Section 4

Subchapter 5M

Abyssal plains

Writing team: Moriaki Yasuhara (coordinating author), Paul V. R. Snelgrove, Daniel O. B. Jones, Malcolm R. Clark, Jeroen Ingels, Roberto Danovaro, Craig R. McClain, Yutaka Michida (co-lead member), Eric Okuku (lead member) and Jingwen Zhang.

Key points

- Despite improvements in understanding abyssal biodiversity, knowledge gaps in abyssal evolution and biogeography, connectivity and biotic responses to natural temporal and anthropogenic change remain. The incomplete knowledge of abyssal systems reflects major challenges in sampling this vast and remote area.
- Abyssal environments support processes underlying deep-sea and global ecosystem functioning and link closely to surface production and pelagic processes.
- Marine carbon dioxide (CO_2) removal and ocean-based carbon interventions may affect abyssal systems directly if deployed on the seafloor or affect pelagic processes that could indirectly result in changes in abyssal ecosystem function.
- Despite knowledge improvements on abyssal biodiversity linked to deep-sea mineral exploration, full assessment of impacts of exploitation on abyssal ecosystems requires further scientific research.

1. Introduction

Abyssal plains refer to the deep-ocean floor between 3000 and 6000 m. Potentially lower alpha biodiversity characterizes abyssal relative to bathyal depths (Rex and Etter, 2010). Yet, given their vastness, abyssal plains likely host similar or more species globally compared to other deep-seafloor habitats. Because most abyssal plains occur beyond national jurisdiction, the diversity and genetic resources they contain fall under the recently adopted Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction,[1] which aims at ensuring the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction. In addition, mineral resource presence and the abyss' potential to help mitigate climate change increase interest in abyssal habitats.

While abyssal environments were briefly described the first *World Ocean Assessment*, a detailed account of abyssal biodiversity was offered in the second *World Ocean Assessment*. Building on these efforts, the present review examines current regional abyssal biodiversity knowledge and how abyssal biodiversity may respond to future changes.

2. Environmental change since the second *World Ocean Assessment*

Changes in the overall status

Ongoing climate change and ocean surface warming will likely carry through to the water column and abyssal depths (Levin and Le Bris, 2015). Models suggest that many abyssal ocean regions will exceed

---

[1] https://www.un.org/bbnjagreement/en.

their historic range of variability over the next decade (Levin and others, 2020). Sutton and others (2024) documented warming at full ocean depth east of New Zealand, driven by ocean heat gradient changes between mid and high latitudes that reduce local flows of deeper and colder sub-Antarctic water masses. These patterns continue at the global level (Johnson and Purkey, 2024). In addition, there is growing recognition that shifting—and often declining—ocean productivity (Bryndum-Buchholz and others, 2019) may be linked to abyssal ecosystems that depend on surface production; these changes, combined with rising temperatures, could affect abyssal biodiversity and ecosystem function (McClain and others, 2012; Smith and others, 2018).

Documenting long-term changes in abyssal communities remains challenging, but some long-term abyssal observations show that climate cycles likely alter communities. At Porcupine Abyssal Plain (48°50′N 16°30′W, 4850 m depth), scavenging amphipod species composition varies with the Atlantic Multi-decadal Oscillation index (Horton and others, 2020) and at Station M (34°50′N, 123° 00′W, 4100 m depth) off the California coast, megafaunal variation may link to heat anomalies (Kuhnz and others, 2020). Climate-driven changes in organic matter supply explain some changes in seafloor oxygen consumption (Smith and others, 2018), feeding activity (Durden and others, 2020) and benthic community structure and standing stocks (Horton and others, 2020; Kuhnz and others, 2020). Increased data resolution shows episodic carbon fluxes vary more temporally than thought (Huffard and others, 2020), while deep-sea fossil records over longer time scales indicate reorganization of deep-sea benthic communities with climatic changes such as reduced deep-water formation and changes in temperature and particulate organ carbon flux (e.g. Cronin and others, 1996; Yasuhara and others, 2014; Yasuhara and others, 2025).

