate Method 1. We used one HOV, four ROVs, and one tow camera with dive track line records to calculate the average length of track line per dive per vehicle type. DSV operators included NDSF/WHOI, NOAA/OE, OET, and Schmidt Ocean Institute (SOI), based in the United States, and National Institute of Water and Atmospheric Research (NIWA), based in New Zealand.

Vehicle	Type	Number of dives with tracks	Min area per dive (km^2)	Max area per dive (km^2)	Operator
<i>Alvin</i>	HOV	224	0.143	0.248	NDSF/WHOI
<i>Deep Discoverer</i>	ROV	374	0.017	0.026	NOAA/OE
<i>Hercules</i>	ROV	540	0.047	0.0844	OET
<i>Jason 2</i>	ROV	94	0.028	0.048	NDSF/WHOI
<i>SuBastian</i>	ROV	273	0.0245	0.045	SOI
<i>DTIS</i>	Tow	1731	0.005	0.01	NIWA

1) For HOVs, we calculated a range of area imaged using 224 HOV *Alvin* dive tracks, assuming a minimum field-of-view estimate of 10 m and a maximum estimate of 20 m.

2) For ROVs, we averaged 1281 dive tracks from four ROV systems: *Deep Discoverer (D2)*, *Hercules*, *Jason 2*, and *SuBastian*, assuming a minimum field-of-view estimate of 10 m and a maximum estimate of 20 m.

3) For camera tows, we calculated the distance between the start and end point of 1731 deployments of the *Deep Towed Imaging System (DTIS)*, resulting in an average of 1042 m per dive. We assumed a minimum field-of-view estimate of 10 m and a maximum estimate of 20 m.

4) For landers, we assumed a single point with a minimum estimate of 15 m² and a maximum estimate of 30 m² visually observed for each deployment.

5) AUV deployments were not considered in this calculation because their deployment records did not consistently indicate what type of data was collected (e.g., visual, sonar, CTD, etc.). In the case of the records that clearly indicated visual data were collected, many did not have adequate navigation data to estimate the area covered. Given this uncertainty, we did not include AUV deployments in this calculation understanding that this decision will likely lead to an underestimation of the area covered.

Next, we used these dive averages to calculate the visual area observed for all HOV, ROV, camera tow, and lander dives in the

database (Table 2). We then plotted the calculated area averages using the buffer tool in QGIS (version 3.28). We dissolved any overlapping buffer areas to account for areas of the seafloor with duplicate observation activity (e.g., Monterey Canyon and Axial Seamount). We also took into account overlapping coverage areas in track lines, and as a result, the maximum area per dive is not necessarily double the minimum area per dive. We calculated the resulting polygon area using WGS1984 Equal Earth Projection (EPSG: 8851), resulting in the estimate of global deep seafloor imaged. Using this method, we estimate a minimum seafloor area of 1259 km² and a maximum of 2130 km².

Method 2: Time-based visual seafloor coverage calculation

We used dive records from three organizations in the United States that had operated DSVs for 10 years or more: National Deep Submergence Facility (NDSF) at the Woods Hole Oceanographic Institution (WHOI), Ocean Exploration Trust (OET), and National Oceanic and Atmospheric Administration Office of Ocean Exploration (NOAA/OE). Many dive records were inconsistent, incomplete, or nonexistent; the calculations below only include the most complete dive data we could compile for each DSV system and operator. For each vehicle system and operator, we included the start and end year of operation, with the end year being the most recent complete year of records, the number of lowerings within that timeframe, total time in the water, and total time on the seafloor (bottom time), if available.

Table 2. Total estimated visual seabed coverage by vehicle type using method 1. Using the average minimum and maximum area calculations per vehicle type (Table 1), point estimates for landers (min 15 m², max 30 m²), and the number of dives per vehicle type in our database, we estimated the minimum and maximum visual area covered of the seabed per vehicle type.

DSV type	Number of dives	Estimated minimum area (km ²)	Estimated maximum area (km ²)
HOV	15,502	1,072	1,806
ROV	14,465	181	311
Tow	4,468	18	35
Lander	11,209	0.15	0.30

Table 3. Reference vehicle systems and summary data used to calculate method 2. The dive records of one HOV, five ROVs, and three camera tows were used for the method 2 time-based calculations. Additional information about dive data can be found in table S2. The assumed visual swath width for all vehicles is 10 m. Assumed vehicle speeds are 0.75 knots for HOV *Alvin*, 0.25 knots for ROVs, and 0.5 knots for camera tows.

Vehicle	Type	Years	Dives	Bottom time (hours)	Total area (km ²)	Average area per year (km ²)	Operator
<i>Alvin</i>	HOV	55	4,817	23,947.6	332.6	6.05	NDSF/WHOI
<i>Jason</i>	ROV	10	200	3,575.5	16.55	1.66	NDSF/WHOI
<i>Jason 2</i>	ROV	21	1,273	17,726.0	82.07	3.91	NDSF/WHOI
<i>Hercules</i>	ROV	15	739	8,366.6	38.7	2.58	OET
<i>Little Hercules</i>	ROV	3	66	380.7	1.76	0.59	NOAA/OE
<i>D2</i>	ROV	8	384	2,067.6	9.57	1.20	NOAA/OE
<i>Argo</i>	Tow	4	64	1,647.5	15.26	3.81	NDSF/WHOI
<i>Argo 2</i>	Tow	6	47	1,759.4	16.29	2.72	NDSF/WHOI
<i>Medea</i>	Tow	2	10	174.9	1.62	0.81	NDSF/WHOI

