Section 4

Subchapter 5P

Hydrothermal vents and cold seeps

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Key points

- Discovery of new sites, novel habitats, new species and new chemosynthetic symbioses continues at a rapid pace for vents and seeps.
- Pressures are growing from climate change, fisheries and seabed mining, but protection for vents and seeps remains limited.
- New recognition, quantification and valuation of critical ecosystem services provided by vents and seeps heighten conservation imperatives.
- Inequities remain in knowledge and capacity transfer, particularly for Indigenous Peoples and low- and middle-income countries.

1. Introduction and context

Summary of baseline state provided by the first and second *World Ocean Assessment*

Hydrothermal vents and cold seeps host high microbial and animal biomass supported by chemosynthesis, involving microbe-animal symbioses, and contribute to broader productivity and fisheries in surrounding systems. They occur at mid-ocean ridges, volcanic arcs and hotspot-associated volcanic intraplate and back-arc spreading centres (vents) and on passive continental margins and subduction zones (seeps). Both vents and seeps exhibit high spatial and temporal variability of constraining environmental factors imposing physiological adaptations. Late successional systems including cold-water corals and inactive sulfide communities may persist over centuries. The high levels of endemism provide significant species discovery and provide model systems for understanding adaptation to extreme conditions and critical climate regulating services, as well as biotechnology and biomedical potential (e.g. Bruno and others, 2019).

Technological advances have enabled discovery of thousands of sites in recent decades, as well as development of deep oil, gas and gas hydrate activities (seeps), and new mining exploration contracts (vents) issued in the Atlantic and Indian Oceans. Additional pressures include global warming, deoxygenation, ocean acidification and altered circulation, deep-sea fishing, waste dumping and plastic debris. There is growing recognition of the need for vent and seep protection. Conservation actions to date include scientific and industry codes of conduct, protected areas and International Union for the Conservation of Nature and Natural Resources Red List designations (Le Bris and others, 2017, 2021).

Scope of the coverage

Recent regional exploration and discovery of vents and seeps are synthesized below, as well as key advances in knowledge and understanding of processes and threats, description of environmental change, social implications and knowledge and capacity gaps.

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

Changes in the overall status

Climate change

Rising ocean temperatures (see sect. 4, chap. 3) caused past gas hydrate destabilization (El bani Altuna and others, 2021). The flux of methane from seabed seeps to the atmosphere is increasing in the Arctic and Antarctic (Workman and others, 2024). In a warming ocean, present-day connectivity pathways may be disrupted due to shorter larval duration (thus smaller dispersal distance) and vertical position shifts (Rakka and others, 2021), changing current patterns (magnitude or direction) (Levin and others, 2020) or loss of suitable habitat (Morato and others, 2020).

Resource exploration and exploitation

Intense research occurs at some vent sites with likely impacts (Juniper and others, 2019). Recovery from a small, induced disturbance at a Mid-Atlantic Ridge vent found altered community structure after two years, with implications for deep-sea mining (Marticorena and others, 2021). As of 2024, ISA has signed seven exploration contracts for vent deposits in the Atlantic and Pacific Oceans (see subsect. 5A, chap. 7). Exploration licenses are active in Japan, Tonga and Papua New Guinea, while Norway has initiated approvals. Exploitation of active vents may cause losses of species, functions and connectivity (Alfaro-Lucas and others, 2024; Tunnicliffe and others, 2024) while knowledge of the ecological value of inactive/extinct sulphides is limited (Van Dover and others, 2020). Offshore oil and gas development continues (see subsect. 5A, subchap. 3B), likely affecting associated methane seeps.

Bottom trawling (see subsect. 5A, subchap. 1C) exerts pressure on cold seep faunas as commercial species often congregate near seeps (e.g. Sen and others, 2019; Turner and others, 2020). Foundation species were reduced at New Zealand seeps (Jones, 2023) and trawl nets were tangled on carbonates on the Canadian Pacific Margin (DFO, 2018). In Norway, broken carbonates and trawl marks had limited recolonization (Bellec and others, 2024). Hydrocarbon exploration on continental margins (see subsect. 5A, subchap. 3B) has located methane seep communities (e.g. Dueñas and others, 2021; Bravo and others, 2024). Extraction will likely diminish the methane supply that fuels chemosynthesis as observed by Boles and others (2023).

