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Application of scientific criteria for identifying hydrothermal ecosystems in need of protection

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ABSTRACT

Deep-sea hydrothermal vent fields are globally rare (abundant in numbers, but extremely small in area) and are rich in extraordinary life based on chemosynthesis rather than photosynthesis. Vent fields are also sources of polymetallic sulfides rich in copper and other metals. Mineral resources of the international seabed beyond national jurisdictions (referred to as the "*Area*") are administered by the International Seabed Authority (ISA), which has the mandate to organize and control mineral resource-related activities and to ensure effective protection of the marine environment from harmful effects which may arise from such activities. To date, the ISA has approved 3 contracts for mineral exploration on the northern Mid-Atlantic Ridge (nMAR) and is developing a Regional Environmental Management Plan (REMPs) for polymetallic sulfide resources in the Area of northern MAR, including the application of area-based management tools to address the potential impacts of mining activities. Several intergovernmental organizations have developed suites of criteria to identify vulnerable, sensitive, and ecologically or biologically significant ecosystems in need of protection. In this case study, we combine criteria developed by FAO for VMEs (Vulnerable Marine Ecosystems), by CBD for EBSAs (Ecologically or Biologically Significant Areas), and by IMO for PSSAs (Particularly Sensitive Sea Areas) to assess whether the 11 confirmed vent fields on the nMAR may meet these criteria. Our assessment indicates that all vent fields meet multiple criteria for vulnerability, sensitivity, and ecological or biological significance, and 10 of 11 vent fields meet all criteria for ecosystems in need of protection.

1. Introduction

Deep-sea hydrothermal vents along the neo-volcanic zones of mid-ocean ridges and back-arc spreading centers of the global ocean are celebrated as extraordinary oases of exotic life based on chemosynthesis rather than photosynthesis [1]. These ecosystems are often associated with hydrothermally active polymetallic sulfides (PMS) and are recognized as rare and vulnerable, with intrinsic value [2]. Measures to protect hydrothermal vent ecosystems are already in place within some Exclusive Economic Zones, on Extended Continental Shelf Claims of some coastal States [3], and through regional sea conventions [4]. Where hot fluids rich in sulfide emerge from the ocean crust, the fluid carries with it dissolved metals that precipitate at the seafloor [5]. When hot vents in a given location are hydrothermally active over thousands of years, sulfide minerals accumulate and can form PMS deposits of commercial interest [6]. Within the area of an active hydrothermal vent

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field, there are typically multiple hydrothermal vent sites - specific, local places where hydrothermal fluid emissions occur or had occurred, and eventually formed large sulfide structures also called edifices. Vent sites within a vent field are connected through vent field subsurface circulation. Single vent sites can be hydrothermally active, with emissions of hydrothermal fluids, but can become hydrothermally inactive [7]. At inactive vent sites, the vent communities turn senescent [8], with a concomitant transition in ecological state and loss of vent-obligate taxa over time [9].

The International Seabed Authority (ISA) is the organization through which State Parties to the United Nations Convention on the Law of the Sea (the Convention) administer mineral resources of the seabed in international waters (the *Area*), in accordance with the Convention and the 1994 Agreement relating to the Implementation of Part XI of the Convention. The ISA regulates exploration and exploitation in the *Area* for the benefit of mankind. The ISA is also mandated to ensure effective protection of the marine environment from harmful effects which may arise from activities in the *Area* (https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf; Article 145 of the Convention). To date, the ISA has awarded contracts for PMS exploration on the Indian Ocean Ridge and on the northern Mid-Atlantic Ridge (nMAR) (Fig. 1; https://www.isa.org.jm/exploration-contracts/polymetallic-sulphides). The nMAR includes 11 confirmed active vent fields [10] (https://doi.pangaea.de/10.1594/PANGAEA.917894), of which ten with hydrothermally active or senescent sulfide deposits, and one with carbonate deposits. These vent fields are, from north to south: Lost City (carbonates), Broken Spur, TAG, Snake Pit, Pobeda, Logatchev 1, Logatchev 2 (senescent), Semyenov 2, Irinovskoe, Ashadze 2 and Ashadze 1 (Fig. 1).

The ISA is developing Regional Environmental Management Plans (REMPs) for the nMAR and other priority regions within the *Area* [11], and its Secretariat recently published a guidance document [12] in which scientific and technical approaches for developing REMPs are discussed. These include “coarse filter” and “fine filter” approaches for spatial planning. The “coarse filter” approach—protection of regional areas of the seabed through a network of areas of particular environmental interest (APEIs)—has precedent within the Clarion-Clipperton zone (CCZ) in the Pacific, where exploration interest focuses on polymetallic nodule resources [13]. Designation of APEI networks is a precautionary approach to set aside large areas of the seabed with self-sustaining populations and representative habitats that would be protected from direct and indirect impacts of mining activities [14]. For mid-ocean ridge systems, it will be important to consider an additional “fine filter” approach, for the protection of vulnerable ecosystems such as hydrothermal vents [15–17], coral reefs, and sponge gardens (http://www.fao.org/in-action/vulnerable-marine-ecosystems/vme-indicators/en/). The “fine filter” approach enables the identification and scientific description of sites, at a finer scale, in need of protection to preserve ecological balance of the marine environment, as stipulated in article 145 of the Convention [12]. Their identification will benefit from systematic application of scientific criteria to assess whether an area/site warrants protection/enhanced management. Criteria (and sub-criteria) have been developed by multiple intergovernmental organizations with different purposes to address different types of human impacts [18] (Table 1). For example, these include criteria for identifying priority areas for protection from fishing [(Food and Agricultural Organization (FAO): Vulnerable Marine Ecosystems (VMEs)] and international maritime activities [International Maritime Organization (IMO): Particularly Sensitive Sea Areas (PSSAs)], while CBD scientific criteria addresses inherent ecological and biological value of marine biodiversity and ecosystems, without considering any particular human impacts[Convention on Biological Diversity (CBD): Ecologically or Biologically Significant Areas (EBSAs)]. Here we assess how 10 active and one senescent hydrothermal-vent field(s) along the nMAR in the *Area* fit these criteria (Table 3).