NDSF/WHOI has operated DSVs since 1965, including HOVs, ROVs, and camera tows (table S2). For this study, we used the records of NDSF/WHOI's operation of HOV *Alvin*, ROVs *Jason* and *Jason 2*, and tow cameras, *Argo 1*, *Argo 2*, and *Medea* (Table 3) (78). Bottom time was unavailable for the 1965–1995 *Alvin* lowerings. To estimate the bottom time of the *Alvin* dives for this period, we used the average bottom time rate for *Alvin* from 1996 to 2023, which was 67.1% of the total dive time. Using the dive data available from NDSF/WHOI, from 1965 to 2023, NDSF/WHOI conducted 4817 HOV dives, totaling 23,947.6 hours on the seafloor; 1473 ROV dives, totaling 21,301.5 hours on the seafloor; and 121 camera tows totaling 3581.7 hours on the seafloor.

NOAA/OE operated ROVs *Little Hercules* from 2010 to 2012 and *Deep Discoverer (D2)* from 2013 to the present from NOAA Ship *Okeanos Explorer*. From 2010 to 2021, they conducted 450 ROV dives, totaling 2448.3 hours on the seafloor.

OET has operated ROV *Hercules* from E/V *Nautilus* since 2009. From 2009 to 2023, they conducted 739 ROV dives, 77 of which do not have bottom time records. For these 77 dives, we estimated bottom time using a rate of 83.9% of total time in the water, based on the time on the seafloor for the same period of the complete dive records. Using both recorded and estimated bottom time, we calculated a total of 8366.6 hours on the seafloor.

Using the estimated bottom time for each vehicle system, the number of operating years, an assumed vehicle speed (0.25 to 0.75 knots, depending on DSV type), and an assumed visual swath width (10 m), we estimated the average seafloor area visually covered per year per vehicle system (Table 3). We then calculated the average seafloor coverage per year for all vehicle systems as 2.9 km²/year.

Assuming that, on average, 20 DSV systems operated at this rate from 1958 through 2023 (66 years), we estimated that the deep submergence community would have visually covered approximately 3823 km² of deep seafloor over that period. Our dive database includes an average of 14.7 active DSV systems per year; the overestimate of 20 operating systems per year takes into account systems that we do not have in our records.

Supplementary Materials

This PDF file includes:

