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Towards a global strategy for the conservation of deep-sea active hydrothermal vents

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Deep-sea active hydrothermal vents are globally diverse, vulnerable, rare, remote, and isolated habitats, yet they face increasing threats from human activities, including deep-sea mining. To address the conservation challenges surrounding these habitats, we present a global assessment of the conservation status of deep-sea active vents. Our findings reveal that while 25% of the known deep active hydrothermal vents are currently under conservation interventions, only 8% benefit of full protection. These conservation interventions, consisting of area-based and regulation-based management measures, are implemented by 17 Sovereign States, three Regional Fisheries Management Organizations and one international treaty through 30 discrete interventions. However, our assessment and comparison of the specific measures for the 155 managed active hydrothermal vents reveal that the current conservation remain fragmented and discordant across jurisdictions and biogeographical provinces, resulting in overall insufficient protection, especially in Areas Beyond National Jurisdiction. Seizing the current momentum for ocean conservation, it is crucial to harmonize the management and protection of active deep-sea vents worldwide, taking into account their global biogeographic context and spatial distribution. This requires aligning current international initiatives that could improve baseline policies for the global protection of deep-sea hydrothermal vents.

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INTRODUCTION

As human activities and resource exploitation continue to expand, the deep sea is facing increasing threats[1,2]. To protect the unique and fragile habitats of the deep sea, as hydrothermal vents are, conservation interventions, such as area-based and regulation-based management measures, are crucial. Active hydrothermal vents in the deep sea (i.e., below 200 m depth) are especially vulnerable due to their small size and rarity, as well as for the variable growth rates and sensitivity to disturbance, which highly depend from geological and environmental characteristics[3–5]. International agencies[6], governments[7], scientists[8], civil society and NGOs[9,10] recognize the significance and value of these ecosystems and their unique endemism, and they have been calling for and applying conservation action towards their preservation[4,11,12].

Deep-sea hydrothermal vents are dynamic ecosystems as they largely depend on the intensity of the vent emission and on chemoautotrophic primary production[13]. Vents habitat on fast-spreading ridges can be ephemeral and quickly change in space and time, but they can also be very stable when found in slow and ultra-slow spreading ridges. Ultimately, environmental characteristics affect the colonization and dispersal of vent organisms[14]. Differences in vent taxa have revealed at least 11 major biogeographic provinces worldwide characterized by distinct assemblages of vent obligated organisms and ecological processes[15–18].

Despite their abundance in number, vents are rare habitats on Earth, as they are small and scattered along ocean ridges, spreading centers, and volcanic arcs[4,19,20]. Deep-sea vents meet the criteria that define Vulnerable Marine Ecosystems (VMEs), Ecologically and Biologically Significant Areas (EBSAs), and Particularly Sensitive Sea Areas (PSSA) due to their rarity, uniqueness, remoteness, vulnerability, scientific and cultural value[21]. They are biologically essential and functionally relevant for primary production (chemosynthesis), and they are crucial for the survival of endemic deep-sea species[13]. Lastly, deep-sea hydrothermal vents have been hypothesized to be among the places where life on Earth might have originated[22].

Various human activities take place in the deep sea, such as bottom trawl fisheries, scientific research, resource extraction[23], biological harvesting for biomolecules[24], and deep-sea tourism activities[25]. Individually, these activities have minimal to moderate effects on vent ecosystems, but their cumulative impacts are yet unknown[8,26]. However, the greatest concern is the potential use of these areas for commercial mineral extraction of massive sulfide deposits in the Area Beyond National Jurisdiction (ABNJ), which refers to the waters and seabed beyond the national jurisdictional boundaries of the continental shelf. The International Seabed Authority (ISA) is required by the United Nations Convention on the Law of the Sea (UNCLOS) to administer seabed-mining activities in the Area (seafloor and subsoil in ABNJ) on behalf of humankind[27]. As part of the ISA's ecosystem-based management strategy, Regional Environmental Management Plans (REMPs) with Area Based Management Tools (ABMTs) and associated regulatory measures for the sustainable use of mineral resources and protection of the marine environment from the impact of mining activities are under development[5,28,29].

Although mineral exploitation will likely focus on mineral deposits associated with inactive or extinct vents, currently all

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exploration contracts encompass both active and inactive sites. Moreover, the proximity and subterrestrial geological connectivity of inactive sites to active sites may endanger the survival of endemic species thriving around their chimneys[30].

The interest in mining massive sulfide deposits is not restricted to concessions on the Area[27]. A few countries have engaged in mineral exploration within their Exclusive Economic Zone (EEZ) with the first attempt in Papua New Guinea with the currently discontinued Nautilus Mineral Solwara 1 project[31,32], and more recently in Japan[33,34] and Norway[35]. Given the destructive impact on the seabed of current technologies, the sustainability of deep-sea mining remains controversial[27]. Deep-sea ecosystems targeted by the mining industry require baseline assessments, monitoring strategies, and environmental impacts assessments to evaluate the natural spatial and temporal variability of these ecosystems and to develop mitigation and restoration strategies[36,37]. A sustainable harvest of minerals from the seabed without some impacts on marine life is highly desired, but currently impossible, and a precautionary approach coupled with the implementation of conservation measures for deep-sea biodiversity is the only mitigation method currently available[29]. Furthermore, conservation measures are increasingly seen as tools to promote passive restoration of degraded deep-sea habitats, which are much less expensive than active restoration activities[38]. Additionally, certain ABMTs encompass deep-sea vents within national and international jurisdictions. These ABMTs provide spatial closures and management measures that offer varying degrees of protection from one or more anthropogenic impacts[12].

Here we review and compare current conservation measures applied to active deep-sea hydrothermal vents. In particular, we collected information on (i) their level of protection; (ii) the process through which the conservation measures were initiated; (iii) the differences among conservation measures across maritime jurisdictions, sovereignties, and territories; and (iv) the coverage of deep-sea vents' protection amongst different biogeographic regions. We also explore the case that deep-sea hydrothermal vents could meet developing criteria for IUCN Red Listed Ecosystems as a possible approach for harmonizing their management, and we highlight the importance of the role of the ISA in promoting actions and synergy with other international strategies for protecting these habitats from deep-sea mining.

RESULTS

Assessment of the conservation of deep-sea active hydrothermal vents

There are a total of 664 records of deep hydrothermal vent fields listed in the InterRidge Vents Database Version 3.4 (see methodology for more information), of which almost 60% are within EEZ[39]. Throughout our collection of evidence on the status of the ecosystem based on biological observations in each field (see supplementary dataset), we verify that 270 are confirmed to be hydrothermally active ecosystems by ground-truthing observations of live biota in addition to the presence of hydrothermal fluids, 336 are inferred active hydrothermal vents that have not been visited yet, and 58 are reported as inactive (Fig. 1, and supplementary dataset). The spatial analysis of conservation interventions and the screening of the associated regulatory frameworks confirms that 25% of the total known active deep-sea hydrothermal vents (155 vents) are currently under management. The majority of the managed vents (133 count, 84%) are directly under the responsibility of 17 sovereign states (Fig. 2). Five of these states include within conservation interventions all the hydrothermal vents in their Exclusive Economic Zone (i.e., Fiji, Papua New Guinea, Vanuatu, Canada, and Portugal) (Fig. 2). Among these, Portugal is also protecting to two hydrothermal vents on its Extended Continental Shelf (Fig. 1). In ABNJ only 16 out of the 258 currently known active vents in the Area are under conservation interventions.