2. Methods

Criteria for designating deep-sea ecosystems as VMEs, EBSAs, or PSSAs are similar, but not identical. We collated these criteria into a derived nomenclature (Table 1, Table 3) for our analysis. Criteria 1–8 (Table 3) are taken verbatim from VME, EBSA, or PSSA criteria. One PSSA criterion (Social, cultural and economic criteria: Social or economic dependency, human dependency, cultural heritage) was deemed not relevant for nMAR hydrothermal ecosystems on a field-by-field basis and was not scored. Instead, a related “Ecosystem services” criterion (Criterion 9, Table 3) is proposed as an alternative. “Ecosystem services” as used here includes supporting, provisioning, regulating, and cultural services [19], and captures social, cultural, scientific, and educational and criteria for PSSAs.

Environmental and biological attributes extracted from the scientific literature and expert knowledge of the authors were used to assess if and how each hydrothermal vent field met each of the criteria. This collated scientific knowledge and evidence (Appendix A) includes information on i) initial discovery and exploration, ii) geological setting, iii) biological characterization, iv) criteria assessment by other intergovernmental organizations and status, and v) scores regarding the relevance of each criterion. Because all active vent ecosystems share a suite of attributes that are relevant to the criteria and because specific vent fields have additional relevant attributes, for each criterion, we summarize (1) how ecosystem attributes associated with the active vent environment apply to that criterion, and (2) additional, specific attributes for each vent field. Where biomass-dominant species are shared across two or more fields, their characteristics for each criterion are repeated verbatim for each vent field in the assessment (see Appendix A).

Relevance scores give evidence on knowledge of ecosystem attributes associated with the environment. The relevance scores were assigned by the authors based on the quality of the evidence provided using the following rules:

High: Well-documented evidence in support of the criterion, including multiple publications, peer-reviewed articles, scientific papers, reports and/or expert knowledge based on direct observations and scientific inference.

Medium: Less well-documented evidence: few publications, but with expert knowledge based on models, indirect observations, scientific inference.

Low: Very limited evidence from publications or expert knowledge and scientific inference.

Unknown: No data/information available.

3. Results and discussion

3.1. Geological, geochemical, and biological features of 11 hydrothermal vent fields on the nMAR

An overview of geological and biological attributes of the 11 vent fields was generated to take into account the major role of the geological and geochemical characteristics of these fields in structuring vent ecosystems and explaining their degree of “uniqueness” (one of the criteria shared among VME, EBSA, and PSSA criteria) (Table 2). The vents considered here occur across a depth range of nearly 3500 m (from 720 to 4200 m) along ~14 degrees of latitude. The estimated areal extent of seafloor massive sulphides at each vent field ranges from 1000 m^2 to 30,000 m^2 (Table 2), with a total areal coverage of 73,000 m^2 (0.073 km^2). The low frequency, abundance, and restricted areal extent of vent fields all support the case that active hydrothermal vent fields on the nMAR are rare, i.e., an indicator of their uniqueness.

Host rock, geological setting, and mineral deposit vary across the different fields. The estimated age of mineral deposits in ka ranges across two orders of magnitude (from 4 to 178 ka). These physical characteristics influence the variations of dissolved chemicals critical to support

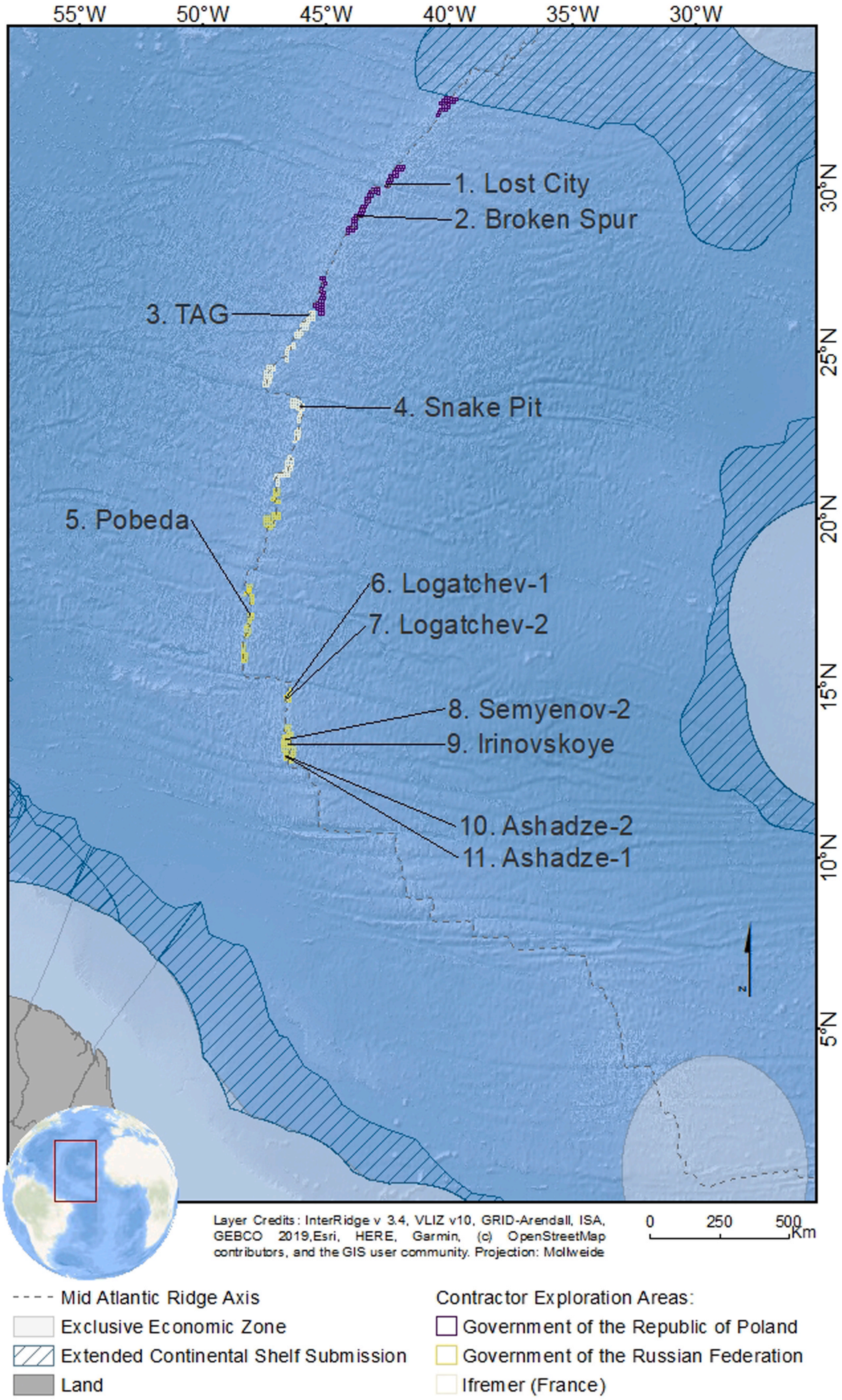

Fig. 1. Locations of the 11 hydrothermal vent fields within the *Area* on the nMAR and of the exploration contract blocks (≤ 10 km x 10 km; not to scale) awarded by the International Seabed Authority to date. Vent field coordinates are from [10] (https://doi.pangaea.de/10.1594/PANGAEA.917894).