Tables S1 and S2

References

REFERENCES AND NOTES

1. C. Amante, B. Eakins, ETOPO1 1 arc-minute global relief model: Procedures, data sources and analysis, *Tech. Rep. Technical Memorandum NESDIS NGDC-24*, NOAA; [https://www.ncei.noaa.gov/sites/g/files/anmtf171/files/2023-01/Hypsographic Curve of Earth's Surface from ETOPO1.pdf](https://www.ncei.noaa.gov/sites/g/files/anmtf171/files/2023-01/Hypsographic%20Curve%20of%20Earth%20Surface%20from%20ETOPO1.pdf).
2. E. Ramirez-Llodra, A. Brandt, R. Danovaro, B. De Mol, E. Escobar, C. R. German, L. A. Levin, P. Martinez Arbizu, L. Menot, P. Buhl-Mortensen, B. E. Narayanaswamy, C. R. Smith, D. P. Tittensor, P. A. Tyler, A. Vanreusel, M. Vecchione, Deep, diverse and definitely different: Unique attributes of the world's largest ecosystem. *Biogeosciences* **7**, 2851–2899 (2010).
3. S. Witman, World's biggest oxygen producers living in swirling ocean waters. *Eos* **98**, 10.1029/2017EO081067 (2017).
4. H. W. Ducklow, D. K. Steinberg, K. O. Buesseler, Upper ocean carbon export and the biological pump. *Oceanography* **14**, 50–58 (2001).
5. D. Ottaviani, Economic value of ecosystem services from the deep seas and the areas beyond national jurisdiction, FAO, Rome (2020).
6. H. Ritchie, M. Roser, Fish and Overfishing, Our World in Data (2021); <https://ourworldindata.org/fish-and-overfishing>.
7. V. J. Paul, C. J. Freeman, V. Agarwal, Chemical ecology of marine sponges: New opportunities through “-Omics”. *Integr. Comp. Biol.* **59**, 765–776 (2019).
8. A. M. Hamoda, B. Fayed, N. S. Ashmawy, A.-N. A. El-Shorbagi, R. Hamdy, S. S. M. Soliman, Marine sponge is a promising natural source of anti-SARS-CoV-2 scaffold. *Front. Pharmacol.* **12**, 666664 (2021).
9. A. F. U. H. Saeed, J. Su, S. Ouyang, Marine-derived drugs: Recent advances in cancer therapy and immune signaling. *Biomed. Pharmacother.* **134**, 111091 (2021).
10. L.-L. Hong, Y.-F. Ding, W. Zhang, H.-W. Lin, Chemical and biological diversity of new natural products from marine sponges: A review (2009–2018). *Mar. Life Sci. Technol.* **4**, 356–372 (2022).
11. A. E. Gauthier, C. E. Chandler, V. Poli, F. M. Gardner, A. Tekiau, R. Smith, K. S. Bonham, E. E. Cordes, T. M. Shank, I. Zanon, D. R. Goodlett, S. J. Biller, R. K. Ernst, R. D. Rotjan, J. C. Kagan, Deep-sea microbes as tools to refine the rules of innate immune pattern recognition. *Sci. Immunol.* **6**, eabe0531 (2021).
12. E. Ramirez-Llodra, P. A. Tyler, M. C. Baker, O. A. Bergstad, M. R. Clark, E. Escobar, L. A. Levin, L. Menot, A. A. Rowden, C. R. Smith, C. L. Van Dover, Man and the last great wilderness: Human impact on the deep sea. *PLOS ONE* **6**, e22588 (2011).
13. *Ocean and climate change dialogue to consider how to strengthen adaptation and mitigation action*, Subsidiary Body for Scientific and Technological Advice (Framework Convention on Climate Change, 2021).
14. D. G. Desbruyères, S. G. Purkey, E. L. McDonagh, G. C. Johnson, B. A. King, Deep and abyssal ocean warming from 35 years of repeat hydrography. *Geophys. Res. Lett.* **43**, 10,356–10,365 (2016).
15. D. Breitburg, L. A. Levin, A. Oschlies, M. Grégoire, F. P. Chavez, D. J. Conley, V. Garçon, D. Gilbert, D. Gutiérrez, K. Isensee, G. S. Jacinto, K. E. Limburg, I. Montes, S. W. A. Naqvi, G. C. Pitcher, N. N. Rabalais, M. R. Roman, K. A. Rose, B. A. Seibel, M. Telszewski, M. Yasuhara, J. Zhang, Declining oxygen in the global ocean and coastal waters. *Science* **359**, eaam7240 (2018).
16. D. Laffoley, J. Baxter, Eds., *Ocean Deoxygenation: Everyone's Problem - Causes, Impacts, Consequences and Solutions* (IUCN, 2019), vol. xxii.
17. IPCC, *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (Cambridge Univ. Press, 2019).
18. G. Li, L. Cheng, J. Zhu, K. E. Trenberth, M. E. Mann, J. P. Abraham, Increasing ocean stratification over the past half-century. *Nat. Clim. Change* **10**, 1116–1123 (2020).
19. A. Sen Gupta, A. Stella, G. M. Pontes, A. S. Taschetto, A. Vergés, V. Rossi, Future changes to the upper ocean Western Boundary Currents across two generations of climate models. *Sci. Rep.* **11**, 9538 (2021).
20. L. A. Levin, J. M. Alfaro-Lucas, A. Colaço, E. E. Cordes, N. Craik, R. Danovaro, H.-J. Hoving, J. Ingels, N. C. Mestre, S. Seabrook, A. R. Thurber, C. Vivian, M. Yasuhara, Deep-sea impacts of climate interventions. *Science* **379**, 978–981 (2023).
21. L. Macheriotou, A. Rigaux, S. Derycke, A. Vanreusel, Phylogenetic clustering and rarity imply risk of local species extinction in prospective deep-sea mining areas of the Clarion Clipperton Fracture Zone. *Proc. R. Soc. B* **287**, 20192666 (2020).
22. J. C. Drazen, C. R. Smith, K. M. Gjerde, S. H. D. Haddock, G. S. Carter, C. A. Choy, M. R. Clark, P. Dutrieux, E. Goetze, C. Hauton, M. Hatta, J. A. Koslow, A. B. Leitner, A. Pacini, J. N. Perelman, T. Peacock, T. T. Sutton, L. Watling, H. Yamamoto, Midwater ecosystems must be considered when evaluating environmental risks of deep-sea mining. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 17455–17460 (2020).
23. L. A. Levin, D. J. Amon, H. Lily, Challenges to the sustainability of deep-seabed mining. *Nat. Sustain.* **3**, 784–794 (2020).
24. R. Crane, C. Laing, K. Littler, K. Moore, C. Roberts, K. Thompson, D. Vogt, J. Scourse, Deep-sea mining poses an unjustifiable environmental risk. *Nat. Sustain.* **7**, 836–838 (2024).
25. S. Lidström, L. A. Levin, S. Seabrook, Laying waste to the deep: Parallel narratives of marine carbon dioxide removal and deep-seabed mining. *NPJ Ocean Sustain.* **3**, 36 (2024).
26. L. A. Levin, IPCC and the deep sea: A case for deeper knowledge. *Front. Clim.* **3**, 10.3389/fclim.2021.720755 (2021).
27. M. Rabone, J. H. Wiethase, E. Simon-Lledó, A. M. Emery, D. O. B. Jones, T. G. Dahlgren, G. Bribiesca-Contreras, H. Wiklund, T. Horton, A. G. Glover, How many metazoan species live in the world's largest mineral exploration region? *Curr. Biol.* **33**, 2383–2396.e5 (2023).
28. A. K. Sweetman, A. J. Smith, D. S. W. de Jonge, T. Hahn, P. Schroedl, M. Silverstein, C. Andrade, R. L. Edwards, A. J. M. Lough, C. Wouldes, W. B. Homoky, A. Koschinsky, S. Fuchs, T. Kuhn, F. Geiger, J. J. Marlow, Evidence of dark oxygen production at the abyssal seafloor. *Nat. Geosci.* **17**, 737–739 (2024).
29. M. Bright, S. Gollner, A. L. de Oliveira, S. Espada-Hinojosa, A. Fulford, I. Vincent Hughes, S. Hourdez, C. Karthäuser, I. Kolar, N. Krause, V. Le Layec, T. Makovec, A. Messora, J. Mitchell, P. Pröts, I. Rodríguez-Ramírez, F. Sieler, S. M. Sievert, J. Steger, T. Tinta, T. R. M. Winter, Z. Bright, R. Coffield, C. Hill, K. Ingram, A. Paris, Animal life in the shallow subseafloor crust at deep-sea hydrothermal vents. *Nat. Commun.* **15**, 8466 (2024).