Historically, most direct human-induced pressures (e.g. trawling, hydrocarbon drilling) have been focused on shelf and bathyal depths (Glover and Smith, 2003), but anthropogenic alterations are deepening (Ramirez-Llodra and others, 2011). Recent studies document organic pollution and microplastics at abyssal depths and deeper (Jamieson and others, 2017; Abel and others, 2021; Nakajima and others, 2021). Some argue that the greening of global society will require advancing blue economy initiatives, such as exploitation of abyssal mineral resources and marine CO_2 removal and ocean-based carbon interventions (see below).

Understanding potential impacts from deep-sea mineral exploitation activities on abyssal habitats and their biodiversity has improved following extensive baseline surveys and experimental studies in the abyssal Clarion-Clipperton Zone in the Pacific Ocean (Muñoz-Royo and others, 2021; Muñoz-Royo and others, 2022; Jones and others, 2025). Trials of polymetallic nodule collectors in the Clarion-Clipperton Zone spurred scientific monitoring (e.g. Gazis and others, 2025) that identified limited impacts on densities and diversity inside test tracks against a background of substantial spatial and potential temporal variation (Lefaible and others, 2024). Gravity flow may dominate benthic sediment plumes, limiting their extent compared with previous predictions (Muñoz-Royo and others, 2022). Despite limited information on the ecological and biological effects of suspended sediment concentrations in abyssal environments (Hauton and others, 2017), multiple stress responses may occur (Stenvers and others, 2023). Effects on community structure (Simon-Lledó and others, 2019a), functioning (de Jonge and others, 2020; Vonnahme and others, 2020) and ecosystem services (Orcutt and others, 2020) may persist for decades (Jones and others, 2025). The timescales of recovery and species-specific responses remain an important knowledge gap and require realistic mining tests and comprehensive monitoring (e.g. Lefaible and others, 2024). Anticipated impacts of chemical toxicity, noise and light related to deep-sea mineral exploitation are equally poorly documented

(Williams and others, 2022). Developing restoration capacity in deep-sea and abyssal ecosystems, an area of active research (Danovaro and others, 2021), will draw on proposed novel technologies (Aguzzi and others, 2024).

Effects of change and interaction with other components of the abyssal marine system

Marine CO_2 removal and ocean-based carbon interventions incorporate diverse potential approaches, including artificial iron fertilization, which will likely change the quantity and quality of carbon flux to the abyss (Keller and others, 2018). A fossil study shows that not only warming but also changes in dust flux and resulting iron fertilization alter deep-sea ecosystems (Yasuhara and others, 2025). Some deep-ocean carbon technologies may directly alter abyssal communities, indicated in small-scale experiments (Barry and others, 2013) and natural analogue studies of organic falls (Amon and others, 2017; Harbour and others, 2021). Precautionary management of marine CO_2 removal and ocean-based carbon interventions should also consider potential second-order effects on abyssal seafloor systems and often-overlooked interactions and feedback between carbon reservoirs (Keller and others, 2018). Importantly, even if these climate mitigations stabilize global temperatures, climate trends and changes in global ocean circulation and shallow-water and deep-sea marine systems may continue (e.g. Sigmond and others, 2020).

3. Region-specific changes in benthic biodiversity knowledge

Arctic Ocean

A recent synthesis revealed high diversity of deep Arctic geomorphological features and a paucity of biodiversity data in deep basins (Ramirez-Llodra and others, 2024). Abyssal Arctic fauna is highly sensitive to sea ice melt and the resulting enhanced algal bloom and flux (Boetius and others, 2013). Ongoing projects are investigating the Arctic seafloor response to changing ice conditions[2] to identify changes at species and community levels but also in functional characteristics across the abyssal Arctic Ocean. Biogeographic distribution information over large spatial scales merits further investigation.