Table 1

Nomenclature for 9 criteria used in this study (Column 1), together with a comprehensive, comparative list of criteria from intergovernmental organisations from which our nomenclature is derived. These include criteria to identify priority areas for protection from, (1) fishing [(Food and Agricultural Organization (FAO): Vulnerable Marine Ecosystems (VMEs)] and (2) international maritime activities [International Maritime Organization (IMO): Particularly Sensitive Sea Areas (PSSAs)], as well as (3) for sustainability of marine biodiversity [Convention on Biological Diversity (CBD): Ecologically or Biologically Significant Areas (EBSAs)]. The numbering of the criteria is free of value. Shaded areas indicate when a criterion is not evidently used for the identification of a VME, or EBSA, or PSSA.

	Criteria Used by Intergovernmental Agencies					
This Study	**VME (FAO, 2009)**		**EBSA (CBD, 2009)**		**PSSA (IMO, 2005)**	
	FAO. International guidelines for the management of deep-sea fisheries in the High Seas. Food and Agriculture Organization of the United Nations; 2009 (Paragraph 42). A marine ecosystem should be classified as vulnerable based on the characteristics that it possesses.		CBD (Convention on Biological Diversity), 2009. Azores scientific criteria and guidance for designing ecologically or biologically significant marine areas and designing representative networks of marine protected areas in open waters and deep sea habitats. EBSAs are special areas in the ocean that serve important purposes, in one way or another, to support the healthy functioning of oceans and the many services that it provides.		IMO. Revised guidelines for the identification and designation of particularly sensitive sea areas. International Maritime Organization; 2005. ResolutionA.982(24). PSSA is an area that needs special protection through action by IMO because of its significance for recognized ecological or socio-economic or scientific reasons and which may be vulnerable to damage by international maritime activities.	
1. Uniqueness or rarity	**Uniqueness or rarity**	An area or ecosystem that is unique or that contains rare species whose loss could not be compensated for by similar areas or ecosystems. These include: habitats that contain endemic species; habitats of rare, threatened or endangered species that occur only in discrete areas; or nurseries or discrete feeding, breeding, or spawning areas.	**Uniqueness or rarity**	Area contains either (i) unique ("the only one of its kind"), rare (occurs only in few locations) or endemic species, populations or communities, and/or (ii) unique, rare or distinct, habitats or ecosystems; and/or (iii) unique or unusual geomorphological or oceanographic feature.	**Uniqueness or rarity**	An area or ecosystem is unique if it is "the only one of its kind". Habitats of rare, threatened, or endangered species that occur only in one area are an example. An area or ecosystem is rare if it only occurs in a few locations or has been seriously depleted across its range. An ecosystem may extend beyond country borders, assuming regional or international significance. Nurseries or certain feeding, breeding, or spawning areas may also be rare or unique.
					Representa-tiveness	An area that is an outstanding and illustrative example of specific biodiversity, ecosystems, ecological or physiographic processes, or community or habitat types or other natural characteristics.
					Biogeographic importance	An area that either contains rare biogeographic qualities or is representative of a biogeographic "type" or types, or contains unique or unusual biological, chemical, physical, or geological features.
2. Functional significance	**Functional significance of the habitat**	Discrete areas or habitats that are necessary for the survival, function, spawning/reproduction or recovery of fish stocks, particular life history stages (e.g. nursery grounds or rearing areas), or of rare, threatened or endangered marine species.	**Special importance for life-history stages of species**	Areas that are required for a population to survive and thrive.	**Critical habitat**	An area that may be essential for the survival, function, or recovery of fish stocks or rare or endangered marine species, or for the support of large marine ecosystems.
					Spawning or breeding grounds	An area that may be a critical spawning or breeding ground or nursery area for marine species which may spend the rest of their life-cycle elsewhere, or is recognized as migratory routes for fish, reptiles, birds, mammals, or invertebrates.
			Importance for threatened, endangered or declining species and/or habitats	Area containing habitat for the survival and recovery of endangered, threatened, declining species or area with significant assemblages of such species.		
3. Fragility	**Fragility**	An ecosystem that is highly susceptible to degradation by anthropogenic activities.	**Vulnerability, fragility, sensitivity, or slow recovery**	Areas that contain a relatively high proportion of sensitive habitats, biotopes or species that are functionally fragile (highly susceptible to degradation or depletion by human activity or by natural events). Areas with slow recovery from disturbance.		
					Integrity	

(*continued on next page*)

Table 1 (*continued*)