30. J. B. Hersey, Ed., *Deep-Sea Photography*, no. 3 in The Johns Hopkins Oceanographic Studies (The Johns Hopkins Press, 1967).
31. B. C. Heezen, C. D. Hollister, *The Face of the Deep* (Oxford Univ. Press, 1971).
32. J. A. Karson, D. S. Kelley, D. J. Fornari, M. R. Perfit, T. M. Shank, *Discovering the Deep* (Cambridge Univ. Press, 2015).
33. J. M. Durden, T. Schoening, F. Althaus, A. Friedmann, R. Garcia, A. G. Glover, J. Greinert, N. J. Stout, D. O. B. Jones, A. Jordt, J. W. Kaeli, K. Köser, L. A. Kuhn, D. Lindsay, K. J. Morris, T. W. Nattkemper, J. Osterloff, H. A. Ruhl, H. Singh, M. Tran, B. J. Bett, "Perspectives in visual imaging for marine biology and ecology: From acquisition to understanding" in *Oceanography and Marine Biology: An Annual Review*, R. N. Hughes, D. J. Hughes, I. P. Smith, A. C. Dale, Eds. (Taylor Francis, 2016), vol. 54, pp. 1–72.
34. L. A. Levin, B. J. Bett, A. R. Gates, P. Heimbach, B. M. Howe, F. Janssen, A. McCurdy, H. A. Ruhl, P. Snelgrove, K. I. Stocks, D. Bailey, S. Baumann-Pickering, C. Beaverson, M. C. Benfield, D. J. Booth, M. Carreiro-Silva, A. Colaço, M. C. Eblé, A. M. Fowler, K. M. Gjerde, D. O. B. Jones, K. Katsumata, D. Kelley, N. Le Bris, A. P. Leonard, F. Lejzerowicz, P. I. Macreadie, D. McLean, F. Meitz, T. Morato, A. Netburn, J. Pawlowski, C. R. Smith, S. Sun, H. Uchida, M. F. Vardaro, R. Venkatesan, R. A. Weller, Global observing needs in the deep ocean. *Front. Mar. Sci.* **6**, 10.3389/fmars.2019.00241 (2019).
35. A. R. Gates, M. C. Benfield, D. J. Booth, A. M. Fowler, D. Skropeta, D. O. B. Jones, Deep sea observations at hydrocarbon drilling locations: Contributions from the SERPENT Project after 120 field visits. *Deep Sea Res. II Top. Stud. Oceanogr.* **137**, 463–479 (2017).
36. B. R. C. Kennedy, K. Cantwell, M. Malik, C. Kelley, J. Potter, K. Elliott, E. Lobercker, L. M. Gray, D. Sowers, M. P. White, S. C. France, S. Auscavitch, C. Mah, V. Moriwake, S. R. D. Bingo, M. Putts, R. D. Rotjan, The unknown and the unexplored: Insights into the Pacific deep-sea following NOAA CAPSTONE expeditions. *Front. Mar. Sci.* **6**, 10.3389/fmars.2019.00480 (2019).
37. S. Long, B. Sparrow-Scinocca, M. E. Blicher, N. Hammeken Arboe, M. Fuhrmann, K. M. Kemp, R. Nygaard, K. Zinglensen, C. Yesson, Identification of a soft coral garden candidate vulnerable marine ecosystem (VME) using video imagery, Davis Strait, West Greenland. *Front. Mar. Sci.* **7**, 10.3389/fmars.2020.00460 (2020).
38. A. A. Rowden, T. R. R. Pearson, D. A. Bowden, O. F. Anderson, M. R. Clark, Deter mining coral density thresholds for identifying structurally complex vulnerable marine ecosystems in the deep sea. *Front. Mar. Sci.* **7**, 10.3389/fmars.2020.00095 (2020).
39. S. D. Hurst, J. A. Karson, Side-scan sonar along the north wall of the Hess Deep Rift: Processing, texture analysis, and geologic ground truth on an oceanic escarpment. *J. Geophys. Res. Solid Earth* **109**, B02107.1–B02107.12 (2004).
40. OSTs, *National Strategy for Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone* (Ocean Science and Technology Subcommittee, Ocean Policy Committee, 2020); <https://www.noaa.gov/sites/default/files/2022-07/NOMECStrategy.pdf>.
41. R. Danovaro, E. Fanelli, J. Aguzzi, D. Billett, L. Carugati, C. Corinaldesi, A. Dell'Anno, K. Gjerde, A. J. Jamieson, S. Kark, C. McClain, L. Levin, N. Levin, E. Ramirez-Llodra, H. Ruhl, C. R. Smith, P. V. R. Snelgrove, L. Thomsen, C. L. Van Dover, M. Yasuhara, Ecological variables for developing a global deep-ocean monitoring and conservation strategy. *Nat. Ecol. Evol.* **4**, 181–192 (2020).
42. F. N. Spiess, K. C. Macdonald, T. Atwater, R. Ballard, A. Carranza, D. Cordoba, C. Cox, V. M. D. Garcia, J. Francheteau, J. Guerrero, R. Hawkins, R. Haymon, R. Hessler, T. Juteau, M. Kastner, R. Larson, B. Luyendyk, J. D. Macdougall, S. Miller, W. Normark, J. Orcutt, C. Rangin, East Pacific Rise: Hot springs and geophysical experiments. *Science* **207**, 1421–1433 (1980).
43. D. S. Kelley, J. A. Karson, D. K. Blackman, G. L. Früh-Green, D. A. Butterfield, M. D. Lilley, E. J. Olson, M. O. Schrenk, K. K. Roe, G. T. Lebon, P. Rivizzigno, The AT3-60 Shipboard Party, An off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30° N. *Nature* **412**, 145–149 (2001).
44. P. T. Schwing, P. A. Montagna, S. B. Joye, C. B. Paris, E. E. Cordes, C. R. McClain, J. P. Kilborn, S. A. Murawski, A synthesis of deep benthic faunal impacts and resilience following the Deepwater Horizon Oil Spill. *Front. Mar. Sci.* **7**, 10.3389/fmars.2020.560012 (2020).
45. R. D. Ballard, F. T. Hiebert, D. F. Coleman, C. Ward, J. S. Smith, K. Willis, B. Foley, K. Croff, C. Major, F. Torre, Deepwater archaeology of the Black Sea: The 2000 season at Sinop, Turkey. *Am. J. Archaeol.* **105**, 607–623 (2001).
46. A. Rogers, E. Ramirez-Llodra, Deep-sea exploration of marine ecosystems—Knowledge and solutions for marine biodiversity. *Int. Hydrogr. Res.* **30**, 10–37 (2024).
47. E. G. Mitchell, S. Harris, Mortality, population and community dynamics of the glass sponge dominated community "The Forest of the Weird" from the Ridge Seamount, Johnston Atoll, Pacific Ocean. *Front. Mar. Sci.* **7**, 10.3389/fmars.2020.565171 (2020).
48. K. Schlining, S. von Thun, L. Kuhn, B. Schlining, L. Lundsten, N. Jacobsen Stout, L. Chaney, J. Connor, Debris in the deep: Using a 22-year video annotation database to survey marine litter in Monterey Canyon, central California, USA. *Deep Sea Res. I Oceanogr. Res. Pap.* **79**, 96–105 (2013).
49. M. Hoeberechts, D. Owens, D. J. Riddell, A. D. Robertson, *OCEANS 2015 - MTS/IEEE Washington* (2015), pp. 1–9.