Factors contributing to the change observed

The changes are driven by rising populations and industry development increasing fishing pressure (see subsect. 5A, subchap. 1C), energy demand (see subsect. 5A, subchap. 3B) and emissions (causing warming) (see sect. 4, chap. 3), as well as rising metal demand and geostrategic contexts (see subsect. 5A, chap. 7), in part for electrification of transport.

Impacts and interactions of the change with other marine system components

Discoveries of large nursery areas of deep-sea species near vents and seeps (e.g. Barry and others, 2023) suggest that changes in these systems can influence recruitment to non-vent species, including from higher trophic levels.

Social, economic and cultural aspects associated with the change (since the second *World Ocean Assessment*)

As potential exploitation draws closer, societal awareness is growing, often with strong disagreements with State or ISA actions (e.g. van Putten and others, 2023; Gilbert, 2024). Mining at vents may intersect with sites of cultural heritage significance (Turner and others, 2020) (see subsect. 5B, chap. 5).

Implications for the 2030 Agenda for Sustainable Development and for the 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

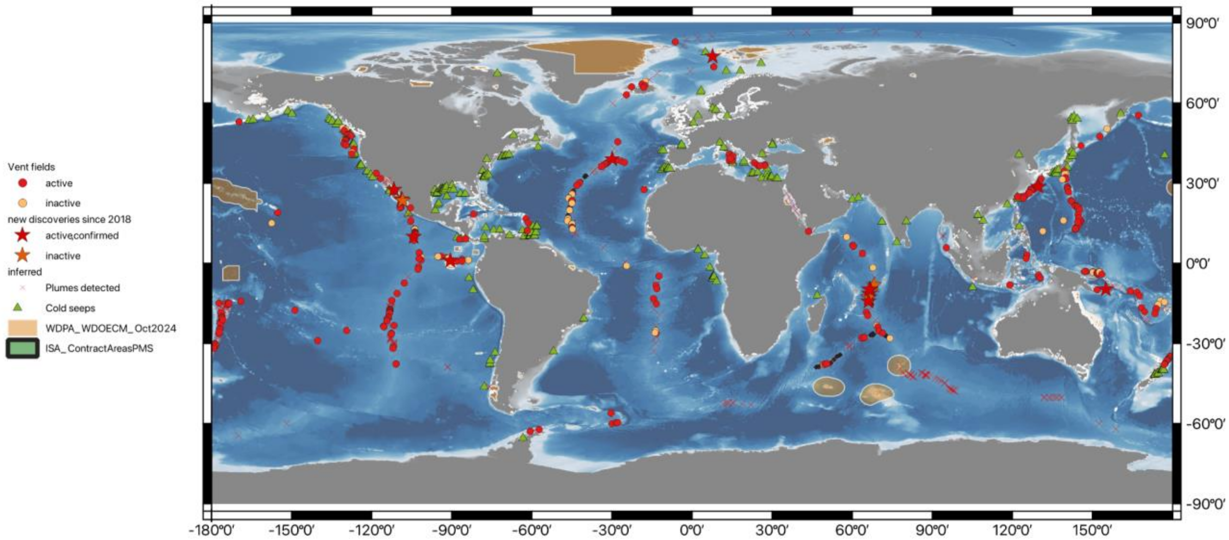
Protection supports Sustainable Development Goal 14 through sustainable management (target 14.2) and strengthening resilience using marine protection areas (MPAs) (Target 14.5). ISA (ISBA/27/C/8) declares support for Goal 14 through its regulatory framework for seabed mining, which requires trade-offs with Goal 7 (energy) and Goal 8 (industry). A draft regional environmental management plan (ISBA/27/C/38) reflects target 14.2 by classifying active hydrothermal vents as needing protection. Current mining code development aims to prevent environmental harm while mining in vent areas. Protection of vents and seeps, plus the ecosystem functions and services they provide, can help meet the Kunming-Montreal Global Biodiversity Framework targets. For the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction all four components are relevant.

3. Region-specific changes: new discoveries and new pressures

The figure below depicts previously known and recently discovered (since 2018) deep vents and seeps.

Figure

Global map of confirmed active (red symbols) or reported inactive vent fields (orange symbols) and cold seeps (green triangles); for vents, stars denote vent fields discovered in 2018-2024. Brown polygons represent designated marine protected areas.