	Criteria Used by Intergovernmental Agencies					
This Study	VME (FAO, 2009)		EBSA (CBD, 2009)		PSSA (IMO, 2005)	
4. Life-history traits of component species that make recovery difficult	**Life-history traits of component species that make recovery difficult**	Ecosystems that are characterized by populations or assemblages of species with one or more of the following characteristics: slow growth rates; late age of maturity; low or unpredictable recruitment; or long-lived.	**Vulnerability, fragility, sensitivity, or slow recovery**			Integrity – An area that is a biologically functional unit, an effective, self-sustaining ecological entity.
5. Structural complexity	**Structural complexity**	An ecosystem that is characterized by complex physical structures created by significant concentrations of biotic and abiotic features. In these ecosystems, ecological processes are usually highly dependent on these structured systems.			**Dependency**	An area where ecological processes are highly dependent on biotically structured systems (e.g. coral reefs, kelp forests, mangrove forests, seagrass beds). Such ecosystems often have high diversity, which is dependent on the structuring organisms. Dependency also embraces the migratory routes of fish, reptiles, birds, mammals, and invertebrates.
6. Biological diversity	**Structural complexity**	Ecosystems with high diversity dependent on the structuring organisms.	**Biological diversity**	Area contains comparatively higher diversity of ecosystems, habitats, communities, or species, or has higher genetic diversity.	**Diversity**	An area that may have an exceptional variety of species or genetic diversity or includes highly varied ecosystems, habitats, and communities.
7. Biological productivity			**Biological productivity**	Area containing species, populations or communities with comparatively higher natural biological productivity.	**Productivity**	An area that has a particularly high rate of natural biological production. Such productivity is the net result of biological and physical processes which result in an increase in biomass in areas such as oceanic fronts, upwelling areas and some gyres.
8. Naturalness			**Naturalness**	Area with a comparatively higher degree of naturalness as a result of the lack of or low level of human-induced disturbance or degradation.	**Naturalness**	An area that has experienced a relative lack of human-induced disturbance or degradation.
9. Ecosystem services					**Scientific and educational criteria**	Research – An area that has high scientific interest. Baseline for monitoring studies – An area that provides suitable baseline conditions with regard to biota or environmental characteristics, because it has not had substantial perturbations or has been in such a state for a long period of time such that it is considered to be in a natural or near-natural condition. Education – An area that offers an exceptional opportunity to demonstrate particular natural phenomena.
					Social, cultural and economic criteria	*Social or economic dependency* – An area where the environmental quality and the use of living marine resources are of particular social or economic importance, including fishing, recreation, tourism, and the livelihoods of people who depend on access to the area. *Human dependency* – An area that is of particular importance for the support of traditional subsistence or food production activities or for the protection of the cultural resources of the local human populations. *Cultural heritage* – An area that is of particular importance because of the presence of significant historical and archaeological sites.

chemosynthetic production. The sulfide (H_2S): methane (CH_4) ratio, for example, ranges from 0.4 to 84. This ratio was shown to influence the relative abundance of methane- and sulfide-oxidizing endosymbiotic bacteria in the mussel *Bathymodiolus azoricus* [28,29].

Similarities in biomass-dominant species among some vent fields reflect the metapopulation [30] and metacommunity nature [31] of vent ecosystems. Despite these commonalities, the presence/absence and relative abundance of the three most dominant symbiont-hosting endemic taxa differ from field-to-field in response to differences in environmental conditions as well as biotic interactions (Table 2; Fig. 2, Video at https://doi.org/10.17882/74349).

Each of the vent fields considered here is singular in terms of its physico-chemical setting and dominant taxa (Table 2, Appendix A). This extreme level of vent-field heterogeneity on the nMAR was recognized more than two decades ago [32,33]. Lost City stands out as an exceptional field among the fields considered, with unique physico-chemical attributes. This carbonate formation harbour fluids emanating at pH > 10 instead of 4.5 for the end-member fluids of the more common sulfide formations (Table 2).

3.2. Generic and field-by-field characteristics of active hydrothermal fields on the nMAR applicable to VME, EBSA, and PSSA criteria

By their very nature, hydrothermal vent fields on the nMAR share fundamental ecological characters relevant to each of the 9 criteria assessed. A summary of these shared attributes is provided here:

1. **Uniqueness and rarity:** Vent fields host small, island-like ecosystems with distinctive biotic and abiotic features [34,35] (Table 2). Globally, the active vent habitat occupies an area less than that of the island of Manhattan [2]. Free-living and autotrophic microorganisms dependent on reduced compounds in the hydrothermal fluids serve as the base of the chemosynthetic ecosystem [36,37]. Juveniles and adults of vent-endemic (vent-obligate) taxa are adapted to the extreme chemical and physical conditions of the vent habitat and thrive in these specialized (unique) ecosystems [38]. Given the very small and discrete areas they inhabit, vent-endemic species are globally rare [2,39].
2. **Functional significance:** All active hydrothermal vents support primary production by microorganisms, serve as discrete feeding area, and are essential for the growth, survival, reproduction, and persistence of vent endemic species [31,38].
3. **Fragility:** All active vent fields are fragile ecosystems that are geographically isolated and discrete [35], hosting populations of benthic invertebrate species that rely on dispersal through pelagic larval stages [40] for maintenance of populations and genetic connectivity. Habitat degradation and fragmentation due to anthropogenic disturbance may result in local loss of biodiversity [41–43] and ecosystem services [44]. Connectivity among metapopulations of species is characterized by source-sink dynamics, making these systems sensitive to reduction or loss of source populations [30,45,46], with ecological consequences on the structure and function of metacommunities [31].
4. **Life-history traits of component species that make recovery difficult:** Recovery dynamics of vent faunal communities on slow-spreading ridges, such as the Mid-Atlantic Ridge, are unknown. Because MAR vent fields are hydrothermally active for longer periods (thousands of years) than those on faster-spreading ridges (years to decades), they may have slower recovery trajectories [47,48]. Some vent species are widespread on the MAR (e.g., *Rimicaris exoculata* shrimp; *Shinkailepas briandi* limpets) [49–51], others are not (e.g., *Bathymodiolus* sp. mussels) [45]. Source/sink and recruitment dynamics in vent ecosystems are poorly known if at all, and are likely to be unpredictable given that organisms disperse in the water column [40,48]. While genetic connectivity observed for some species at vents on the nMAR depends on long-distance dispersal [45], population maintenance at a given site may depend primarily on self-recruitment (i.e., local sources and sinks) [52]. There is currently little data available on the autecology of smaller species (macrofauna & meiofauna). For example, some meiofauna have distinct life-history traits compared to the macrofauna, such as the lack of larval dispersal for nematodes [53], which may make recovery after disturbance difficult [8,54].
5. **Structural complexity:** At all active hydrothermal fields, there are complex gradients of geological, geochemical, and thermal conditions that correlate with ecological zonation [38,55]. Engineer (foundation) species modify physical and (or) chemical environments by altering fluid flow and chemistry [56], contributing to increased environmental heterogeneity. This structural complexity within a field is illustrated by a photomontage of microhabitats at the Snake Pit vent field (Fig. 3), including mussel beds (Fig. 3a), adult (Fig. 3b) and juvenile (Fig. 3c) shrimp swarms, and gastropod patches (Fig. 3d). Through evolutionary processes, species at active hydrothermal vents have adapted to extreme environmental conditions, including tolerance to high temperature, low oxygen, and high metal concentrations [57].
6. **Biological diversity:** Biodiversity of microbial communities is very rich at hydrothermal vents [58,59]. Vent-endemic animal species contribute novel diversity to the deep-sea fauna, often at taxonomic levels higher than genus and with radiations correlated with environmental attributes including ocean basin, depth, fluid chemistry, and temperature (e.g. polynoid scale worms, alvinocaridid shrimp, bathymodiolin mussels, bythograeid crabs). Habitat heterogeneity and structural complexity provide niches for diverse species [38]. As an example, 79 metazoan species were encountered on a single vent edifice at the Lucky Strike vent field on the nMAR [60]. There is no recently updated species list from nMAR vents, but in 2006, Gebruk & Mironov listed 191 invertebrate species and ~40 fish species [61]. More than 100 animal species are formally described from the nMAR and many of these are endemic to the vent environment [62]. Hydrothermal vent organisms are valued for their genetic diversity [2,63].
7. **Biological productivity:** Chemoautotrophic microorganisms use the chemical energy of hydrothermal fluids to fix inorganic carbon and produce biomass [59]. High biological in situ productivity is found at most active hydrothermal vents [38]. Chemoautotrophic productivity occurs below the seafloor [64], on the seafloor as free-living microbes (attached or suspended), or living in symbiosis with large invertebrate species. This production is transferred to higher trophic levels [38,65].
8. **Naturalness:** Hydrothermal vents are relatively undisturbed [66]. The only interventions to date are those of scientists and mineral resource explorers. An *Interridge Code of Conduct* guides scientific research and emphasizes avoidance of any scientific activity that would have a deleterious effect on the persistence of populations or that would lead to sustained alteration or visible degradation [67].
9. **Ecosystem Services:** Living resources from hydrothermal vent ecosystems provide or have high potential to provide provisioning services, including genetic resources, bioprospecting or bioinspired materials/processes [2]. Hydrothermal vents also harbour energetical and mineral resources not yet exploited. Hydrothermal vents contribute to regulating and supporting services including carbon sequestration by biological pump, or microbial oxidation of the greenhouse gas methane [68] and represent major source of iron, an essential trace element that controls marine productivity, in the global ocean [69]. Vents offer cultural services in the form of exceptional inspiration for arts, science, technology and our world [2]. Hydrothermal vents have been and continue to be fruitful areas for fundamental, interdisciplinary, scientific research. Discovery of hydrothermal vents [70] revolutionized our view of life in our oceans and the potential for life on other planetary bodies [38]. Hydrothermal vents are living libraries that open new paths for