50. A. T. Fundis, K. L. C. Bell, Inspiring, engaging, and educating the next generation of STEM learners. *J. Ocean Technol.* **9**, 73–78 (2014).
51. A. Rogers, A. Brierley, P. Croot, M. Cunha, R. Danovaro, C. Devery, A. H. Hoel, H. Ruhl, P.-M. Sarradin, S. Trevisanut, S. van den Hove, H. Vieira, M. Visbeck, N. McDonough, K. Donaldson, K. Larkin, Delving Deeper: Critical challenges for 21st century deep sea research. *Position Paper*, K. Larkin, K. Donaldson, N. McDonough, Eds., no. 22 (European Marine Board, 2015), p. 224.
52. GEBCO 2022 Grid, GEBCO Compilation Group (2022); 10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c.
53. K. N. Johannes, B. R. C. Kennedy, K. L. C. Bell, Seafloor observation scenario exploration tool: Enabling representative exploration of the global deep seafloor. *Front. Mar. Sci.* **10**, 10.3389/fmars.2023.1251562 (2023).
54. Maritime Boundaries Geodatabase (Tech. Rep. 12, Flanders Marine Institute, 2023); <https://doi.org/10.14284/628>.
55. *Convention on the Law of the Sea* (UN General Assembly, 1982).
56. UN Statistics Division, *Methodology: Standard country or area codes for statistical use (M49)* (2024); <https://unstats.un.org/unsd/methodology/m49/overview/>.
57. The World Bank, *World Bank Country and Lending Groups*, 2022 ed. <https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups>.
58. P. T. Harris, M. Macmillan-Lawler, J. Rupp, E. K. Baker, Geomorphology of the oceans. *Mar. Geol.* **352**, 4–24 (2014).
59. U. S. Census, State Area Measurements and Internal Point Coordinates (2010); <https://census.gov/geographies/reference-files/2010/geo/state-area.html>.
60. Geographical Description of Belgium, Belgian Federal Government (2024); https://belgium.be/en/about_belgium/country/geography.
61. M. Pidwirny, "Introduction to the oceans" in *Fundamentals of Physical Geography*, M. Pidwirny, S. Jones, Eds. (University of British Columbia Okanagan, ed. 2, 2006); <http://physicalgeography.net/fundamentals/8o.html>.
62. U. S. Census, QuickFacts, (Houston City, 2020); <https://census.gov/quickfacts/fact/table/houstoncitytexas/POP010220>.
63. A. Retzer, B. Ciytak, F. Khatsuria, J. El-awaisi, I. M. Harris, L. Chapman, T. Kelly, J. Richards, E. Lam, P. N. Newsome, M. Calvert, NIHR Birmingham Biomedical Research Centre REP-EQUITY Group, A toolkit for capturing a representative and equitable sample in health research. *Nat. Med.* **29**, 3259–3267 (2023).
64. M. Winter, W. Fiedler, W. M. Hochachka, A. Koehncke, S. Meiri, I. De la Riva, Patterns and biases in climate change research on amphibians and reptiles: A systematic review. *R. Soc. Open Sci.* **3**, 160158 (2016).
65. N. Record, L. Vera, Uncovering big data bias in sustainability science. *Spire: The Maine Journal of Conservation and Sustainability* **5** (2021).
66. B. Boden-Albala, Confronting legacies of underrepresentation in clinical trials: The case for greater diversity in research. *Neuron* **110**, 746–748 (2022).
67. R. Debnath, F. Creutzig, B. K. Sovacool, E. Shuckburgh, Harnessing human and machine intelligence for planetary-level climate action. *NPJ Clim. Action* **2**, 20 (2023).
68. A. S. Rich, T. M. Gureckis, Lessons for artificial intelligence from the study of natural stupidity. *Nat. Mach. Intell.* **1**, 174–180 (2019).
69. Y. M. Bar-On, R. Milo, The biomass composition of the oceans: A blueprint of our blue planet. *Cell* **179**, 1451–1454 (2019).
70. J. B. Corliss, J. Dymond, L. I. Gordon, J. M. Edmond, R. P. von Herzen, R. D. Ballard, K. Green, D. Williams, A. Bainbridge, K. Crane, T. H. van Andel, Submarine thermal springs on the Galápagos Rift. *Science* **203**, 1073–1083 (1979).
71. W. Martin, J. Baross, D. Kelley, M. J. Russell, Hydrothermal vents and the origin of life. *Nat. Rev. Microbiol.* **6**, 805–814 (2008).
72. C. R. German, Hydrothermal exploration and astrobiology: Oases for life in distant oceans? *Int. J. Astrobiol.* **3**, 81–95 (2004).
73. M. Sibuet, K. Olu, Biogeography, biodiversity and fluid dependence of deep-sea cold-seep communities at active and passive margins. *Deep Sea Res. II Top. Stud. Oceanogr.* **45**, 517–567 (1998).
74. S. Carey, R. Ballard, K. L. C. Bell, R. J. Bell, P. Connally, F. Dondin, S. Fuller, J. Gobin, P. Miloslavich, B. Phillips, C. Roman, B. Seibel, N. Siu, C. Smart, Cold seeps associated with a submarine debris avalanche deposit at Kick'em Jenny volcano, Grenada (Lesser Antilles). *Deep Sea Res. I Oceanogr. Res. Pap.* **93**, 156–160 (2014).
75. C. L. Van Dover, S. Arnaud-Haond, M. Gianni, S. Helmreich, J. A. Huber, A. L. Jaekel, A. Metaxas, L. H. Pendleton, S. Petersen, E. Ramirez-Llodra, P. E. Steinberg, V. Tunnicliffe, H. Yamamoto, Scientific rationale and international obligations for protection of active hydrothermal vent ecosystems from deep-sea mining. *Mar. Policy* **90**, 20–28 (2018).
76. K. L. C. Bell, M. C. Quinzin, S. Poulton, A. Hope, D. Amon, Eds., 2022 *Global Deep-Sea Capacity Assessment* (Ocean Discovery League, 2022).
77. K. L. C. Bell, M. C. Quinzin, D. Amon, S. Poulton, A. Hope, O. Sarti, T. E. Cañete, A. M. Smith, H. I. Baldwin, D. M. Lira, S. Cambroneiro-Solano, T.-R. A. Chung, B. Brady, Exposing inequities in deep-sea exploration and research: Results of the 2022 Global Deep-Sea Capacity Assessment. *Front. Mar. Sci.* **10**, 10.3389/fmars.2023.1217227 (2023).
78. B. R. C. Kennedy, R. D. Rotjan, Mind the gap: Comparing exploration effort with global biodiversity patterns and climate projections to determine ocean areas with greatest exploration needs. *Front. Mar. Sci.* **10**, 10.3389/fmars.2023.1219799 (2023).

