

DEEPMAP: A DECISION-SUPPORT CARTOGRAPHIC FRAMEWORK FOR INTEGRATED SPATIAL GOVERNANCE OF DEEP-SEA MINING IN THE ATLANTIC OCEAN

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Abstract

The governance of seafloor massive sulphide (SMS) mining in the Atlantic Ocean faces a recurring spatial tension: many Mid-Atlantic Ridge (MAR) vent fields with high ecological uniqueness lie within, or near, zones of present or potential commercial interest. Existing instruments — the International Seabed Authority (ISA) contract framework and the OSPAR Marine Protected Area network — provide partial, at times legally uneven protection. We present DEEPMAP (Deep-sea Environmental Atlas and Mapping for Policy), an integrated cartographic and analytical framework synthesising 23 confirmed hydrothermal vent fields, three active ISA SMS contracts (~30,000 km²), nine OSPAR MPAs in Areas Beyond National Jurisdiction, the Azores moratorium (Lei 36/2025), ecological sensitivity zones, plume dispersal envelopes, and cold-water coral distributions. A five-criterion weighted vulnerability framework (validated against an independent ranking; Cohen's $\kappa = 0.85$) classifies six fields as HIGH vulnerability: Lucky Strike, Lost City, Rainbow, Logatchev, Menez Gwen, and TAG. All six fall within ISA contract areas, identified commercial extraction targets, or zones where the Portuguese moratorium provides the principal operative protection; one field (Rainbow) lies within a formal OSPAR MPA, and nine fields lie in unprotected Areas Beyond National Jurisdiction. A basin-scale Biodiversity Risk Index, computed on a hexagonal grid using OBIS records and chemosynthetic habitat proximity, extends the

pattern to the Rio Grande Rise, East Scotia Ridge, Drake Passage, and South MAR. Monte Carlo sensitivity analysis confirms classification robustness to weight uncertainty. We derive five governance recommendations addressing the ISA REMP process, OSPAR MPA expansion, Lost City APEI designation, and Atlantic intergovernmental coordination.

Keywords: deep-sea mining; seafloor massive sulphides; vulnerability mapping; marine spatial planning; Mid-Atlantic Ridge; ISA REMP; OSPAR; ocean governance

1. Introduction

The global demand for copper, zinc, cobalt, and manganese — essential to electric vehicle batteries, offshore wind turbines, and grid-scale energy storage — has intensified industrial interest in seafloor massive sulphides (SMS), formed where metalliferous hydrothermal fluids precipitate upon contact with seawater at mid-ocean ridges and volcanic arcs (Hannington et al., 2011; Hein et al., 2020). The International Seabed Authority (ISA) has issued seven 15-year SMS exploration contracts, three of which delineate ~30,000 km² of the Mid-Atlantic Ridge (MAR) for potential extraction. In January 2024, Norway authorised commercial SMS exploration on its extended continental shelf, becoming the first sovereign state to do so and generating substantial scientific and diplomatic pushback (Duarte et al., 2025). These developments frame a question of mounting urgency: whether the existing

governance architecture is capable of discharging the obligations that international law — principally UNCLOS Articles 145 and 194 — places on states and international organisations to prevent serious harm to the marine environment from seabed exploitation.

The governance architecture, in its current state, is not adequate to that task. The ISA Mining Code remains unfinished after two decades; OSPAR MPA coverage of Atlantic vent fields is almost negligible; and the ecological baseline for most Atlantic hydrothermal systems is fragmentary, scattered across specialist databases inaccessible to policy audiences, and entirely absent for several fields of high commercial interest (Boschen-Rose et al., 2021; Chapman et al., 2024; Dunn et al., 2018). This informational deficit is not merely a scientific inconvenience: it is a governance risk, because decisions affecting irreplaceable deep-ocean ecosystems are being made in conditions of institutional uncertainty that the precautionary principle, as enshrined in UNCLOS, is expressly designed to address.

The Atlantic basin compounds this challenge with distinctive governance complexity. Unlike the Pacific's Clarion-Clipperton Zone (CCZ), where a single ISA management framework covers a geologically uniform nodule field in a relatively consolidated jurisdictional space, the Atlantic SMS governance landscape fragments across overlapping national EEZs, OSPAR regulatory jurisdiction (North Atlantic), the EU Blue Economy strategy, the emerging BBNJ Agreement framework, and the specific maritime claims of island states — Portugal (Azores), the United Kingdom (Ascension Island, Tristan da Cunha, South Georgia), Brazil (Rio Grande Rise extended shelf) — whose EEZs contain some of the ecologically most sensitive vent fields on the ridge. Managing this patchwork requires spatial intelligence that currently does not exist in a synthesised, accessible form.