Table 2

Selected attributes of 11 vent fields on the northern Mid-Atlantic Ridge. Area (m^2) refers to estimated areal extent of seafloor massive sulphides (or carbonates, in the case of Lost City) and may be smaller than the total estimated area of a vent field; []: concentration in mmol kg^{-1}, end-member fluid; n.d.: no data.

ATTRIBUTE	HYDROTHERMAL VENT FIELD (north to south)										
	Lost City	**Broken Spur**	**TAG**	**Snake Pit**	**Pobeda**	**Logatchev 1**	**Logatchev 2 (senescent)**	**Semyenov 2**	**Irinovskoe**	**Ashadze 2**	**Ashadze 1**
Latitude	30°07′N	29°10′N	26° 8′N	23° 22′N	17°07′N–17°08′N	14°45′N	14°43′N	13°31′N	13°19′N	12°59′N	12°58′N
Depth (m)	720–850	3100	3436—3670	3350—3500	1950—3100	3050	2640—2760	2360—2580	2700–2890	3260—3300	4200
Host rock	serpentinized peridotite	basalt	basalt	basalt	n.d.	basalt serpentinized peridotite	basalt serpentinized peridotite	basalt	serpentinized peridotite	serpentinized peridotite	serpentinized peridotite
Geological setting	tectonic	magmatic	tectonic	magmatic	n.d.	tectonic	tectonic	tectonic	tectonic	tectonic	tectonic
Area (m^2)	10,000	5000	30,000	3000	n.d.	5000	1000	3000	10000	1000	5000
Mineral	carbonate	sulfide	sulfide	sulfide	sulfide	sulfide	sulfide	sulfide	sulfide	sulfide	sulfide
T_{max} (°C) end-member fluid	116	364	321	350	n.d.	352	320	n.d.	n.d.	296	370
pH_{min}	10.4	n.d.	3.1	3.7	n.d.	3.3	4.4	n.d.	n.d.	n.d.	3.9
$[H_2S]_{max}$	n.d.	11	6.7	5.9	n.d.	0.8	< 0.5	n.d.	n.d.	n.d.	< 0.5
$[CH_4]_{max}$	1.26	0.13	0.147	0.062	n.d.	2.1	“very high”	n.d.	n.d.	n.d.	“very high”
$[H_2]_{max}$	10.8	1.03	0.37	0.48	n.d.	12	“very high”	n.d.	n.d.	n.d.	“very high”
Deposit Age_{max} (ka)	120	177.5	20	3.7	177	58	7	76	69	27	7.2
Vent-endemic Taxa (for further details and references see Appendix A)											
Rimicaris exoculata shrimp	absent	biomass dominant	biomass dominant	biomass dominant	n.d.	biomass dominant	absent	absent	n.d.	n.d.	present
Bathymodiolus spp. *mussel*	present	biomass dominant	absent	biomass dominant	n.d.	biomass dominant	present	biomass dominant	present	n.d.	absent
Maractis rimicarivora anemone	absent	biomass dominant	biomass dominant	present	n.d.	present	absent	absent	n.d.	n.d.	biomass dominant
Other Taxa	microbial communities with high pH affinities	*Keldyshicaris vavilovi* shrimp; mussel hybrids	chaetopterid polychaetes	cutthroat eels	“shrimp and bivalves”; shells from *Bathymodiolus* and *Thyasira*	*Abyssogena southwardae* clams	extensive field of mussel shells; *Rimicaris chacei* & *Microcaris fortunata* shrimp	*Opaepele susannae* shrimp	n.d.	*Mirocaris fortunata shrimp*	*Phyllochaetopterus polus* polychaetes

Sources: [10,19–27].