79. T. Gallaudet, J. Sims, E. Lobecker, A. Netburn, C. Alexander, K. D. Goodwin, A. Skrivaneck, A. Autonomy, artificial intelligence, and telepresence: Advancing ocean science at sea in the COVID-19 era. *J. Ocean Technol.* **15**, 1–13 (2020).
80. T. Boyer, H.-M. Zhang, K. O'Brien, J. Reagan, S. Diggs, E. Freeman, H. Garcia, E. Heslop, P. Hogan, B. Huang, L.-Q. Jiang, A. Kozyr, C. Liu, R. Locarnini, A. V. Mishonov, C. Paver, Z. Wang, M. Zweng, S. Alin, L. Barbero, J. A. Barth, M. Belbeoch, J. Cebrian, K. J. Connell, R. Cowley, D. Dukhovskoy, N. R. Galbraith, G. Goni, F. Katz, M. Kramp, A. Kumar, D. M. Legler, R. Lumpkin, C. R. McMahon, D. Pierrot, A. J. Plueddemann, E. A. Smith, A. Sutton, V. Turpin, L. Jiang, V. Suneel, R. Wanninkhof, R. A. Weller, A. P. S. Wong, Effects of the pandemic on observing the global ocean. *Bull. Am. Meteorol. Soc.* **104**, E389–E410 (2023).
81. P. T. Harris, M. Macmillan-Lawler, *Global Overview of Continental Shelf Geomorphology Based on the SRTM30 PLUS 30-Arc Second Database* (Springer International Publishing, 2016), pp. 169–190.
82. World seafloor geomorphology from GRID Arendal [map layer], Esri Oceans, Living Atlas of the World (2024).
83. DeepData Database, International Seabed Authority (2023); <https://isa.org/jm/deepdata-database/>.
84. J. Williams, T. Ingleton, M. Sutherland, P. Davies, J. Monk, N. Barrett, A. Jordan, Mapping and characterising reef habitat and fish assemblages of the Hunter Marine Park, Report to the National Environmental Science Program, Marine Biodiversity Hub (2020).
85. D. Dong, X. Li, Galatheid and chirostylid crustaceans (Decapoda: Anomura) from a cold seep environment in the northeastern South China Sea. *Zootaxa* **4057**, 91–105 (2015).
86. D. Dong, X. Li, B. Lu, C. Wang, Three squat lobsters (Crustacea: Decapoda: Anomura) from tropical West Pacific seamounts, with description of a new species of *Uroptychus* Henderson, 1888. *Zootaxa* **4311**, 389–398 (2017).
87. Q. Liang, Y. Hu, D. Feng, J. Peckmann, L. Chen, S. Yang, J. Liang, J. Tao, D. Chen, Authigenic carbonates from newly discovered active cold seeps on the northwestern slope of the South China Sea: Constraints on fluid sources, formation environments, and seepage dynamics. *Deep Sea Res. I Oceanogr. Res. Pap.* **124**, 31–41 (2017).
88. S.-Y. V. Liu, Y.-C. Hsin, Y.-R. Cheng, Using particle tracking and genetic approaches to infer population connectivity in the deep-sea scleractinian coral *Deltocyathus magnificus* in the South China Sea. *Deep-Sea Res. I Oceanogr. Res. Pap.* **161**, 103297 (2020).
89. D. Dong, Z. Gan, X. Li, Descriptions of eleven new species of squat lobsters (Crustacea: Anomura) from seamounts around the Yap and Mariana Trenches with notes on DNA barcodes and phylogeny. *Zool. J. Linn. Soc.* **192**, 306–355 (2021).
90. Y. Zhou, C. Chen, D. Zhang, Y. Wang, H. K. Watanabe, J. Sun, D. Bissessor, R. Zhang, Y. Han, D. Sun, P. Xu, B. Lu, H. Zhai, X. Han, C. Tao, Z. Qiu, Y. Sun, Z. Liu, J. W. Qiu, C. Wang, Delineating biogeographic regions in Indian Ocean deep-sea vents and implications for conservation. *Divers. Distrib.* **28**, 2858–2870 (2022).
91. Hawaii Undersea Research Laboratory Archive, Hawaii Undersea Research Laboratory (2022); <https://uhm.maps.arcgis.com/apps/webappviewer/index.html>.
92. GeoMapApp (2023); www.geomapp.org.
93. I. E. Baremore, R. T. Graham, S. R. D. Owen, M. J. Witt, Small-scale fishing has affected abundance and size distributions of deepwater snappers and groupers in the Mesoamerican region. *Rev. Fish Biol. Fish.* **33**, 1547–1568 (2023).
94. A. M. Friedlander, J. Giddens, E. Ballesteros, S. Blum, E. K. Brown, J. E. Caselle, B. Henning, C. Jost, P. Salinas-de León, E. Sala, Marine biodiversity from zero to a thousand meters at Clipperton Atoll (Île de La Passion), Tropical Eastern Pacific. *PeerJ* **7**, e7279 (2019).
95. J. Giddens, W. Goodell, A. Friedlander, P. S. de León, C. Shepard, B. Henning, E. Berkenpas, E. Sala, A. Turchik, Patterns in bathyal demersal biodiversity and community composition around archipelagos in the Tropical Eastern Pacific. *Front. Mar. Sci.* **6**, 10.3389/fmars.2019.00388 (2019).
96. A. M. Friedlander, C. F. Gaymer, Progress, opportunities and challenges for marine conservation in the Pacific Islands. *Aquat. Conserv.* **31**, 221–231 (2021).
97. A. M. Friedlander, W. Goodell, J. Giddens, E. E. Easton, D. Wagner, Deep-sea biodiversity at the extremes of the Salas y Gómez and Nazca ridges with implications for conservation. *PLOS ONE* **16**, e0253213 (2021).