Source: Vent field locations are from the InterRidge Vent Database (Beaulieu and Szanfranski 2020) completed by recent references (Zhou and others, 2018; Soule and others, 2018; Paduan and others, 2019; Ryu and others, 2019; Jang and others, 2023, Boulart and others, 2022; McDermott and others, 2022; Borhrman and others, 2022; Zhou and others, 2022; Chen and others, 2024; Dang and others, 2024; Lecoeuvre and others, 2021). Seep site data listed in the Biogeography of Deep-Water Chemosynthetic Ecosystems Database (ChEssBase, 2019) were completed from other inventories (Olu and others, 2010; Quattrini and others, 2015; Baumberger and others, 2018; Feng and others, 2018; Etiope and others, 2019; McDonald and others, 2020; Aguillar and others, 2024).

Note: MPAs are taken from Protected Planet: The World Database on Protected Areas and World Database on Other Effective Area-based Conservation Measures: UNEP-WCMC and IUCN (2024) (Available at: www.protectedplanet.net. Bathymetry is the GEBCO One Minute Grid map from https://www.gebco.net/data_and_products/gridded_bathymetry_data/.) This map was built using QGIS 2.18.20.

At shallow vents and seeps (less than 200 m; not mapped in the figure), species may coexist alongside photosynthetic algae and seagrass, and have greater exposure to anthropogenic changes including warming, ocean acidification, bottom fishing, pollution, or invasive species (Ramirez-Lodra and others, 2010; Åström and others, 2018). New technologies were increasingly used for analysing deep-sea biota, revealing magnificent vent assemblages (e.g. Gerdes and others, 2021; Ramirez-Llodra and others, 2024; Sun and others, 2020). Vent and seep faunas show heterogeneity linked to depth, surface production, oxygen minimum zones and geology (Seabrook and others, 2024).

Arctic Ocean

First found in the 1990s, cold seep discovery continues in the Arctic (e.g. Waghorn and others, 2022; Sen and others, 2019; Serov and others, 2024), as well as two recently discovered vent fields (Stensland and others, 2019; Sahlström and others, 2023) and many new vent species (Eilertsen and others, 2024) (see sect. 4, subchap. 5O).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

New vents were discovered on the Mid-Atlantic Ridge (Butterfield and others, 2023). Other new vents discovered south of Iceland at the Reykjanes Ridge were noticeably lacking typical vent macrofauna (Taylor and others, 2021). In the northwest Atlantic margin, acoustic imaging revealed approximately

1,139 unique methane flare sites; most are shallower than 400 m, but some extend to 1400 m (Ruppel and others, 2024). A newly discovered squat lobster in the Gulf of Mexico is the first west Atlantic seep endemic (Rodriguez-Flores and others, 2024).

South Atlantic Ocean and wider Caribbean

Seeps in the West Atlantic, the Caribbean and off Colombia are associated with linear diapir systems, salt diapirs resulting from salt tectonics, regions of mud volcanism and compact seafloor mounds; most knowledge is still associated with the oil and gas industry, with limited access to the science community and limited faunal studies (Aguilar Pérez and others, 2024). Argentina's first methane seeps (approximately 500 m) are reported with dense infaunal assemblages (Bravo and others, 2024).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

New discoveries include a rare serpentinite-hosted field (Lecoeuvre and others, 2021) and the first actively diffusing vent system in the Red Sea (Van der Zwan and others, 2023); both host unique microbial communities without typical vent macrofauna. Faunal studies described over 30 new taxa and indicate within-region biogeographic discontinuity (e.g. Jang and others, 2023). Two new seep communities were reported in the northern Indian Ocean with biogeographic affiliations with the West Pacific vent/seep communities (Mazumdar and others, 2019), and a new active cold seep site occurs in the Bay of Bengal (Sangodkar and others, 2023).

North Pacific Ocean

Serpentine-hosted seep communities at mud volcanoes on the Mariana Forearc, where methane-rich fluids are highly alkaline (pH over 12), support many novel species (Chen and others, 2023, 2024a) (see sect. 4, subchap. 5L). New northeast Pacific Ocean vent and seep sites continue to be discovered (Galkin and others, 2019) notably including 1,600 methane flares mapped in the Canadian Pacific (DFO, 2018) and eight new seeps off the coast in Oregon and Washington (Seabrook and others, 2024). Low temperature ridge-flank hydrothermal springs in the northeast Pacific Ocean support deep-sea octopus nurseries (Barry and others, 2023).

South Pacific Ocean and equatorial Pacific Ocean

A newly discovered vent site in the Southwest Pacific may contribute to faunal connectivity (Boulart and others, 2022). Other new vent sites in the Galapagos Rift expand the records of vent species (Chen and others, 2024b).