Baltic Sea, Northeast Atlantic Ocean, Mediterranean Sea

The Baltic Sea does not reach abyssal depths and the Mediterranean Sea's abyss (Calypso Deep, Ionian Sea) remains poorly investigated. Hence, the focus is on comparatively well-described and studied Northeast Atlantic Ocean abyssal systems, including newly discovered rocky habitats and biodiversity (Riehl and others, 2020). Integrated taxonomic study demonstrates the importance of knowledge on habitat heterogeneity for inferring large-scale biodiversity patterns (e.g. Schmidt and others, 2024). Understanding of deep-water mass properties and how they influence biodiversity and biogeography of Northeast Atlantic abyssal ecosystems has improved, including the role climatic changes play in these processes (Puerta and others, 2020). Improved understanding of deep-sea change critically requires abyssal temporal observations. Despite the fact that there are only a few deep-sea long-term monitoring stations, those that exist have provided crucial information. These stations include Porcupine Abyssal Plain in the Northeast Atlantic, operational since the mid-1980s (Horton and others, 2020). Recent insights from Porcupine Abyssal Plain highlight regional oxygen differences over decadal time scales (Ruhl and others, 2024). Although funding cuts threaten these time series, assessing long-term abyssal ecosystem changes requires extended temporal observations. Paleoecological data from deep-sea sediment cores such as the International Ocean Discovery

---

[2] See www.arctic.ac.uk.

Programme provide historical biodiversity time-series spanning much longer durations (e.g. tens of thousands to millions of years (Yasuhara and others, 2008; Thomas and Gooday, 1996)) and causally link deep-sea diversity to deep-sea temperature (Doi and others, 2021) as an important driver of abyssal biodiversity. A better understanding of abyssal biodiversity dynamics and its drivers will require more scientific effort.

South Atlantic Ocean and the wider Caribbean

Bridges and others (2023) recently emphasized the paucity of recent abyssal biodiversity studies in the Central and South Atlantic region. Shallow coastal studies dominate Caribbean Sea biodiversity research. The scarce available information shows some regional megafauna variation in the Caribbean abyss (Briggs and others, 1996) and reduced biodiversity in the continental rise-abyssal zone relative to slope depths (Hernández-Ávila and others, 2018).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf, Strait of Malacca and South China Sea

Noting that the Gulf of Aden, the Persian Gulf and the Strait of Malacca do not reach abyssal depths and the limited Red Sea abyssal areas, these seas are omitted here and the focus is on the Indian Ocean (including the Bay of Bengal) and the South China Sea.

Despite some abyssal Indian Ocean biodiversity records in the Ocean Biodiversity Information System (Thomas and others, 2024) data remains very limited (Saraswat and others, 2022). The presence of deep-sea minerals motivated Indian-led abyssal research since the 1980s, but efforts have slowed, reinforcing a need for wider Indian Ocean biodiversity research.

In the deep South China Sea, biodiverse communities on large plastic debris dumps demonstrate plastics as habitats for deep-sea epibenthos (Song and others, 2021). South China Sea biodiversity knowledge generally remains limited for abyssal depths (Ng and Tan, 2000; Liu, 2013). Deep-sea biological investigations in the South China Sea in the last decade have emphasized bathyal cold seep habitats (e.g. Wang and others, 2022).

North Pacific Ocean

Since the publication of the second *World Ocean Assessment*, considerable new abyssal knowledge has accrued for the North Pacific Ocean, in particular the Clarion-Clipperton Zone with its abyssal polymetallic nodule fields. Higher species richness may characterize some Clarion-Clipperton Zone fauna compared to other abyssal habitats (Stewart and others, 2023). Regional Clarion-Clipperton Zone animal species richness is estimated at 6,000 to over 8,000, 88% to 92% of which are undescribed (Rabone and others, 2023). Although experts describe new abyssal species each year (Rabone and others, 2023) and target new geographic locations (Bribiesca-Contreras and others, 2022), limited taxonomic expertise constrains descriptions of new species. Regional-scale syntheses have enabled better understanding of biodiversity and identified knowledge gaps and standardization issues (e.g. Wear and others, 2021; Hauquier and others, 2019; Smith and others, 2021; Stewart and others, 2023; Simon-Lledó and others, 2023a). Findings include linking basin-scale productivity gradients and a major biogeographic discontinuity related to the carbonate compensation depth (Simon-Lledó and others, 2023a). High environmental heterogeneity characterizes abyssal environments (Washburn and others, 2021), noting the role of topography (Simon-Lledó and others, 2019a), substratum (Francesca and others, 2021; Simon-Lledó and others, 2019b), episodic food supply (Simon-Lledó and others, 2023b) and ecosystem engineers (Danovaro and others, 2024; Quintanilla and others, 2022).