Biogeographic coverage of protection measures

About half (6) of the 11 biogeographic provinces described for deep-sea hydrothermal vents[15] are at least partially represented within conservation interventions (Fig. 1 – Table 1). East Scotia Ridge, Central SW Pacific, Kermadec Arc, and the NE Pacific are fully or mostly included within conservation interventions. On the contrary, the N East Pacific Rise and the Mid Atlantic Ridge are minimally represented within conservation interventions. None of the defined biogeographical provinces in ABNJ, which is likely where most of the deep-sea vents of the world are located, are currently under any kind of conservation measures (Fig. 1). Recent studies included other possible biogeographic provinces for deep hydrothermal vents[17]: the Mediterranean Sea, where several active sites have been discovered in the Aeolian volcanic Arc (Tyrrhenian Sea)[40], and Antarctica. Both of these potentially diverse biogeographic provinces are currently included within conservation interventions, but for the Mediterranean Sea the partial protection is largely insufficient mainly for the lack of specificity of administrative and regulatory measures that do not include the seabed, or hydrothermal habitat, within specific ABMTs designation even if they encompass within their limits (i.e: The Pelagos Sanctuary and the Aeolian Archipelago Special Conservation Area)[41,42].

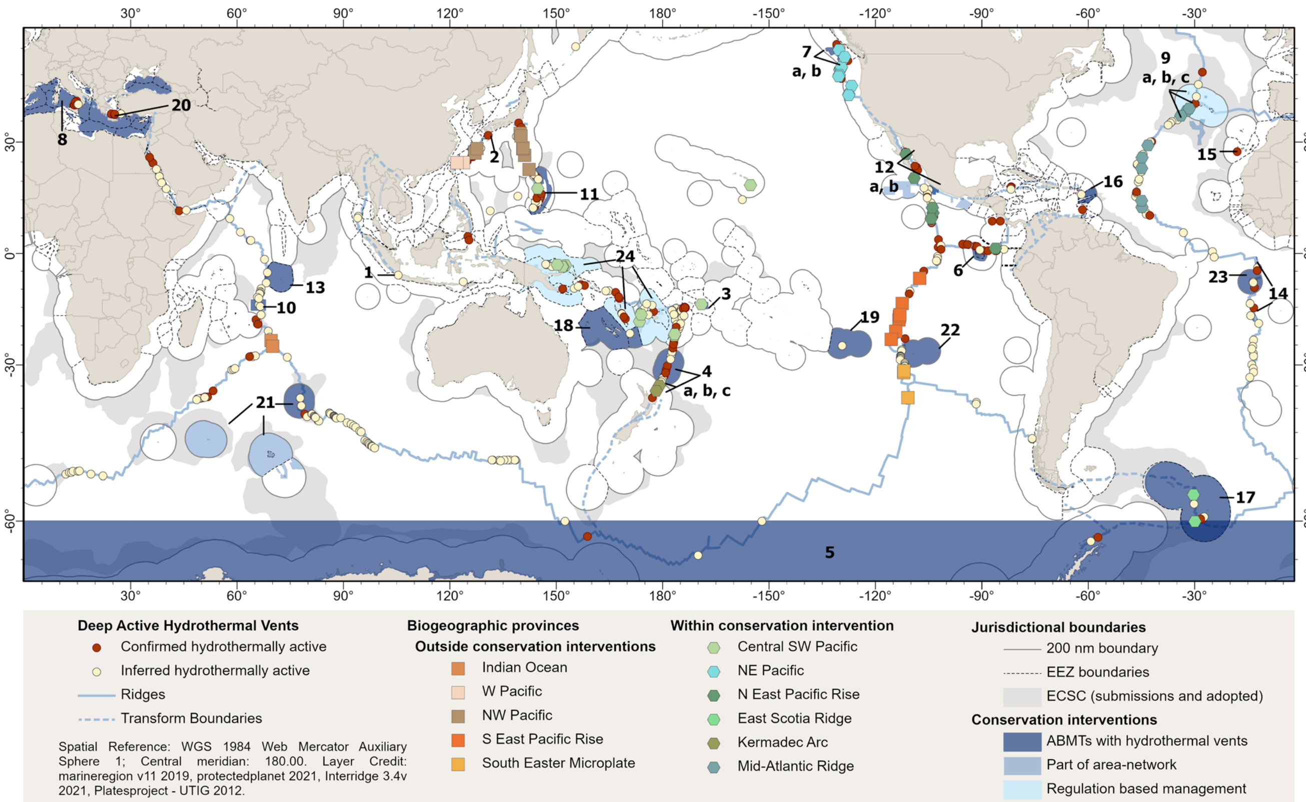
Conservation Interventions across jurisdictions

There are 30 individual conservation interventions (Fig. 1 – Table 1). Of these, two are regulation-based management approaches applied on the entirety of the EEZ (Fig. 1): a deep-sea trawl-ban on the Azores archipelago (Portugal)[43], and a 10-year deep-sea mining moratorium by the island states of Fiji, Papua New Guinea, and Vanuatu[31,44]. The remaining 28 conservation interventions are ABMTs, including both standalone areas and subareas or discrete portion part of area-networks (Figs. 1 and 2). Eight are sectoral based and 20 are multisectoral (Table 1).

In ABNJ, there are four conservation interventions. In the southern ocean the vast area defined by the Antarctic Treaty Area (the Southern Ocean below the −60° parallel), is holding mineral exploitation until after 2048 under the Protocol on Environmental Protection, and manages fisheries through the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR)[45,46]. The Fishery Restricted Area (FRA) in the Mediterranean Sea, established by the the General Fishery Commission for the Mediterranean (GFCM), prohibits trawling under 1000 m depth in the whole basin, including on deep hydrothermal vents that are on the Italian continental shelf (Fig. 1 – Table 1)[12]. In the Atlantic Ocean on the north and south of the Ascension Island MPA, the South-East Atlantic Fishery Organization (SEAFO) is implementing VMEs closures (Fig. 1). In the Indian Ocean, the independent fishing industry group of the South Indian Ocean Deep Fishery Association (SIODFA), implemented a voluntary sectoral Benthic Protection Area to protect deep-sea ecosystems following the list of VMEs in collaboration with IUCN[47], which overlaps with the polymetallic sulfide exploration contract granted to the Republic of Korea by the International Seabed Authority[48].