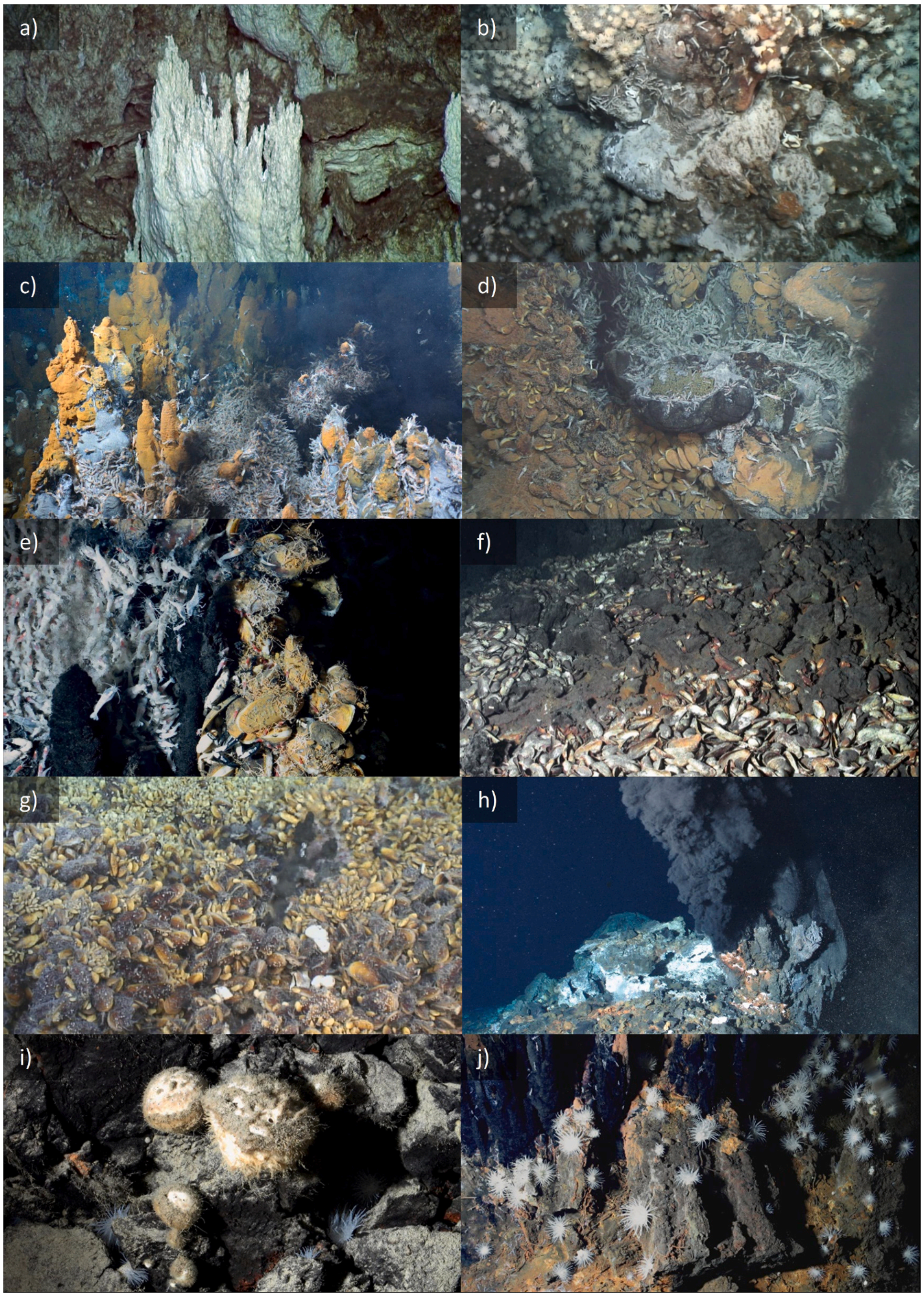

Fig. 2. Selected ecological features of 11 hydrothermal vent fields on the nMAR. a) Lost City with carbonate structures and microbial communities with affinities to high pH (>10); b) Broken Spur with anemones, *Rimicaris* shrimp (and hybrid *Bathymodiolus azoricus/puteoserpentis* mussels not shown); c) TAG with dense *Rimicaris exoculata* shrimp swarms; d) Snake Pit with dense *Bathymodiolus puteoserpentis* mussel beds, *Rimicaris exoculata* shrimp swarms (and cutthroat eels, not shown); e) Logatchev-1 with dense *Bathymodiolus puteoserpentis* mussel beds, *Rimicaris exoculata* shrimp swarms (*Abyssogena southwardae* clams not shown); f) Logatchev-2 with extensive mussel shell field (senescent vent); g) Semyenov-2 with dense *Bathymodiolus puteoserpentis* mussels (and *Opaepele* shrimp not shown); h) Irinovskoe (with *Bathymodiolus puteoserpentis* mussels, not shown); i) Ashadze-2 (with *Mirocaris* shrimp not shown); j) Ashadze-1 with anemone field. No photograph was available for the vent field Pobeda (with shrimp and bivalves). All images are copyright Ifremer (a, b: TRANSECT cruise 2018; c, d: BICOSE 2 cruise 2018; e, f, i, j: SERPENTINE cruise 2007; g, h: ODEMAR cruise 2013).

understanding the intersection of Life and Earth processes [2,71]. Every studied vent field to date has increased the scientific knowledge, documented through the prolific and highly cited scientific literature [71]. Hydrothermal vents serve as scientific research grounds—several vent fields along the nMAR are amongst the most-studied worldwide and a 10 year observatory is deployed on one of them in the EEZ of Portugal (EMSO-Açores). As such, these repeatedly visited vent fields are yielding time-series data that help us understand system dynamics; they are used as experimental sites and they constitute a baseline for monitoring anthropogenic induced changes. Due to their uniqueness, each of the 11 vent fields may be used as a science or education example of particular geological, geophysical or biological attributes.