Southern Ocean

Three new deep-sea vent sites have been reported in the Atlantic region of the Southern Ocean (Bohrmann 2019; Linse and others, 2022). Major new seepage sites in the Ross Sea indicate likely widespread climate-sensitive phenomena around Antarctica (Seabrook and others, 2023).

4. Remaining key knowledge and capacity gaps and new gaps

Advances in technology

Many technological advances have improved understanding of chemosynthetic ecosystems, such as: (i) evolving molecular tools to support systematics and studies of adaptations to extreme environments and genetic connectivity (e.g. Zeng and others, 2020); (ii) photogrammetry methods for 3D reconstructions to aid habitat change studies (e.g. Van Audenhaege and others, 2024); (iii) neural network approaches to image classification (Vega and others, 2024); and, (iv) novel computer algorithms for seep identification (Vrolijk and others, 2021; Ruppel and others, 2024).

Novel habitats and processes

Important new findings include subseafloor vent faunal habitats (Bright and others, 2024) and off-axis hydrothermalism (McDermott and others, 2022, Parsons and others, 2024) and novel chemo-symbioses (Goffredi and others, 2020, 2021) and inactive vent species (Chen and others, 2024a). Microbial processes are implicated in primary productivity at inactive vent deposits (Achberger and others, 2024), in carbon cycling and nutrient export (Versteegh and others, 2023) and in trophic networks in vent communities (Murdock and others, 2021). A comprehensive genomic catalogue of microbes from seeps (Han and others, 2023) enables exploration of functional processes such as biogeochemical cycling.

Dynamics, succession and sphere of influence

Long-term observations and experiments reveal high stability and slow recovery of vent ecosystems in slow-spreading ridges following disturbance (Van Audenhaege and others, 2022, Marticorena and others, 2021). Evidence that vents and seeps affect the ocean outside their perimeters accumulates, such as iron from rising vent plumes inducing phytoplankton blooms in the Southern Ocean (Ardyna and others, 2019) and enhanced faunal abundance on the seafloor (Klunder and others, 2020). At seeps, input from both chemosynthesis and photosynthesis support distinctive infaunal communities in an intermediate zone between methane seeps and background (Ashford and others, 2021).

Stepping stones

Population connectivity could enhance resilience to disturbance. Highly divergent gene flow directions and ranges exist among closely allied vent species (e.g. Breusing and others, 2023; Methou and others, 2024). A novel, but isolated, Arctic vent ecosystem in a region with imminent mineral exploration provides evidence for historical connectivity (Eilertsen and others, 2024). Range analyses divide the Indian Ocean into three vent provinces that suggest separate management areas (Zhou and others, 2022). In the northwest Pacific Ocean, the Okinawa Trough has high endemicity (Brunner and others, 2022) while connectivity along the volcanic arcs appears limited for many species (Giguère and Tunnicliffe, 2021). Most vent species are known only within one limited region; for a few species, the Manus Basin is the key region for cross-equator linkages (Brunner and others, 2022, Tunnicliffe and others, 2024). At both vents and seeps, some widespread species form localized genetic units with rare long-distance dispersal events (Jollivet and others, 2024).

Ecosystem services

Hydrothermal vents provide regulating services such as biogeochemical cycling of manganese, iron and nitrogen and carbon fixation. Provisioning services include marine genetic resources (e.g. Fuelzyme, Bravakos and others, 2021, Giordano, 2020) (see subsect. 5A, chap. 5) and potential metals from mining (see subsect. 5A, chap. 7). Supporting services include nutrient transfers to deep-sea and nursery areas at both active and inactive vents. Cultural values flow from scientific research (e.g. models for extraterrestrial life) and creative inspiration (DOSI, 2023). Cold seeps provide provisioning services through commercial fish/crustacean species and regulating services through carbon sequestration (Le and others, 2022). This new understanding heightens conservation imperatives.

Consequences of environmental impacts, governance challenges, conservation status

About half of known vent sites fall in areas beyond national jurisdiction where many are under mining exploration contracts; regulations on the conservation status of vents within contract areas are under development. Of all other vents, 17% are covered by non-targeted conservation interventions while 8% benefit from vent-specific actions (Menini and others, 2023). For new and updated areas, see the table below. Four southwest Pacific States initially declared a moratorium on deep-sea mining (Melanesian Spearhead Group (MSG) Secretariat, 2020); today 32 States have taken a position against deep-seabed mining in international waters. Thomas and others (2021) find the limited distribution of most vent molluscs is the key vulnerability, with notable extinction threat in mining contract areas. However, regular distribution assessment updates are needed. Conservation is in place for very few cold seeps although many are vulnerable to anthropogenic disturbance and climate change (Le and others, 2022; Bellec and others, 2024). An economic valuation identified highest willingness to pay to conserve Costa Rican seeps with endemic species (Pereira and others, 2024). Governance in the areas beyond national jurisdiction is problematic due to fragmented and variable approaches (Menini and others, 2023), and protections remain limited.