Protection levels

While there are 20 conservation interventions that offer multisectoral or cross-sectoral management approaches, the level of protection they provide to most deep hydrothermal vents is still limited (Fig. 2 – Table 1). Partial protection is mainly offered through single-sector management interventions, such as fishery closures that prohibit bottom trawling and specific temporal measures for seabed mining. However, there are some cases



1. Palau Anak Krakatau Nature Reserve; 2. Kirishima- Kinkowan National Park; 3. National Marine Sanctuary of American Samoa; 4-a. Kermadec Marine Reserve and BPA, 4-b. Seamount Closure 6B2a – 6B2b (SO), 4-c. Tectonic Reach BPA (SO); 5. Antarctic Treaty Area (SO); 6. Galapagos Marine Reserve; 7-a. Endeavour Hydrothermal vents MPA (PO), 7-b. Offshore Pacific Seamounts and Vents Closure (PO); 8. GFCM Deep Water Fisheries Regulated Area (SO); 9-a. Azores Marine Park (PO), 9-b. Luso hydrothermal field MPA, 9-b. Trawl ban (PO); 10. SIODFA BPA on Mid Indian Ridge (SO); 11. Mariana Arc of Fire Wildlife Refuge (PO); 12-a. Hydrothermal vents of Guaymas Basin and East Pacific Rise MPA and Sanctuary (PO), 12-b. Deep Mexican Pacific Biosphere Reserve (SO); 13. British Indian Ocean Territory Chagos MPA; 14. SEAFO VME Closures (PO); 15. Mar de Las Calmas SAC; 16. Agoa Sanctuary; 17. South Georgia and South Sandwich Island MPA; 18. Natural Park of the Coral Sea; 19. Pitcairn Island MPA; 20. Thalassia Periochi Koloumvo SCI (PO); 21. Protected Perimeter Around National Nature Reserve of the French Southern Lands - Saint Paul and Amsterdam Islands (SO); 22. Rapa Nui Multiple-Use Coastal MPA (SO); 23. The Ascension Island MPA (SO); 24. 10 y moratorium for seabed mining on the EEZ of PNG, Vanuatu and Fiji

Fig. 1 Conservation interventions with deep active hydrothermal vents in relation to their biogeographical provinces. Map illustrating the conservation interventions, such as area-based and regulation-based management measures, adopted for deep active hydrothermal vents worldwide. Numbers correspond to the order of establishment; lower-case letters indicate discrete Area Based Management Tools (ABMTs) in the same region. EEZ Exclusive Economic Zone, ECSC Extended Continental Shelf Claim. Some area-based management measures might not be visible due to the Mercator projection distortion or to the size of the ABMT.

where multi-sectoral measures present conflicting regulations among equally disruptive extracting activities. For example, the MPAs implemented by France on its overseas territories are multisectoral ABMTs but do not offer full protection. The Southern French Territories and the Natural Park of the Coral Sea prohibit bottom-contact fisheries but not seabed mining (Table 1). The French government regulates mining through permits as it exercises sovereign rights on the seabed and subsoil[49,50]. In the Agoa Sanctuary (implemented for marine mammals) the extraction of non-living resources is prohibited to avoid noise pollution disturbances, but there is no mention of bottom trawling[51]. Two MPAs implemented by the United Kingdom on its overseas territories (Ascension Islands and South Georgia and South Sandwich Island MPAs) do not explicitly mention commercial harvesting for biotechnological purposes[52,53]. In the Azores archipelago, the recently discovered hydrothermal vent Luso is now a standalone MPA regulating only fisheries activities[54], which contrasts with the full protection applied by the Azores Marine Park (Table 1).

Full protection is applied only to 55 deep-sea hydrothermal vents, about a third of the vents within conservation interventions. The ABMTs that are currently applying full protection are the Mariana Arc of Fire, the National Marine Sanctuary of American Samoa (United States), the Azores Marine Park (Portugal), the Rapa Nui National Park (Chile), Hydrothermal vents of Guaymas Basin and East Pacific Rise MPA and Sanctuary, the Deep Mexican Pacific Biosphere Reserve (Mexico), Endeavour Hydrothermal Vents MPA (Canada), Galapagos Marine Reserve (Ecuador), and the Pitcairn Island MPA (UK) (Fig. 2 – Table 1).

Vent-tailored protection measures

Through the survey conducted on the management plans and regulatory measures we identified three main categories of conservation interventions: a) *Intentional*, b) *Adapted*, and c) *Incidental* (Table 1). These categories are based on how hydrothermal vents are considered within the regulatory framework of each intervention. *Intentional* conservation interventions have been specifically established to protect one or more deep-sea hydrothermal vents and consider their characteristics and vulnerability within the regulatory framework (Table 2). Despite the intentionality and the consideration of vents as primary or secondary objective of the conservation intervention, the majority do not fully protect the deep-sea hydrothermal vents, mostly because of their sectoral designation (Table 1). The *Adapted* interventions have been modified after their initial implementation to include deep-sea vents in their management, through spatial expansion (The Marine Sanctuary of American Samoa, South Georgia and South Sandwich Island MPA, and Kermadec BPA) or modifications in their management plans (Natural Park of the Coral Sea). Finally, the *Incidental* interventions are all multi-sectoral ABMTs that were not planned to protect the deep-sea