In addition to these general features of nMAR hydrothermal-vent ecosystems, there is scientific evidence specific to each field that supports each criterion for identifying marine areas in need of enhanced management and protection (Appendix A). The outcome of the generic and field-by-field collation of scientific evidence is that all active hydrothermal vent fields considered meet multiple criteria, and 10 of 11 active fields meet at least one sub-criterion for each criterion at a high level of relevance (Table 3). Three sub-criteria related to specific life-history traits [slow growth rates (4.1), late age of maturity (4.2), long-lived species (4.4)] are of low-to-moderate relevance. We acknowledge that the quantity of scientific data highly differs between vent fields, with for example high amount of scientific studies at Broken Spur, TAG, Snake Pit, and Logatchev-1. This contrasts with the low amount of scientific studies at Pobeda and Ashadze-2. We conclude that the high scientific knowledge on fundamental ecological processes and characteristics of active hydrothermal vents, in combination with in situ

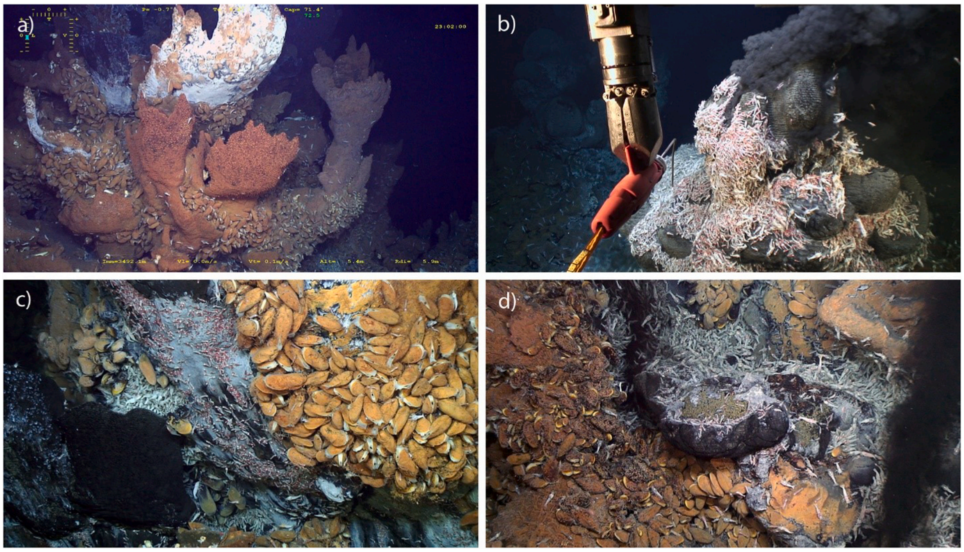

Fig. 3. Structural and habitat diversity within the vent field Snake Pit (3350–3500 m). Images show patchy *Bathymodiolus puteoserpentis* mussel assemblages on the Elan edifice (a); *Rimicaris exoculata* (adult) shrimp swarms on Les Ruches (b); juvenile shrimp swarms & large mussels on Elan (c); *Peltospira smaragdina* gastropod assemblages (center) surrounded by shrimp and mussels on Elan (d). BICOSE 2014 cruise copyright Ifremer. Video of a, b, and d is available at https://doi.org/10.17882/74349.

evidence of hydrothermal activity and presence of typical vent megafauna, justifies "high" evidence ranking, also for the relatively poorly studied Pobeda and Ashadze-2. Still, it is acknowledged that future scientific studies shall be undertaken to further strengthen the here proposed rating of these two vent fields, currently based on direct observations and scientific interference.

In contrast to our high scientific understanding of active vent communities, our scientific understanding of ecological processes and characters of senescent vent communities is very limited. This led to high uncertainty regarding the degree to which the Logatchev-2 vent field meets most of the criteria (indicated by "?" in Table 3). Logatchev-2 harbours a senescent vent community with extensive dead mussel shell fields and only a few live mussels, as well as shrimp were recorded on the single active chimney [72]. Although some vent endemic invertebrates have been observed at this field, it is currently not clear to which extent Logatchev-2 is essential for the survival, reproduction, and recovery of vent endemic species. There are no data on associated fauna from the senescent Logatchev-2, but studies at the East Pacific Rise showed that nematodes, which lack larval phases, and harpacticoid copepods were thriving at senescent vents and may play an important role for the recovery of meiofaunal communities at active vents [8,54]. In addition, there may be a functional significance of senescent vents with regard to productivity transfer to other deep-sea ecosystems [55]. Additional scientific studies of senescent vent communities are crucial to reduce current uncertainties.

3.3. Existing conservation tools for 11 hydrothermal vent fields on the nMAR

Notably, four of the 11 fields (Lost City, Broken Spur, TAG, Snake Pit) on the nMAR in the *Area* are already described as *Ecologically or Biologically Significant Areas* through the Convention on Biological Diversity (https://chm.cbd.int/database/record?documentID=204107). The other 7 fields fell outside the geographical scope of the Northwest Atlantic Regional EBSA Workshop, but active vent fields known south of Snake Pit, were recommended for consideration as EBSAs in the future. Lost City has also been recognized in the world heritage reports for its potential outstanding universal value in the high seas [73].

The FAO recognizes that hydrothermal vents are VMEs and host VME species: resolution 61/105, Paragraph 83 (adopted by the UNGA in 2006) states that "In respect of areas where vulnerable marine ecosystems, including seamounts, hydrothermal vents and cold water corals, are known to occur or are likely to occur based on the best available scientific information, to close such areas to bottom fishing and ensure that such activities do not proceed unless conservation and management measures have been established to prevent significant adverse impacts on vulnerable marine ecosystems" (http://www.fao.org/in-action/vulnerable-marine-ecosystems/criteria/en/). The Western Central Atlantic Fishery Commission (WECAFC) delineated an area on the Mid-Atlantic Ridge from ~31°N to ~23°N known to contain active hydrothermal vents (Lost City, Broken Spur, TAG, Snake Pit) (see Figure 25 in [74]), but as WECAFC is a Regional Fisheries Body (RFB) without a management remit, the VME database does not include this delineation (http://www.fao.org/in-action/vulnerable-marine-ecosystems/vme-database/en/vme.html). The IMO has to date no designated PSSA areas along the nMAR in the *Area*. The ISA is currently considering "fine filter" approaches to identify sites in need of protection [12,75].