98. P. V. Stefanoudis, N. Fassbender, K. Samimi-Namin, P.-A. Adam, A. Ebrahim, J. Harlay, A. Koester, M. Samoily, H. Sims, D. Swanborn, S. Talma, S. Winter, L. C. Woodall, Trait-based approaches reveal that deep reef ecosystems in the Western Indian Ocean are functionally distinct. *Sci. Total Environ.* **872**, 162111 (2023).
99. Northeast Fisheries Science Center, Habitat Mapping Camera (HABCAM) from 2010-06-15 to 2024-05-09. NOAA National Centers for Environmental Information (2024); <https://fisheries.noaa.gov/inport/item/27598>.
100. Data access, NOAA Office of Ocean Exploration (2024); <https://oceanexplorer.noaa.gov/data/access/access.html>.
101. Cruise inventory, National Oceanography Centre / British Oceanographic Data Centre (2021); https://bodc.ac.uk/resources/inventories/cruise_inventory/search/.
102. H. A. Ruhl, "RRS Discovery Cruise 377 & 378, 05–27 Jul 2012, Southampton to Southampton. Autonomous ecological surveying of the abyss: Understanding mesoscale spatial heterogeneity at the Porcupine Abyssal Plain," National Oceanography Centre Cruise Report, 23. Southampton, UK. National Oceanography Centre (2013), pp. 73.
103. D. O. B. Jones, "RRS James Cook Cruise JC120, 15 Apr - 19 May 2015. Manzanillo to Manzanillo, Mexico. Managing Impacts of Deep-sea resource exploitation (MIDAS): Clarion-Clipperton Zone, North Eastern Area of Particular Environmental Interest," National Oceanography Centre Cruise Report, No. 32. Southampton, UK. National Oceanography Centre (2015), pp. 117.
104. H.-H. Chen, Y.-C. Chou, C.-C. Wang, S.-C. Chen, P.-J. Su, Y.-J. Lin, "Seafloor imaging exploration off the northeastern coast of Taiwan using a deep-towed vehicle," OCEANS 2024 - Halifax, Halifax, NS, Canada (2024), pp. 1–8; 10.1109/OCEANS55160.2024.10754088.
105. A. M. Sagalevich, P. T. Isley, *The Deep: Voyages to Titanic and Beyond* (Botanical Press, 2009).
106. SERPENT, Maps/missions, Scientific and Environmental ROV Partnership using Existing Industrial Technology (2023); <https://serpentproject.com/mapsmissions>.
107. W. Misa, J. C. Drazen, C. D. Kelley, V. N. Moriwake, Establishing species-habitat associations for 4 eel line snappers with the use of a baited stereo-video camera system. *Fish. Bull.* **111**, 293–308 (2013).
108. C. H. Moore, J. C. Drazen, C. D. Kelley, W. F. X. E. Misa, Deepwater marine protected areas of the main Hawaiian Islands: Establishing baselines for commercially valuable bottomfish populations. *Mar. Ecol. Prog. Ser.* **476**, 167–183 (2013).
109. A. M. Friedlander, K. A. Stamoulis, J. N. Kittinger, J. C. Drazen, B. N. Tissot, Understanding the scale of marine protection in Hawai'i: From community-based management to the remote Northwestern Hawaiian Islands. *Adv. Mar. Biol.* **69**, 153–203 (2014).
110. D. K. Sackett, J. C. Drazen, V. N. Moriwake, C. D. Kelley, B. D. Schumacher, W. F. X. E. Misa, Marine protected areas for deepwater fish populations: An evaluation of their effects in Hawai'i. *Mar. Biol.* **161**, 411–425 (2014).
111. W. F. X. E. Misa, B. L. Richards, G. T. DiNardo, C. D. Kelley, V. N. Moriwake, J. C. Drazen, Evaluating the effect of soak time on bottomfish abundance and length data from stereo video surveys. *J. Exp. Mar. Biol. Ecol.* **479**, 20–34 (2016).
112. C. Moore, J. C. Drazen, B. T. Radford, C. Kelley, S. J. Newman, Improving essential fish habitat designation to support sustainable ecosystem-based fisheries management. *Mar. Policy* **69**, 32–41 (2016).
113. B. L. Richards, S. G. Smith, J. S. Ault, G. T. DiNardo, D. Kobayashi, R. Domokos, J. Anderson, J. Taylor, W. Misa, L. Giuseffi, A. Rollo, D. Merritt, J. C. Drazen, M. E. Clarke, C. Tam, "Design and implementation of a bottomfish fishery-independent survey in the main Hawaiian Islands," NOAA Technical Memorandum NMFS-PIFSC 53 (NOAA, 2016).
114. Z. S. Oyafuso, J. C. Drazen, C. H. Moore, E. C. Franklin, Habitat-based species distribution modelling of the Hawaiian deepwater snapper-grouper complex. *Fish. Res.* **195**, 19–27 (2017).
115. D. K. Sackett, C. D. Kelley, J. C. Drazen, Spilling over deepwater boundaries: Evidence of spillover from two deepwater restricted fishing areas in Hawaii. *Mar. Ecol. Prog. Ser.* **568**, 175–190 (2017).
116. Rechnitzer, A. B., U.S. Navy Electronics Laboratory (San Diego, Calif.), Summary of the bathyscaph Trieste research program results: (1958–1960) (NEL-1095) (Navy Electronics Laboratory, 1962).
117. NDSF; Tethered Vehicles Ops Summaries & Alvin dive log (2024); <https://nds.fwhoi.edu/data/>.