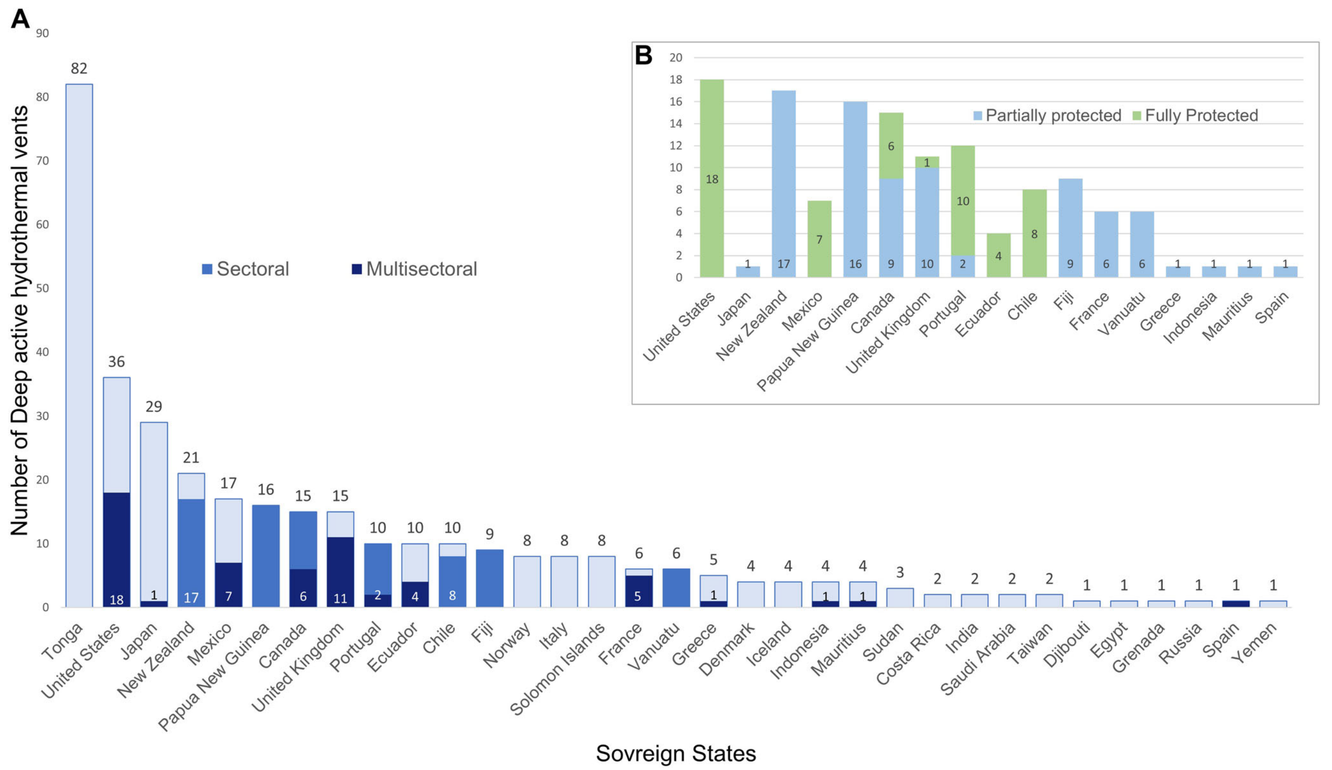


Fig. 2 **Modalities of management and level of protection in conservation intervention with deep active hydrothermal vents. A** Number and modalities of management of active deep hydrothermal vents (HVs) by Sovereign States. Numbers above each bar indicate the total number of HVs within the Exclusive Economic Zone. Numbers within the bars indicate the subset of HV within conservation interventions and modalities of management which are sectoral (Blue) and/or multi-sectoral (Dark Blue). The bar's background color (light blue) represents the HVs that are not included in conservation intervention by the Sovereign State. **B** Number of partially and fully protected HVs by sovereign states.

vents (as in some cases they were adopted before censusing the presence of vents) but resulted in partial or full protection of these habitats (Table 1). Within the *Incidental* ABMTs, despite no management measures related explicitly to deep-sea hydrothermal vents (Table 2), regulations often extend to the whole marine environment, implicitly including any species and habitat in the area.

DISCUSSION

Fragmentation and discordancy of conservation interventions

Our analysis confirms that the number of conservation interventions including hydrothermal vents is growing[12], as well as the global recognition of their ecosystem value[55]. However, only 55 vents (8%) are benefiting from full protection, while for the remaining 100 active vent fields partially protected, conservation results fragmented. Some of the conservation interventions often miss to regulate destructive activities, and their location do not help to represent the global bioregionalism of hydrothermal vents (Table 2). Overall, there are still 453 deep-sea vents unprotected.

The 25% of vents currently under conservation interventions do not sufficiently represent diversity across ocean basins and biogeographic regions, since no fully protected vents are in ABNJ. Hydrothermal vents species differ among sites, fields, region and ocean basins[4]. Even if scientific advancements have improved the knowledge related to these habitats[56], the biological and ecological information on deep-sea hydrothermal vents are still insufficient to delineate with certainty the boundaries and characteristics of their biogeography[57,58]. Therefore, even when an entire biogeographic province seems to be fully included in conservation interventions, it might be widely unprotected, and if species loss or local extinction occur, the maintenance of genetic connectivity could be disrupt[58,59]. Future biogeographical research may identify new biogeographical provinces or sub-provinces for active vents, expanding our understanding of the distribution and composition of hydrothermal vent communities. However, it is essential to consider this information within regional and global strategies for conservation. Ensuring the representativity and adequate coverage of biogeographical provinces and the relative variation in community composition will effectively improve the maintenance of local and regional ecological functions and processes[56,60,61].

The discordance among the conservation interventions analyzed in this study is evident from the variability within our three management categories: *Intentional*, *Adapted* and *Incidental* interventions. Regardless of the category, there is no consistency on the level of protection applied, type of sectors regulated or how human activities are managed (Tables 1 and 2). Despite some of the interventions having been implemented with the intention to protect hydrothermal vents, only a small fraction of vents are fully protected, whether they are considered the *Intentional* conservation intervention's primary or secondary objective (Table 1 – Fig. 2).

The existing regulations are inadequate to protect the deep-sea vents from numerous anthropogenic threats, including seabed mining - the most apparent and significant concern. The level of protection provided to these rare and vulnerable deep-sea habitats within ABMTs depends on how and which types of activities are regulated or prohibited, as illustrated by the array of national regulatory frameworks presented in Table 2. Despite being designated as multisectoral ABMTs, some MPAs still allow the inquiry of seabed mining permits for exploration licenses[50] or

Table 1. Management categories of conservation interventions and regulation of human activities in respect to deep active hydrothermal vents.

Management category conservation interventions	Year of establishment	Year of inclusion of HV	Management typology	Level of protection	Biogeographic provinces	Zoning		Regulation of human activities in respect to HVs									
						Vertical zoning	*Sub-zoning*	*Deep-sea Mining*	*Bottom fisheries*	*Commercial harvesting*	*Pollution and dumping*	*Scientific research*	*Cable and pipelines*	*Midwater fisheries*	*Aquaculture*	*Vessel traffic*	*Tourism*
Intentional																	
Antarctic Treaty Area (SO)	1991	1991	MS	P	n.y.d.	n	y	X	R	-	X	✓	-	✓	-	✓	-
Seamount Closure 6B2a – 6B2b (SO)	2001	2001	S	P	KA	y	n	-	X	-	X	✓	-	✓	-	✓	-
Endeavour Hydrothermal vents MPA (PO)	2003	2003	MS	F	NEP	n	y	X	X	X	X	R	-	✓	-	✓	R
GFCM Deep Water Fisheries Regulated Area (SO)	2005	2005	S	P	n.y.d.	y	n	-	X	-	-	-	-	✓	-	-	-
Azores Marine Park (PO)	2006	2006	MS	F	MAR	n	y	X	X	X	R	R	R	✓	R	✓	R
SIODFA BPA on Mid Indian Ridge (SO)	2006	2006	S	P	IO	n	n	-	X	-	-	-	-	X	-	-	-
Tectonic Reach BPA (SO)	2007	2007	S	P	KA	y	y	-	X	-	X	✓	-	✓	-	✓	-
Mariana Arc of Fire Wildlife Refuge (PO)	2009	2009	MS	F	CSWP	n	y	X	X	X	X	R	-	R	-	-	-
Hydrothermal vents of Guaymas Basin and East Pacific Rise MPA and Sanctuary (PO)	2009	2009	MS	F	NEPR	y	y	X	X	X	X	R	-	X	-	R	X
Trawl ban in the Azores EEZ (SO)	2010	n.a.	S	P	MAR	n	n	-	X	-	-	R	-	R	-	-	-
SEAFO VME Closures (PO)	2011	2011	S	P	n.y.d.	n	n	-	X	-	-	-	-	X	-	-	-
Deep Mexican Pacific Biosphere Reserve (SO)	2016	2016	MS	F	NEPR	y	y	X	X	X	X	R	-	R	X	R	R
Offshore Pacific Seamounts and Vents Closure (PO)	2017	2017	S	P	NEP	n	y	-	X	-	X	✓	-	✓	-	✓	-
Thalassia Periochi Koloumvo SCI (PO)	2017	2017	MS	n.a.	n.y.d.	n	n	-	-	-	-	-	-	-	-	-	-
Protected Perimeter Around National Nature Reserve of the French Southern Lands - Saint Paul and Amsterdam Islands (SO)	2017	2017	MS	P	n.y.d.	n	y	R	X	-	X	R	R	R	-	✓	R
Rapa Nui Multiple-Use Coastal MPA (SO)	2018	2018	MS	F	n.y.d.	n	y	X	X	X	X	✓	-	R	-	-	✓
The Ascension Island MPA (SO)	2019	2019	MS	P	n.y.d.	n	y	X	X	-	X	✓	R	X	-	✓	✓