Table
Emerging threats, risks and conservation measures since 2019

Basin	*Threat actions*	*Other risks*	*Conservation measures*	*Citations*
Arctic	Norway approved (but paused in Dec. 2024) exploration for extraction of polymetallic sulphides	Warming waters could bring colonists to seeps and vents northward challenging endemic species		Delivorias, A. 2024. Åström, E.K. and others, 2020
North Atlantic and Mediterranean	Exploration of three ISA contract areas in progress in active vent sites	Bottom contact fishing on shallower vent areas. Marine litter (mostly plastics) in vent habitats from abandoned fishing gear	Luso hydrothermal field MPA in Portugal. ISA considers regional environmental management plan proposal to protect all active vents from mining in contract areas	Governo dos Açores. 2022 ISA, 2022 Consoli, P. and others, 2021

Western tropical Atlantic and Caribbean		Submarine slides caused by methane hydrate destabi-lization in a warming ocean. Lack of literacy and capacity to address impacts		Ruffine, L. and others, 2023 Amon D. and others, 2022
South Atlantic	Oil and gas exploration in deep water continues off Argentina near newly discovered seeps		Ascension Island MPA; (United Kingdom). Covers 750 km of ridge crest with known vent sites	Ascension Island Government, 2021 Bravo M. and others, 2024
Northeast Pacific	Notable climate-induced deoxygenation in the MPA (Ross and others, 2020) may affect shallow vents and larvae	Bottom contact fishing on shallower vent areas. Deep seabed mining could affect vents	Tang.g̱wan-ḥačxwiqak-Tsig̱is MPA now including all confirmed hydrothermal vents in Canada and some methane seeps	Canada Gazette, 2024 Ross, T. and others, 2020
Northwest Pacific		Microplastic accumulation in cold seep animals	Northern part of Central (Naka) Mariana Ridge and West Mariana Ridge MPA, Japan. Includes three vent sites	Teng, J. and others, 2023 Watanabe H.K. and Yamakita T, 2022 Government of Japan, 2020.
Southwest Pacific	Potential renewal of seabed exploitation licence for polymetallic sulphides at Solwara, Manus Basin, Papua New Guinea			Monga Bay, 2024

Indian Ocean	Exploration of four ISA mining contract areas in progress at active vent sites	Microplastic accumulation in vent animals		Park, B. and others, 2024
Global	Seabed mining	Ocean warming and acidification	Assessment of hydro-thermal vent species against the International Union for Conservation of Nature (IUCN) and Natural Resources Red List criteria. Of these, 114 fall into the vulnerable, endangered or critically endangered categories	Thomas, E.A. and others, 2021

Source: Prepared by the writing team

Key remaining knowledge gaps

Many knowledge gaps identified in the second *World Ocean Assessment* (Le Bris and others, 2021) remain, including the distribution, biogeography and connectivity of vent and seep biota, resilience and time and space scales of recovery from disturbance (trawling, mining, climate change) and vent and seep roles in biogeochemical cycles. Capacity gaps are being identified (Bell and others, 2023) and addressed (Johannes and others, 2023), but limited access to funding, research vessels, low-cost instruments and taxonomic expertise remain, creating global inequity. Small island developing States, for example, although often in close proximity, have limited access to hydrothermal vents and seeps. Currently several international programmes offer training opportunities and philanthropic foundations offer some research vessel support.

Newly recognized knowledge gaps

Regional gaps in location of new sites and in novel habitats, functions, symbioses and other mutualistic interactions among species, and genetic resource potential at vents and seeps exist. Additional key gaps include vent-seep-organic fall connectivity and stepping-stone functions including the role of inactive and ecotone/transition vent (Boschen and Colaco, 2021; Neufeld and Metaxas, 2022) and seep (Pereira and others, 2021) sites, and animal-microbe interactions at active vents (Murdock and others, 2021), seeps (Pereira, 2024) and inactive sites.

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