Acknowledgments: We would like to acknowledge and offer sincere thanks to all the individuals who contributed historical data records to this project, without whom this work would not have been possible. Table S2 contains a list of all the previously published contributed work. Additional data were provided by T. Noyes (BIOS), A. Andresen (Caladan Oceanic/Inkfish), R. Skelly (Canada DFO), V. Wade (Fish 'N Fins), F. Abegg and K. Hissman (GEOMAR), S. Pomponi (HBOI), O. Soubigou (IFREMER), D. Lindsay (JAMSTEC), J. Escartin (MARUM), B. Robison (MBARI), W. Goodell (NGS), L. Woodall (Nekton), K. Mackay and D. Bowden (NIWA), C. Rooper (NOAA/NFSC), C.-L. Wei (NSTC), D. Wagner (OET), C. Bassin (SOI), E. Cordes (Temple University), and A. Catsambis (NHHC). We also thank P. Girguis, L. Levin, and the Levin Lab for thoughtful feedback on this work and manuscript. We would also like to thank the reviewers whose extremely detailed reviews greatly improved this work. Additional thanks go to K. Cantner for help with the layout of the figures. **Funding:** This work was supported by National Geographic Society to K.L.C.B., K.N.J., B.R.C.K., and S.E.P., Cabot Family Charitable Trust to K.N.J., and Lyda Hill Philanthropies to K.L.C.B., K.N.J., and S.E.P. **Author contributions:** K.L.C.B.: Writing—original draft, conceptualization, investigation, writing—review and editing, methodology, resources, funding acquisition, supervision, project administration, and visualization. K.N.J.: Writing—original draft, conceptualization, investigation, writing—review and editing, resources, data curation, validation, project administration, and visualization. B.R.C.K.: Writing—original draft, conceptualization, investigation, writing—review and editing, methodology, resources, funding acquisition, data curation, validation, formal analysis, and software. S.E.P.: Writing—original draft, conceptualization, writing—review and editing, funding acquisition, and project

administration. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper, the Supplementary Materials, and/or archived on Zenodo (<https://zenodo.org/records/13948032>).

Submitted 29 July 2024
Accepted 18 March 2025
Published 7 May 2025
10.1126/sciadv.adp8602