Table 1 continued

Management category conservation interventions	Year of establishment	Year of inclusion of HV	Management typology	Level of protection	Biogeographic provinces	Zoning		Regulation of human activities in respect to HVs									
						Vertical zoning	*Sub-zoning*	*Deep-sea Mining*	*Bottom fisheries*	*Commercial harvesting*	*Pollution and dumping*	*Scientific research*	*Cable and pipelines*	*Midwater fisheries*	*Aquaculture*	*Vessel traffic*	*Tourism*
Luso hydrothermal field MPA (PO)	2019	2019	S	P	MAR	n	n	R	X	-	-	✓	-	X	-	R	-
10-year moratorium for seabed mining within EEZ of PNG, Vanuatu, and Fiji (PO)	2020	2020	S	P	CSWP	n	n	X	-	-	-	✓	-	-	-	-	-
Adapted																	
National Marine Sanctuary of American Samoa	1986	2009	MS	F	CSWP	n	y	X	X	X	X	✓	-	R	-	R	✓
Kermadec Marine Reserve and BPA	1990	2007	S	P	KA	y	y	-	X	-	X	✓	-	✓	-	✓	-
South Georgia and South Sandwich Island MPA	2012	2013	MS	P	ESR	n	y	X	X	-	R	R	-	R	-	R	R
Natural Park of the Coral Sea	2014	2016	MS	P	CSWP	n	n	R	X	-	-	R	-	R	-	-	✓
Incidental																	
Palau Anak Krakatau Nature Reserve	1921	n.a.	MS	P	n.y.d.	n	n	-	R	-	X	✓	-	R	-	-	✓
Kirishima-Kinkowan National Park	1934	n.a.	MS	P	NWP	n	n	X	-	-	-	-	-	-	-	-	-
Galapagos Marine Reserve	1998	n.a.	MS	F	NEPR	n	y	X	R[a]	X	X	R	-	R	-	✓	-
British Indian Ocean Territory Chagos MPA	2010	n.a.	MS	P	n.y.d.	n	n	X	X	-	X	✓	-	X	-	-	-
Mar de Las Calmas SAC	2011	n.a.	MS	P	n.y.d.	n	n	X	-	-	-	✓	-	R	-	✓	✓
Agoa Sanctuary	2012	n.a.	MS	P	n.y.d.	n	n	X	-	-	X	✓	-	R	-	-	-
Pitcairn Island MPA	2016	n.a.	MS	F	n.y.d.	n	n	X	X	X	X	R	-	R		-	-

Attributes of conservation interventions with active deep hydrothermal vents (HVs), ordered by management category and date of establishment. *Intentional*: HVs explicitly included in the scope of the conservation at the moment of establishment, *PO:* HVs are the principal objective of the conservation intervention, *SO:* HV are secondary objective of the conservation intervention. *Adapted*: HVs are included in an update of the management framework subsequent to the establishment. *Incidental* : intervention implicitly protects hydrothermal vents without mentioning them – see methodology for definition. Year of inclusion of HVs within the management plans are noted (*n.a.* not applicable). Management typology: Single-sector (S) or Multi-sector (MS). Level of protection: Partial (P) or Full (F). Biogeographic Provinces, *IO* Indian Ocean, *MAR* Mid Atlantic Ridge, *ESR* East Scotia Ridge, *WP* West Pacific, *NWP* North West pacific, *NEP* North East Pacific, *NEPR* Northern East Pacific Rise, *SEPR* South East Pacific Rise, *SEM* South of Easter Microplate, *n.y.d.* not yet defined). Zoning: *n* not implemented, *y* implemented. Regulation of human activities: ✓: allowed; R: regulated; X: prohibited; -: not mentioned.
GFCM General Fishery Commission of the Mediterranean, *SEAFO* South East Atlantic Fisheries Organization, *SIODFA* South Indian Ocean Deep Fishery Association, *VME* Vulnerable Marine Ecosystems, *MPA* Marine Protected Areas, *BPA* Benthic Protection Areas, *SCI* Site of Community Importance (EU Habitat Directive), *SAC* Special Area of Conservation (EU Habitat Directive).
[a]Sub-zoning allows specific traditional bottom fisheries, but none of these areas include HVs.

Table 2. Specific regulations and management measures for the conservation of deep active hydrothermal vents.

Activity	Regulations	ABMTs
Extraction of non-living resources (soil and subsoil)	Extraction of minerals, sediments, and/or stones prohibited within 1 km of the marine park boundary.	Kirishima- Kinkowan National Park[98]
	Disturbance or removal of non-living natural material from the seabed or subsoil prohibited.	Pitcairn Island MPA[99]
	Pollution resulting, directly or indirectly, from activities relating to the exploration and exploitation of the seabed and its subsoil, extraction, and collection of materials that can cause a dysfunction of the hydrobiological system and mining activities prohibited.	Agoa Marine Sanctuary[51]
	The exploitation of seabed resources using invasive techniques, including minerals, hydrates, and other energy compounds, geothermal energy prohibited.	Azores Marine Park[100]
	Removal of chimneys and rocks from hydrothermal vents for geological studies, chemical sampling, other invasive techniques (including explosives) prohibited; exploration, mining, and extraction of stone material prohibited.	Deep Mexican Pacific Biosphere Reserve, Hydrothermal Vents of Guaymas Basin and the East Pacific Rise Sanctuary[101,102]
	Extraction of mineral or Mineral extraction of other non-living resources prohibited. Disturb, damage or destroy, or remove from the area any part of the seabed, including a venting structure, any part of the subsoil, or any living organism or any part of its habitat for exploitation purposes, is prohibited besides in areas where scientific research allows it.	Endeavour Hydrothermal Vents MPA[103]
	Mineral extraction requires authorization from the competent authority.	Protected Perimeter Around National Nature Reserve of the French Southern Lands - Saint Paul and Amsterdam Islands[50]
Bottom fisheries	Bottom trawling and other bottom contact fisheries are prohibited.	All BPAs, large no-take MPAs, VME closures, and FRA
	Adverse activities are prohibited within a 1 nm radius of seamounts and hydrothermal fields.	Mariana Arc of Fire Wildlife Refuge[104]
Commercial harvesting of living resources for biotechnological purposes	Alteration or destruction of habitats is prohibited.	Deep Mexican Pacific Biosphere Reserve[101]
	Exploration and exploitation of wildlife for marine genetic resources are prohibited.	Hydrothermal Vents of Guaymas Basin and the East Pacific Rise Sanctuary[102]
	Biotechnological explorations and any activities that disturb the natural balance are prohibited.	Azores Marine Park[100]
Pollution and dumping	Discharging or throwing, in inland waters, marine reserve area, coasts or beaches areas, waste ballast bilges, sewage, garbage or waste, or any other contaminating element of the medium aquatic prohibited unless such elements have been treated as required by regulations.	Galapagos Marine Reserve[105]
	Dumping of waste or other matter, including from vessels or structures prohibited.	Pitcairn Island MPA[99]
	Use of weapons, toxic or polluting substances, or explosives that may cause damage or disturbance to the species is prohibited.	Azores Marine Park[100]
Scientific research	Explorations for mineral, biological, or energy resources involving invasive techniques that may endanger the seabed and associated ecosystems are prohibited. Any scientific research or monitoring activity for conserving nature and biodiversity and safeguarding natural values must be regulated.	Azores Marine Park[100]
	Regulations on research vessel clearance and research process for any domestic or international vessel and sub-zones for zero, medium, and high impact scientific research are applied.	Endeavour Hydrothermal vents MPA[103]
	Wildlife refuge special-use permits required for commercial activities, including non-news-related photography, videography, audiography, ecotours, and recreational charter fishing; for research and monitoring activities including scientific expeditions by students, universities, private institutions, or other non-refuge-system organizations; other education and outreach activities.	Mariana Arc of Fire[104]
	Research bottom trawling permitted in certain areas, subject to permit issued by the competent authority.	South Georgia and South Sandwich Islands MPA[53]