Despite increasing studies of abyssal connectivity, understanding remains limited and inconsistent among faunal groups (Taylor and Roterman, 2017), an important gap in the context of potential deep-sea mineral exploitation. Most abyssal studies note the high proportion of rarely sampled species (McClain, 2021), but population genetic studies at multiple locations suggest well-connected populations over broad regions (Stewart and others, 2023; Taboada and others, 2018). At the global scale, biogeophysical environments broadly define deep-sea biogeographic provinces (Watling and others, 2013; Maureaud and others, 2023), although Watling and Lapointe (2022) found weaker support using lower bathyal data for anthozoans. Brandt and others (2019) noted that the hadal Kuril Kamchatka trench potentially limited connectivity and created faunal discontinuities in some abyssal faunal groups in the northwest Pacific Ocean.

South Pacific Ocean

Outside areas of mineral resource interest, few studies have addressed South Pacific abyssal environments. However, in 2024, the Ocean Census Programme sampled the Bounty Trough east of New Zealand to 5000 m depth, focusing on biodiversity discovery (Mills and others, 2024) and documented numerous new species and extended many distributional records.

The Hunga Tonga-Hunga Ha'apai eruption off Tonga in 2022, among the largest in recent history (Proud and others, 2022; Seabrook and others, 2023), catalysed several scientific voyages to map changes in topography and faunal communities. Few epifauna and macro-infauna survived the ash that blanketed hydrothermal vent fields more than 80 km from the volcano (Beinart and others, 2024) and adjacent abyssal plains, except where topographic highs such as knolls and hills provided shelter from direct sediment flows (Mackay and others, 2022; Seabrook and others, 2023). Surveys from 2024 and 2025 are investigating the recovery of benthic communities from this eruption. In addition, efforts to map and prioritize hydrothermal vent ecosystem protection at a global scale continue (Menini and others, 2023).

Southern Ocean

Noting limited advances in knowledge regarding biodiversity and biogeography on Southern Ocean abyssal plains, researchers nonetheless report new species and habitats. Sampling of a Ross Sea seamount at 3,380 m depth revealed seven new species (Lörz and others, 2023). Numerous hydrothermal vents reported from the South Sandwich Arc in the Southern Ocean (Linse and others, 2022) lack characteristic vent or seep megafauna, although taxa in the vicinity varied greatly.

4. Implications for achieving the targets of the 2030 Agenda for Sustainable Development and its Sustainable Development Goals

Society must determine the appropriate balance between economic and socioclimatic gains and the environmental consequences of human activities, including deep-sea mineral exploitation and marine CO_2 removal.

Long-term research of abyssal ecosystems demonstrates community responses to temporal changes in organic carbon flux, underscoring their critical role in global ocean processes. The increase in environmental baseline studies — particularly in the context of mineral exploration in the Clarion-

Clipperton Zone, the Central Indian basin and the Northwest Pacific Ocean — has accelerated abyssal taxonomic and ecological research, as reflected in a stock-taking report on the contribution of the International Seabed Authority (ISA) to the scientific objectives of the United Nations Decade of Ocean Science for Sustainable Development. However, the need for biological research, environmental monitoring and evidence-based decision-making to guide sustainable management and conservation of these ecosystems remains, reflecting requirements described under the United Nations Convention on the Law of the Sea and the regulatory mandate of ISA.

5. Key remaining knowledge and capacity gaps and new gaps

Despite increased biological sampling in areas of interest for mineral resources, considerable knowledge gaps remain (Amon and others, 2022). These gaps include understanding of trophic relationships, life histories, population and ecosystem connectivity and natural temporal variability of communities. Roest and others (2024) prioritized ecosystem-level functioning as a key management focus, recognizing the impracticality of obtaining detailed species-level data.

Key knowledge gaps include:

- A global paucity of abyssal biodiversity knowledge, particularly for hard-bottom habitats;
- Knowledge of species geographic ranges, connectivity patterns and resilience of assemblages to climate stressors and human activities in the abyss;
- Emerging geoengineering technologies may present new opportunities to combat global change, yet may also pose risks of impact to abyssal ecosystems. Sustained monitoring, fundamental ecological research and evidence-based governance are needed.

References

Abel, Serena M., and others (2021). Systematic identification of microplastics in abyssal and hadal sediments of the Kuril Kamchatka trench. Environmental Pollution, vol. 269, art. 116095.

Aguzzi, Jacopo, and others (2024). New Technologies for Monitoring and Upscaling Marine Ecosystem Restoration in Deep-Sea Environments. Engineering, vol. 34, pp. 195–211.