4. Conclusions

Scientific criteria used to identify VMEs, PSSAs, and EBSAs can be applied to deep-sea hydrothermal vent environments and may assist the ISA in creating a robust "fine filter" approach to protect vulnerable, sensitive, and ecologically or biologically important ecosystems from the impacts of mining activities. Collation of scientific evidence for 10 active and one senescent hydrothermal vent(s) in the *Area* on the nMAR highlights the uniqueness or rarity of these fields, their functional significance and fragility. It identifies life-history traits that make recovery difficult, shows structural complexity, highlights biodiversity and productivity patterns, as well as the ecosystem services of these specific ecosystems. By the criteria used here and advanced by the FAO, IMO, and CBD, these hydrothermal fields are vulnerable, sensitive, and ecologically and biologically significant ecosystems in need of protection. Field-by-field assessment of the importance of each vent field as undertaken here is an essential step in designing a future network of protected areas on mid-ocean ridges. The implementation of a "fine filter" approach combined with a regional "coarse filter" approach using network criteria (i.e. representativity, connectivity, replication or adequacy) could help the ISA address the full range of regional environmental planning objectives [12,17].

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Table 3

Definition and application of scientific criteria for identifying hydrothermal ecosystems in need of conservation at 11 hydrothermal vent fields on the nMAR. Fauna and microorganisms were considered, with recognition that microorganisms are not strictly considered "species". "Endemic" refers to "vent-endemic", as applied by FAO ("Seep and vent communities comprised of invertebrate and microbial species found nowhere else i.e. endemic"). color codes for levels of relevance for each criterion: Green: high (+); yellow: medium (=); red: low (-); ?: insufficient information. Details of the scientific evidence supporting each score are provided in Appendix A.

Criterion	Subcriteria	nMAR Vent Fields in the *Area* (North to South)										
		Lost City	Broken Spur	TAG	Snake Pit	Pobeda	Logatchev 1	Logatchev 2	SemVenov	Irinovskoe	Ashadze 2	Ashadze 1
1.Uniqueness or rarity. An area or ecosystem that is unique or that contains rare species whose loss could not be compensated for by similar areas or ecosystems. These include	1.1 habitats that contain endemic species	+	+	+	+	+	+	=	+	+	+	+
	1.2 habitats of rare, threatened, or endangered species; only in discrete areas	+	+	+	+	+	+	=	+	+	+	+
	1.3 nurseries or discrete feeding, breeding, or spawning areas	?	+	+	+	+	+	=	+	+	+	+
	1.4 unique or unusual biotic or abiotic features (chemical, physical, geological)	+	+	+	+	+	+	+	+	+	+	+
2. Functional significance. A discrete area or habitats that are necessary	2.1 for survival, function (e.g. feeding), spawning/reproduction, or recovery of species	+	+	+	+	+	+	?	+	+	+	+
	2.2 for particular life history stages (e.g., nursery grounds or rearing areas, migratory routes for fish, reptiles, birds, mammals, invertebrates)	?	+	+	+	+	+	?	+	+	+	+
	2.3 for rare, threatened, or endangered marine species	+	+	+	+	+	+	?	+	+	+	+
3. Fragility	3.1 An area that contains a relatively high proportion of sensitive habitats, biotopes or species that are functionally fragile (highly susceptible to degradation or depletion by human activity or by natural events)	+	+	+	+	+	+	+	+	+	+	+
4. Life-history traits that make recovery difficult. Ecosystems that are characterized by populations or assemblages of species with one or more of the following characteristics	4.1 slow growth rates	-	-	-	-	-	-	?	-	-	-	-
	4.2 late age of maturity	-	-	-	-	-	-	?	-	-	-	-
	4.3 low or unpredictable recruitment	+	+	+	+	+	+	?	+	+	+	+
	4.4 long-lived species	=	=	=	=	=	=	?	=	=	=	=
5. Structural complexity. An area or ecosystem that is characterized by	5.1 complex physical structures created by biotic and abiotic features	+	+	+	+	+	+	+	+	+	+	+
	5.2 ecological processes are dependent on these structured physical systems	+	+	+	+	+	+	?	+	+	+	+
6. Biological diversity	6.1 An area that contains comparatively higher diversity of ecosystems (including high diversity associated to complex structures), habitats, communities, or species, or has higher genetic diversity	+	+	+	+	+	+	+	+	+	+	+
7. Biological productivity	7.1 An area that has a particularly high rate of natural biological production. Such productivity is the net result of biological and physical processes which result in an increase in biomass	+	+	+	+	+	+	?	+	+	+	+
8. Naturalness	8.1 An area with a comparatively higher degree of naturalness as a result of the lack of or low level of human-induced disturbance or degradation	+	+	+	+	+	+	+	+	+	+	+
9. Ecosystem services. An area or ecosystem that provides or has high potential to provide	9.1 provisioning services, such as food, materials and energy, which are directly used by people (including marine genetic resources and bioprospecting, bioinspired materials, bioinspired processes)	+	+	+	+	+	+	?	+	+	+	+
	9.2 regulating services, that cover the way ecosystems regulate other environmental media or processes (including climate regulation, biological pump and carbon sequestration)	+	+	+	+	+	+	?	+	+	+	+
	9.3 cultural services that are related to the cultural or spiritual needs of people. These include spiritual services, aesthetic services, recreation, education (e.g. an area that offers an exceptional opportunity to demonstrate particular natural phenomena), and science (e.g. an research area hat has high scientific interest, increasing scientific knowledge; or e.g. an area that provides suitable baseline monitoring conditions because it is in near natural condition)	+	+	+	+	+	+	+	+	+	+	+
	9.4 supporting services, such as ecosystem processes and functions that underpin other three types of services (including primary production, nutrient cycling)	+	+	+	+	+	+	?	+	+	+	+

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CRediT authorship contribution statement

All authors contributed to the conception and design of the study, acquisition of data, and interpretation of the data. All authors drafted the manuscript and the appendix. All authors revised the manuscript critically for intellectual content and approved the final version of the manuscript.

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Competing interests

The authors declare no competing interests.

Data and materials availability

All data is available in the main text or in the appendix.

Appendix A

A collation of scientific evidence for describing/identifying hydrothermal ecosystems in need of conservation at 11 hydrothermal vent fields on the nMAR. This evidence includes information on i) initial discovery and explorations, ii) geological setting, iii) biological characterization, iv) ecological importance criteria assessment by other inter-governmental organizations and status, and v) scores regarding the relevance of each criterion. Where biomass-dominant species are shared across two or more fields, their characteristics for each criterion are repeated verbatim for each vent field in the assessment. The same repetitive procedure is used for ecosystem attributes associated with the active vent environment. Scientific evidence supporting a criterion that applies across all vent fields, is summarized in the main manuscript text.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2021.104641.

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