Table 2 continued

Activity	Regulations	ABMTs
Cables and pipelines	Installation of submarine communications, power transmission cables, gas, hydrocarbon, or other pipelines regulated.	Azores Marine Park[100]
Mid-water fisheries	Trawling fisheries within 100 m of the seabed are prohibited; electronic net monitoring systems to control depth between the ground rope and seabed is a requirement on board.	Kermadec and Tectonic Reach BPAs[106]
	Fishing below 800 m is prohibited.	Deep Mexican Pacific Biosphere Reserve[101]
	Longline bottom fishing is permitted only between 700 and 2500 m.	South Georgia and South Sandwich Islands MPA[53]
	Fishing prohibited below 500 m; A 2-km-wide management and control buffer is applied around the sanctuary.	Hydrothermal Vents of Guaymas Basin and the East Pacific Rise Sanctuary[102]
Aquaculture	Introduction of species and genetically modified organisms prohibited.	Hydrothermal Vents of Guaymas Basin and the East Pacific Rise Sanctuary[102]
	Aquaculture is prohibited within "core sub-zones".	Deep Mexican Pacific Biosphere Reserve[101]
Vessel Traffic, including shipping	Fishing vessels are prohibited in no-take areas, except in the exercise of the right of innocent passage.	South Georgia and South Sandwich Islands MPA[53]
	Occupancy or transit of any vessel with fishing gear onboard is prohibited.	Luso Hydrothermal Field MPA[54]
Tourism	Filming for commercial or advertising purposes, visitation, and nature tourism activities are regulated.	Azores Marine Park[100]

List of regulations and management measures categorized by human activities retrieved from management plans, regulations and legislative documents associated to conservation interventions with hydrothermal vents.

do not regulate the harvesting of natural resources for technological purposes[53]. This poses a tangible risk of ineffective protection.

Our analysis suggests that the current level of protection is insufficient for hydrothermal vent ecosystems. Destructive activities like deep-sea mining, trawling, harvesting of biomass for technological purposes, and other activities that damage habitats and threaten the survival of endemic species should not be allowed within protected areas, as they are currently incompatible with the sustainable use of natural resources. It is vital to create and enforce protected areas that provide greater environmental protection to preserve these unique and critical ecosystems[27].

Moving forward, to implement a more effective protection of deep-sea active hydrothermal vents, their global environmental and ecological characteristics should be taken into account for a more significant and representative protection.

The global heterogeneity of hydrothermal vents has not been taken into account in global analyses of systematic planning or prioritization exercises for the application of conservation targets. Several studies have analyzed present and future scenarios of ocean protection based on international conservation targets but either ignored hydrothermal ecosystems[62–65] or did not consider them as a discrete topographic unit, including them in ocean ridges without differentiating their tectonic settings or biogeography[66,67]. With the specific threats posed by seabed mining on the singular massive sulfide deposits, the environmental settings that influence hydrothermal vents' heterogeneity should be included in conservation initiatives and interventions at a global level. Therefore, a global conservation strategy for active deep-sea hydrothermal vents is essential to coordinate existing and future efforts to adequately protect these vital habitats.

Existing strategy to enhance the protection of deep-sea hydrothermal vents

The absence of clear guidelines for effective conservation measures associated with deep active vents hinders their protection. However, there are many existing international initiatives that can be used (and improved) to develop baseline policies in national and international arenas.

Ecological and biologically significant marine areas. Hydrothermal vents have been previously described as EBSAs by the Convention of Biological Diversity. They are one of the habitats used as example for the creation of the EBSA site criteria[68]. Multiple regional assessments using these seven criteria have confirmed that hydrothermal vents are "unique and rare", they are described as areas of special importance for "life-history stages of species" and "threatened, endangered, or declining species and/or habitats", they are characterized by "vulnerability, fragility and sensitivity of slow recovery", they are biologically "productive" and "diverse", and they remain pristine in their "naturalness"[4,56,59,69]. The CBD Conference of the Party confirmed the EBSA designation of hydrothermal vents on the Northeast Pacific Rise in the gulf of California, on the Juan de Fuca segment of the North East Pacific off the coast of British Columbia, and on the Mid Atlantic Ridge[70,71]. Despite EBSAs do not prescribe management or protection, and do not implement protected areas, they are a source of scientific knowledge exchange and capacity building among experts and policy makers, that sometimes can result in the implementation of conservation practices. For example, the Guaymas Basin Hydrothermal Vent sanctuary in Mexico, and Endeavour Hydrothermal vents MPA in Canada are protecting the described EBSAs in national jurisdiction. In ABNJ, the information and knowledge accumulated during the EBSA process was useful to describe the deep-sea hydrothermal vents proposed as Site in Need of Protection during the REMP workshop on the Area of the Northern MAR[72].