Amon, Diva J., and others (2022). Assessment of scientific gaps related to the effective environmental management of deep-seabed mining. Marine Policy, vol. 138, art. 105006.

Barry, James P., and others (2013). The response of abyssal organisms to low pH conditions during a series of CO2-release experiments simulating deep-sea carbon sequestration. Deep Sea Research Part II: Topical Studies in Oceanography, vol. 92, pp. 249–260.

Beinart, Roxanne A., and others (2024). Deep seafloor hydrothermal vent communities buried by volcanic ash from the 2022 Hunga eruption. Communications Earth & Environment, vol. 5, No. 1, art. 254.

Boetius, Antje, and others (2013). Export of Algal Biomass from the Melting Arctic Sea Ice. Science, vol. 339, No. 6126, pp. 1430–1432.

Brandt, Angelika, and others (2019). Biodiversity and biogeography of the abyssal and hadal Kuril-Kamchatka Trench and adjacent NW Pacific deep-sea regions. Progress in Oceanography, vol. 181, art. 102232.

Bribiesca-Contreras, Guadalupe, and others (2022). Benthic megafauna of the western Clarion-Clipperton Zone, Pacific Ocean. Zookeys, vol. 1113, pp. 1–110.

Bridges, Amelia, and others (2023). Review of the Central and South Atlantic Shelf and Deep-Sea Benthos: Science, Policy, and Management. Oceanography and Marine Biology: An Annual Review, vol. 61, pp. 127–218.

Briggs, Kevin B., and others (1996). The classification and structure of megafaunal assemblages in the Venezuela Basin, Caribbean Sea. Journal of Marine Research, vol. 54, pp. 705–730.

Bryndum-Buchholz, Andrea, and others (2019). Twenty-first-century climate change impacts on marine animal biomass and ecosystem structure across ocean basins. Global Change Biology, vol. 25, No. 2, pp. 459–472.

Cronin, Tom, and others (1996). Pliocene (3.2-2.4 Ma) ostracode faunal cycles and deep ocean circulation, North Atlantic Ocean. Geology, vol. 24, No. 8, pp. 695–698.

Danovaro, Roberto, and others (2021). Marine ecosystem restoration in a changing ocean. Restoration Ecology, vol. 29, No. S2, art. e13432.

Danovaro, Roberto, and others (2024). Microbes as marine habitat formers and ecosystem engineers. Nature Ecology & Evolution, vol. 8, No. 8, pp. 1407–1419.

De Jonge, Daniëlle S.W., and others (2020). Abyssal food-web model indicates faunal carbon flow recovery and impaired microbial loop 26 years after a sediment disturbance experiment. Progress in Oceanography, vol. 189, art. 102446.

Doi, Hideyuki, and others (2021). Causal analysis of the temperature impact on deep-sea biodiversity. Biology Letters, vol. 17, No. 7, art. 20200666.

Durden, Jennifer M., and others (2020). Response of deep-sea deposit-feeders to detrital inputs: A comparison of two abyssal time-series sites. Deep Sea Research Part II: Topical Studies in Oceanography, vol. 173, art. 104677.

Francesca, Pasotti, and others (2021). A local scale analysis of manganese nodules influence on the Clarion-Clipperton Fracture Zone macrobenthos. Deep Sea Research Part I: Oceanographic Research Papers, vol. 168, art. 103449.

Gazis, Iason-Zois, and others (2025). Monitoring benthic plumes, sediment redeposition and seafloor imprints caused by deep-sea polymetallic nodule mining. Nature Communications, vol. 16, No. 1, art. 1229.

Glover, Adrian G., and Smith, Craig R. (2003). The deep-sea floor ecosystem: current status and prospects of anthropogenic change by the year 2025. Environmental Conservation, vol. 30, No. 3, pp. 219–241.

Harbour, Rob P., and others (2021). Biodiversity, community structure and ecosystem function on kelp and wood falls in the Norwegian deep sea. Marine Ecology Progress Series, vol. 657, pp. 73–91.

Hauquier, Frejia, and others (2019). Distribution of free-living marine nematodes in the Clarion–Clipperton Zone: implications for future deep-sea mining scenarios. Biogeosciences, vol. 16, No. 18, pp. 3475–3489.

Hauton, Chris, and others (2017). Identifying Toxic Impacts of Metals Potentially Released during Deep-Sea Mining—A Synthesis of the Challenges to Quantifying Risk. Frontiers in Marine Science, vol. 4.

Hernández-Ávila, Iván, and others (2018). Variation in species diversity of deep-water megafauna assemblages in the Caribbean across depth and ecoregions. PLoS One, vol. 13, No. 8, art. e0201269.

Horton, Tammy, and others (2020). Are abyssal scavenging amphipod assemblages linked to climate cycles? Progress in Oceanography, vol. 184, art. 102318.

Huffard, Christine L., and others (2020). Temporally-resolved mechanisms of deep-ocean particle flux and impact on the seafloor carbon cycle in the northeast Pacific. Deep Sea Research Part II: Topical Studies in Oceanography, vol. 173, art. 104763.

Jamieson, Alan J., and others (2017). Bioaccumulation of persistent organic pollutants in the deepest ocean fauna. Nature Ecology & Evolution, vol. 1, No. 3, art. 0051.

Johnson, Gregory C., and Purkey, Sarah G. (2024). Refined Estimates of Global Ocean Deep and Abyssal Decadal Warming Trends. Geophysical Research Letters, vol. 51, No. 18, art. e2024GL111229.

Jones, Daniel O. B., and others (2025). Long-term impact and biological recovery in a deep-sea mining track. Nature, vol. 642, No. 8066, pp. 112–118.

Keller, David P., and others (2018). The Effects of Carbon Dioxide Removal on the Carbon Cycle. Current Climate Change Reports, vol. 4, No. 3, pp. 250–265.

Kuhnz, Linda, and others (2020). Benthic megafauna assemblage change over three decades in the abyss: Variations from species to functional groups. Deep Sea Research Part II Topical Studies in Oceanography, vol. 173, art. 104761.

Lefaible, Nene, and others (2024). Industrial mining trial for polymetallic nodules in the Clarion-Clipperton Zone indicates complex and variable disturbances of meiofaunal communities. Frontiers in Marine Science, vol. 11.

Levin, Lisa A., Amon, Diva J., and Lily, Hannah (2020). Challenges to the sustainability of deep-seabed mining. Nature Sustainability, vol. 3, No. 10, pp. 784–794.

Levin, Lisa A., and Le Bris, Nadine (2015). The deep ocean under climate change. Science, vol. 350, No. 6262, pp. 766–768.

Linse, Katrin, and others (2022). Megabenthos habitats influenced by nearby hydrothermal activity on the Sandwich Plate, Southern Ocean. Deep Sea Research Part II: Topical Studies in Oceanography, vol. 198, art. 105075.

Liu, J. Y. (2013). Status of marine biodiversity of the China seas. PLoS One, vol. 8, No. 1, art. e50719.

Lörz, Anne-Nina, and others (2023). Multi-ocean distribution of a brooding predator in the abyssal benthos. Scientific Reports, vol. 13, No. 1, art. 15867.

Mackay, Kevin, and others (2023). Environmental impacts of the 2022 eruption of Hunga Tonga-Hunga Ha'apai: voyage report of part 1 of the TesMAP survey of the region in April-May 2022 (TAN2206). Wellington: National Institute of Water and Atmospheric Research Ltd..

Maureaud, Aurore A., and others (2023). A global biogeographic regionalization of the benthic ocean. OSF Preprints.

McClain, Craig R. (2021). The commonness of rarity in a deep-sea taxon. Oikos, vol. 130, No. 6, pp. 863–878.

McClain, Craig R., and others (2012). Energetics of life on the deep seafloor. Proceedings of the National Academy of Sciences, vol. 109, No. 38, pp. 15366–15371.

Menini, Elisabetta, and others (2023). Towards a global strategy for the conservation of deep-sea active hydrothermal vents. npj Ocean Sustainability, vol. 2, No. 1, art. 22.

Mills, Sadie, and others (2024). Ocean Census Bounty Trough: voyage report of the TAN2402 survey in February 2024. NIWA Client Report No. 2024098WN.

Muñoz-Royo, Carlos, and others. An in situ study of abyssal turbidity-current sediment plumes generated by a deep seabed polymetallic nodule mining preprototype collector vehicle. Science Advances, vol. 8, No. 38, art. eabn1219, 2022.