Regional environmental management plans. REMPs are part of the conservation strategy of the ISA. Currently the ISA is managing mining claims including hydrothermal vents on the North MAR and on the Indian Ocean Ridge. The procedure to finalize the North MAR REMP is ongoing with proposed Sites and Areas in

Need of Protection and Precaution[73], while the development of the REMP in the Indian Ocean is still outstanding with the first workshop happened in May 2023. The use of Vulnerable Marine Ecosystems (VMEs) and EBSA criteria during the ISA's REMP workshops on the Area of the Northern Mid Atlantic Ridge opens synergetic channels to implement cross-sectoral protection measures in ABNJ[21]. In particular, site criteria have been used to propose 11 active vents as Sites in Need of Protection. Active deep-sea hydrothermal vents could become the first natural ecosystem internationally protected if the members of the council of the ISA decide to designate for protection these sites in the Area of the Northern Mid Atlantic Ridge[21,73]. If the ISA expands protection to all the active hydrothermal vents of the Area, this could motivate all countries in its council to manage the vents falling in their EEZ similarly, thus offering the possibility of expanding deep-sea protections to the missing biogeographic regions as well.

The international agreement on biodiversity beyond national jurisdiction. A draft agreement of the international legally binding instrument under the UNCLOS on the conservation and sustainable use of marine biological diversity of ABNJ was adopted in March 2023 after a long negotiation through a series of Intergovernmental conferences started in 2018[74]. The BBNJ agreement aims to improve coordination and cooperation among different institutions currently operating in ABNJ by addressing four package elements: Marine genetic resources and access to benefit-sharing, ABMTs including MPAs, Environmental Impact Assessments, and Capacity building and transfer of marine technologies. Among these four package elements, "ABMTs" is among the most critical topics since it has the potential to create a coherent institutional link with other governing body in ABNJ[75–77], especially with the pressure from the new post-2020 Kunming-Montreal Global Biodiversity Framework signed by the CBD Conference of the Parties, which introduced a conservation target of the 30% of Earth surface by 2030[78]. Improving connectivity among the processes and fragmented conservation interventions we have identified in this study could strengthen relationships among institutions, processes, and instruments operating in ABNJ, providing coherence in the conservation of hydrothermal vents, which are common among many environmental management approaches currently established in ABNJ (REMPs, VMEs) and future MPAs that might be proposed under the new agreement[73,76].

The international union for conservation of nature red list of ecosystems. the IUCN launched this initiative in 2014. The IUCN Red List of Ecosystems (RLEs) offers a standardized tool to assess the potential and effective degradation of an ecosystem, its geographical distribution and the status of its components and processes compiled into a public database (http://assessments.iucnrle.org/)[79]. The five rule-based criteria to assess ecosystems are a combination of qualitative and quantitative categories: (A) Reduction in geographic distribution, (B) Restricted geographic distribution, (C) Environmental degradation, (D) Disruption of biotic processes or interactions, and (E) Quantitative analysis that estimated the probability of ecosystem collapse[74]. Under the IUCN RLEs, an ecosystem with an extent of occurrences of 2000 km^2 falls within the category "critically endangered", the highest category before the final "collapsed"[80]. The variables incorporated in the assessment include the past and predicted restriction of the geographical and spatial distribution and extent of an ecosystem, and the environmental degradation and loss of abiotic or biotic components over past and future times[80]. Deep-sea vents are estimated to have a cumulative geographical extent of circa 60 km^2 [24], thus they would likely fit this criterion. The recent development of a Red List of vent endemic mollusc species for the IUCN[69] provides an example that their inclusion in the IUCN RLEs is not only technically possible but should be a priority. The IUCN aims to complete the list of Endangered Ecosystems by 2025. Assessing hydrothermal vents against the IUCN RLEs criteria would be another recognition of their conservation importance. This act alone could push single states and intergovernmental organizations to protect active deep-sea vents from the direct and indirect impact of human activities in the ocean.

In summary, initiatives such as EBSAs from the CBD, the REMPs by the ISA, the BBNJ negotiation at the UN, and the IUCN RLEs provide momentum towards a global commitment in ocean conservation, which can inspire the global protection of active hydrothermal vents in the deep sea. Recently, countries' representatives, international and intergovernmental organizations, and NGOs have called for a global moratorium on seabed mining in ABNJ which resonate throughout many ocean governance events[81–85]. While seabed mining is the greatest potential concern for the future of deep-sea vents, it is not the only human activity threatening these vulnerable ecosystems. Thus, even a global moratorium or complete ban of deep-sea mining in active vent areas may not be sufficient. The protection of hydrothermal vents in ABNJ depends only in part on the actions of the ISA, and more comprehensive set of holistic and multi-sectoral measures and interventions are needed to protect the deep sea in ABNJ.

THE WAY FORWARD: FULL PROTECTION FOR ACTIVE HYDROTHERMAL VENTS

Although there has been a growing interest in the management and protection of deep-sea vents, the long-term protection of these ecosystems remains inadequate. Currently, only around 25% of total vents are under some form of protection. The approach is fragmented and incoherent, and apply different regulations or management modalities to equally damaging extractive activities. Moreover, the protection measures currently in place do not cover half of the vent biogeographic regions, failing to represent the global biodiversity of these habitats, which may depend on regional larval connectivity and dispersal. With deep-sea mining emerging as the most serious threat, it is essential to harmonize and implement full protection for active deep-sea vents and prioritize the unrepresented vent areas to preserve these rare ecosystems, and their unique biodiversity. Multi-sector approaches offer better protection, but they must be adequately planned and enforced. Countries currently implementing intentional and full-protection measures represent a model for others to adapt to existing regulatory frameworks. In ABNJ, the ISA could play an essential role in facilitating the transition from a limited or sectoral approach to multi-sectoral management by designating active vents as Sites in Need of Protection in the Area. Supporting the call for a global moratorium on deep-sea mining will provide time to explore the evidence of experimental mining to test the survival of the ecosystem's functionality after direct and indirect impacts, when and if inactive vents will be mined.

Including active hydrothermal vents in the IUCN Red List of Ecosystems could provide a more uniform and consistent identification of critical vent habitats across both national and international jurisdictions. To effectively protect hydrothermal vents, it is necessary to address the direct causes of environmental impact and execute specific conservation efforts across jurisdictions. Using international tools and joint actions, we call for an international effort enabling the monitoring of the activity and changes in vent-associated biodiversity over time, together with the census of new hydrothermal vent areas, to implement their protection.

METHODS

Geographic coverage

This study encompasses the deep seabed (>200-m depths) at a global scale. For the designation of national jurisdictional boundaries, we used the Exclusive Economic Zone (within 200 nautical miles from coastline) defined by marineregion.org (https://www.marineregions.org/disclaimer.php. - Accessed: 18th May 2021)[86]. Extended Continental Shelf Claims (ECSC) include submitted and adopted ECSC (http://www.continentalshelf.org/onestopdatashop.aspx.) as of May 30, 2021[87], with the remaining area considered to be ABNJ. ArcGIS Pro 2.4.0[88] was used for spatial analysis and data visualization.