Muñoz-Royo, Carlos, and others. Extent of impact of deep-sea nodule mining midwater plumes is influenced by sediment loading, turbulence and thresholds. Communications Earth & Environment, vol. 2, No. 1, pp. 148, 2021.

Nakajima, Ryota, and others (2021). Massive occurrence of benthic plastic debris at the abyssal seafloor beneath the Kuroshio Extension, the North West Pacific. Marine Pollution Bulletin, vol. 166, art. 112188.

Ng, Peter K.L., and Tan, K.S. (2000). The state of marine biodiversity in the South China Sea. The Raffles Bulletin of Zoology, vol. 48, No. 8, pp. 3–7.

Orcutt, Beth N., and others (2020). Impacts of deep-sea mining on microbial ecosystem services. Limnology and Oceanography, vol. 65, No. 7, pp. 1489–1510.

Proud, Simon R., and others (2022). The January 2022 eruption of Hunga Tonga-Hunga Ha'apai volcano reached the mesosphere. Science, vol. 378, No. 6619, pp. 554–557.

Puerta, Patricia, and others (2020). Influence of water masses on the biodiversity and biogeography of deep-sea benthic ecosystems in the North Atlantic. Frontiers in Marine Science, vol. 7, art. 239.

Quintanilla, Elena, and others (2022). Microbial Associations of Abyssal Gorgonians and Anemones (>4,000 m Depth) at the Clarion-Clipperton Fracture Zone. Frontiers in Microbiology, vol. 13.

Rabone, Muriel, and others (2023). How many metazoan species live in the world's largest mineral exploration region? Current Biology, vol. 33, No. 12, pp. 2383–2396.e5.

Ramirez-Llodra, Eva, and others (2011). Man and the last great wilderness: human impact on the deep sea. PLoS One, vol. 6, No. 8, art. e22588.

Rex, Michael A., and Etter, Ron K. (2010). Deep-Sea Biodiversity: Pattern and Scale. Cambridge: Harvard University Press.

Riehl, Torben, and others (2020). Discovery of widely available abyssal rock patches reveals overlooked habitat type and prompts rethinking deep-sea biodiversity. Proceedings of the National Academy of Sciences, vol. 117, No. 27, pp. 15450–15459.

Roest, Walter R, and others (2024). The scientific challenges of deep-sea mining. In Routledge Handbook of Seabed Mining and the Law of the Sea, Campanella, Virginie T., ed. New York, Routledge.

Saraswat, Rajeev, and others (2022). Editorial: Benthic Biodiversity of the Indian Ocean. Frontiers in Marine Science, vol. 9.

Schmidt, Lydia A., and others (2024). Unveiling ophiuroid biodiversity across North Atlantic habitats via an integrative perspective. Scientific Reports, vol. 14, No. 1, art. 20405.

Seabrook, Sarah, and others (2023). Volcaniclastic density currents explain widespread and diverse seafloor impacts of the 2022 Hunga Volcano eruption. Nature Communications, vol. 14, No. 1, art. 7881.

Sigmond, Michael, and others (2020). Ongoing AMOC and related sea-level and temperature changes after achieving the Paris targets. Nature Climate Change, vol. 10, No. 7, pp. 672–677.

Simon-Lledó, Erik, and others (2023a). Carbonate compensation depth drives abyssal biogeography in the northeast Pacific. Nature Ecology & Evolution, vol. 7, No. 9, pp. 1388–1397.

Simon-Lledó, Erik, and others (2023b). Mass falls of crustacean carcasses link surface waters and the deep seafloor. Ecology, vol. 104, No. 2, pp. e3898.

Simon-Lledó, Erik, and others (2019a). Megafaunal variation in the abyssal landscape of the Clarion Clipperton Zone. Progress in Oceanography, vol. 170, pp. 119–133.

Simon-Lledó, Erik, and others (2019b). Ecology of a polymetallic nodule occurrence gradient: Implications for deep-sea mining. Limnology and Oceanography, vol. 64, No. 5, pp. 1883–1894.