We selected the eleven biogeographic provinces identified by Rogers et al. which includes all the taxa present in 65 georeferenced hydrothermal sites [see results and supplementary material of Bachraty et al. and Rogers et al. of[15,16]]. We followed the nomenclature used by Boschen et al.: (1) Indian Ocean [IO]; (2) Mid-Atlantic Ridge [MAR]; (3) East Scotia Ridge [ESR] in the Southern Ocean; four provinces in the Western Pacific: (4) West Pacific [WP]; (5) North West Pacific [NWP]; (6) Central South West Pacific [CSWP]; (7) Kermadec Arc [KA]; and four provinces in the Eastern Pacific: (8) North East Pacific [NEP] off the west coast of Canada; (9) Northern East Pacific Rise [NEPR]; (10) Southern East Pacific Rise [SEPR]; (11) South of the Easter Microplate [SEM][89].

Active hydrothermal vents

With the term *active hydrothermal vents* or *active vents*, we consider collectively confirmed-active and inferred-active deep hydrothermal vents based on documented information on the live biota of each vent field. Deep hydrothermal vent fields were selected based on the value ≥ 200 m of the field “Maximum or single reported depth” in the current InterRidge Vents Database (Version 3.4)[39]. The InterRidge database is to date the most up-to-date collection of georeferenced submarine hydrothermal fields. The database was chosen for the comprehensiveness of its data and for the approach behind its creation, which maintains the information public for academic research and education. We hope that the information collected during the study will be integrated into the new version of the database. The information on live biota were retrieved from “Notes Relevant to Biology”[39] complemented with additional information from primary and gray scientific literature. Search terms used to collect additional information were “[name of the hydrothermal vent field]”, “hydrothermal”, “biodiversity”, “biology”, “biota”, “fauna” in Google, Google Scholar, and Scopus search engines. The information on presence and absence of biota, notes, and references are available in the csv file in the Supplementary Dataset. Since the hydrothermal vents took into analysis in this study were only the ones found below 200 meters depth, in case we found updated depth record of fields or sites, we changed the dataset accordingly. For example, the field named Seven Sisters was removed after finding new reference of its depth at 130 m[90].

Conservation interventions

For the purpose of this study, we define conservation intervention as the implementation, establishment or adoption of an intervention that regulates, manages or protects deep-sea hydrothermal vents through regulatory and/or spatial measures applied to a discrete area (i.e., Area Based Management Tools – ABMTs)[91] or to the entire extension of national maritime jurisdiction. These include sectoral and cross-sectoral measures: (i) sectoral or single-sector measures include intervention that manages only one human sector (Fisheries Regulated Areas (FRA), Benthic Protection Areas (BPAs), Vulnerable Marine Ecosystems (VMEs) closures, or temporal moratoria for seabed mining); (ii) cross-sectoral or multi-sectoral measures include interventions that protect the marine environment managing multiple human sectors within their regulatory framework (Marine Protected Areas (MPAs), Sanctuaries, National Monuments, or other effective area-based management measures (OECMs)[12,92]. The shapefiles were downloaded from protectedplanet.net (https://www.protectedplanet.net/en/) (Accessed: March 24, 2021)[93], and from the Vulnerable Marine Ecosystem (VME) closures FAO online dataset (http://www.fao.org/in-action/vulnerable-marine-ecosystems/background/vme-tools/en/#c325329) (Accessed: 21st May 2021)[94]. All the management frameworks, regulations, and legal documents associated with these conservation interventions were obtained from official websites when available and translated into English when necessary.

Protection levels

The distinction between the partial or full level of protection is based on the definition used by Zupan et al.[95], which distinguishes fully and partially marine protected areas based on the prohibition of extractive activities. For the purpose of this study, Zupan’s definition is adapted to hydrothermal vents. Therefore, the relevant extractive activities in this context are the ones considered threatening to hydrothermal vents, namely: seabed mining, bottom trawling fisheries, and commercial harvest for biotechnological purposes[28]. Full protection is assigned to the conservation interventions that prohibit all these three extractive activities. Partial protection is assigned to the conservation interventions that allow, with or without specific regulations, these three extractive activities. We also consider partial protection when one of the three relevant extractive activities is not mentioned in the management measures or in the regulations, or a full protection is not implied with a strong statement such as “all extractive activities that can harm the marine environment and its biota are prohibited”.

Categories of conservation interventions and management of human activities

In this study, conservation interventions are categorized into three groups based on the management measures towards deep hydrothermal vents, named: (i) *Intentional:* hydrothermal vents are explicitly included in the scope of the conservation intervention at the moment of establishment. The management of hydrothermal vents may be a Principal Objective (PO: an intervention specifically established to manage active vents) or a Secondary Objective (SO: an intervention established to manage the deep-sea benthic environment, including hydrothermal vents). (ii) *Adapted:* hydrothermal vents are included in an update of the management framework subsequent to the establishment of the intervention. (iii) *Incidental:* the intervention implicitly protects hydrothermal vents without mentioning them in the management framework.

Additional information captured for each conservation intervention are: (1) year of establishment; (2) year of inclusion of hydrothermal vents in the management framework; (3) whether an intervention is sectoral or cross-sectoral; (4) which biogeographic province defined by Rogers et al. is within the intervention; (5) whether the intervention includes vertical zoning and/or sub-zoning; (6) “Allowed”, “Regulated”, or “Prohibited” human activities within each intervention listed from the most to the least potentially harmful to hydrothermal vents according to Van Dover and Washburn et al.[26,28]: (1) deep-sea mining; (2) bottom fisheries; (3) commercial harvesting for biotechnological purposes (named “commercial harvesting” in Table 1); (4) pollution and dumping; (5) scientific research; (6) cables and pipelines; (7) midwater fisheries; (8) aquaculture; (9) vessel traffic; and (10) tourism.

Limitation of this analysis

This study does not address the long-term effectiveness or the adequacy of the management interventions considered. The lack of baseline and monitoring data on deep-sea marine protected areas prevents a detailed understanding of alternative conservation measures as compared to a multi-sectoral full protection approach. The current achievement of adequate protection of hydrothermal vents must be based on the application of the precautionary principle. The ban of any extractive activity that directly impacts active hydrothermal vent ecosystems (e.g., non-living resource extraction, the harvest of biodiversity or biomass through bottom trawling) and the provision of specific guidelines for activities that only indirectly or accidentally have an impact on the deep sea, is now the only option available.

Another limitation is our understanding of the national and international authorities' ability to enforce necessary controls in the management of active hydrothermal sites within their respective competence, especially considering the remote nature of the activities. From the experience gained from other international parks and sanctuaries, we now know that, without adequate controls, no matter the specificity or complexity of the management measures adopted, the establishment of new protected areas could lead to unmanaged and undermanaged ABMTs (i.e., "paper parks").

Finally, the discrimination between active and inactive hydrothermal sites is sometimes difficult to ascertain due to the possibility of local-scale displacement of the fluid emission or their intermittent activity. This could be crucially important to understand the rationale and effectiveness of protection efforts or its duration over time. From a precautionary management perspective, both active and inactive vents could require protection because inactive vent sites can also host vent-endemic taxa as well as distinctive biodiversity assemblages, and because inactive vents can return to active status over relatively short periods of time[96,97].

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AUTHOR CONTRIBUTIONS

E.Me conceived the study concept, design, analysis, interpretation, and writing. H.C., E.Ma, R.D., and P.N.H. contributed to the discussion, revision, and to the writing of the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

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