Smith, Craig, and others (2021). Editorial: Biodiversity, Connectivity and Ecosystem Function Across the Clarion-Clipperton Zone: A Regional Synthesis for an Area Targeted for Nodule Mining. Frontiers in Marine Science, vol. 8, art. 797516.

Smith, Kenneth L., and others (2018). Episodic organic carbon fluxes from surface ocean to abyssal depths during long-term monitoring in NE Pacific. Proceedings of the National Academy of Sciences, vol. 115, No. 48, pp. 12235–12240.

Song, Xikun, and others (2021). Large Plastic Debris Dumps: New Biodiversity Hot Spots Emerging on the Deep-Sea Floor. Environmental Science & Technology Letters, vol. 8, No. 2, pp. 148–154.

Stenvers, Vanessa I., and others (2023). Experimental mining plumes and ocean warming trigger stress in a deep pelagic jellyfish. Nature Communications, vol. 14, No. 1, art. 7352.

Stewart, Eva C.D., and others (2023). Biodiversity, biogeography, and connectivity of polychaetes in the world's largest marine minerals exploration frontier. Diversity and Distributions, vol. 29, No. 6, pp. 727–747.

Sutton, Philip J. H., and others (2024). Southwest Pacific Ocean Warming Driven by Circulation Changes. Geophysical Research Letters, vol. 51, No. 13, art. e2024GL109174.

Taboada, Sergi, and others (2018). Implications of population connectivity studies for the design of marine protected areas in the deep sea: An example of a demosponge from the Clarion-Clipperton Zone. Molecular Ecology, vol. 27, No. 23, pp. 4657–4679.

Taylor, Michelle L., and Roterman, C. N. (2017). Invertebrate population genetics across Earth's largest habitat: The deep-sea floor. Molecular Ecology, vol. 26, No. 19, pp. 4872–4896.

Thomas, Ellen, and Gooday, Andrew J. (1996). Cenozoic deep-sea benthic foraminifers: Tracers for changes in oceanic productivity? Geology, vol. 24, No. 4, pp. 355–358.

Thomas, E.A., Bond, T., Kolbusz, J.L., Niyazi, Y., Swanborn, D.J.B. and Jamieson, A.J., (2024). Deep-sea ecosystems of the Indian Ocean >1000 m. Science of The Total Environment, 957: 176794.

Vonnahme, Tobias R., and others (2020). Effects of a deep-sea mining experiment on seafloor microbial communities and functions after 26 years. Science Advances, vol. 6, No. 18, art. eaaz5922.

Wang, Xudong, and others (2022). Macro-ecology of cold seeps in the South China Sea. Geosystems and Geoenvironment, vol. 1, No. 3, art. 100081.

Washburn, Travis W., and others (2021). Environmental Heterogeneity Throughout the Clarion-Clipperton Zone and the Potential Representativity of the APEI Network. Frontiers in Marine Science, vol. 8, No. 319, art. 661685.

Watling, Les, and others (2013). A proposed biogeography of the deep ocean floor. Progress in Oceanography, vol. 111, pp. 91–112.

Watling, Les, and Lapointe, Abby (2022). Global biogeography of the lower bathyal (700–3000 m) as determined from the distributions of cnidarian anthozoans. Deep Sea Research Part I: Oceanographic Research Papers, vol. 181, art. 103703.

Wear, Emma, and others (2021). Bacterial and Archaeal Communities in Polymetallic Nodules, Sediments, and Bottom Waters of the Abyssal Clarion-Clipperton Zone: Emerging Patterns and Future Monitoring Considerations. Frontiers in Marine Science, vol. 8, art. 480.

Williams, Rob, and others (2022). Noise from deep-sea mining may span vast ocean areas. Science, vol. 377, No. 6602, pp. 157–158.

Yasuhara, Moriaki, and others (2008). Abrupt climate change and collapse of deep-sea ecosystems. Proceedings of the National Academy of Sciences, vol. 105, No. 5, pp. 1556–1560.

Yasuhara, Moriaki, and others (2025). Climatic forcing of the Southern Ocean deep-sea ecosystem. Current Biology, vol. 35, No. 2, pp. 347–353.e1.

Yasuhara, Moriaki, and others (2014). Response of deep-sea biodiversity to abrupt deglacial and Holocene climate changes in the North Atlantic Ocean. Global Ecology and Biogeography, vol. 23, No. 9, pp. 957–967.