Portugal's enactment of Law No. 36/2025 (31 March 2025), establishing a moratorium on deepsea mineral exploitation within the Azores EEZ until 2050, constitutes the most significant Atlantic governance milestone of recent years. The Azores EEZ encompasses three HIGH-vulnerability vent fields — Menez Gwen, Lucky Strike, and Rainbow — together with the diffuse-flow field at Saldanha, protected fields that anchor the primary larval connectivity corridor of the northern MAR (Boschen-Rose et al., 2021). The moratorium was endorsed by more than 30 nations and 700 scientists and aligns the Azores with the global precautionary movement initiated at the 2022 UN Ocean Conference. However, a moratorium without an accompanying programme of spatial knowledge production risks becoming a governance symbol rather than a governance tool — effective only so long as it is not legally challenged by actors with commercial interests and UNCLOS standing. The scientific evidence needed to defend and replicate the moratorium must be built while the moratorium is in force.

To our knowledge, prior assessments have either focused on subsets of MAR vent fields or have addressed individual governance instruments separately rather than in combination. The need to view ecological vulnerability and the suite of governance overlays (ISA contracts, OSPAR MPAs, and national jurisdiction boundaries) in a single spatial frame motivates the present synthesis. Dunn et al. (2018) integrated biodiversity and geological data to support REMP development for a subset of northern MAR sites, providing an important baseline that the present work extends to additional fields and to the wider Atlantic basin. Boschen-Rose et al. (2021) developed a functional trait sensitivity framework for northern MAR assemblages, with a primary emphasis on taxa-level sensitivity. The present study draws on that framework as an external benchmark for field-level vulnerability

classification (Section 2.3). Van Dover et al. (2018) articulated the scientific rationale for active vent field protection. The present manuscript builds on that argument by combining a transparent multi-criterion scoring scheme with explicit overlay of governance instruments. DEEPMAP combines three elements that are useful when considered together: (i) a transparent multi-criterion vulnerability score applied consistently across the 23 currently catalogued MAR vent fields; (ii) explicit spatial overlay with the principal governance instruments active in the Atlantic; and (iii) cartographic outputs designed to be readable by non-specialist policy audiences. An accompanying Biodiversity Risk Index (BRI) extends the analysis to the wider Atlantic basin using a hexagonal grid, providing a spatially continuous indicator that complements the field-level vulnerability classification.

The DEEPMAP project (Deep-sea Environmental Atlas and Mapping for Policy) was developed to address this requirement directly. DEEPMAP integrates geological, ecological, and regulatory data for the Atlantic basin into a unified cartographic synthesis combined with a validated vulnerability classification framework and a spatially explicit Atlantic-scale Biodiversity Risk Index (BRI). The present paper describes DEEPMAP's methodology (Section 2), presents its principal spatial results for the MAR (Section 3.1–3.3) and the extended Atlantic with weight sensitivity analysis (Section 3.4), discusses the governance implications of the congruence paradox (Section 4), and advances five concrete policy recommendations (Section 5).

2. Materials and Methods

2.1 Study Area

The primary study area spans the Mid-Atlantic Ridge between 63°06'N (Steinahóll, Reykjanes Ridge) and 8°18'S (Nibelungen, equatorial

MAR), covering the full latitudinal range of confirmed hydrothermal vent fields on the ridge. The extended Atlantic analysis encompasses 70°N–60°S and 100°W–20°E, capturing the Rio Grande Rise (~30°S, 38°W), South MAR (~38–45°S), Drake Passage (~55°S), East Scotia Ridge (~57°S), Canary Basin (~28°N, 20°W), Cape Verde hydrothermal province (~16°N), and the Gulf of Guinea SMS province (~3°N). All analyses use the WGS 84 datum (EPSG:4326).

2.2 Data Compilation

Data were compiled from seven primary source categories with cross-referencing against ≥ 2 independent sources before inclusion. Hydrothermal vent field records were extracted from the InterRidge Global Database v3.4 (Beaulieu and Szafranski, 2020; PANGAEA doi:10.1594/PANGAEA.917894) and enriched through systematic literature review. Targeted Web of Science and Scopus searches (2020–2025) captured three post-v3.4 discoveries: Puy des Folles (Schmidt Ocean Institute, 2023; R/V Falkor(too) FK230804; 5 active sites, 18 km², first MAR discovery in that latitude band in >40 years), Koralovoe (Sudarikov et al., 2021), and the expanded Steinahóll complex incorporating Hafgufa, Stökkull, and Lyngbakr (Devey et al., 2021). Russian-language primary literature was accessed through Doklady Earth Sciences and crossreferenced with English-language reviews. For each field, the following attributes were compiled: geographic coordinates (decimal degrees, WGS 84, verified against original cruise reports), depth (m), activity status, host-rock lithology, SMS deposit characteristics where available, discovery expedition, and primary references.

ISA SMS exploration contract boundaries (n = 3) were digitised from ISA Technical Documents and Decision Notices as bounding rectangles based on published coordinate ranges. The three

MAR contracts are: (a) Yuzhmoregeologiya (Russia, 12–21°N, ~10,000 km², encompassing Logatchev, Ashadze, Semenov, Krasnov, Zenith-Victory, Pobeda, Irinovskoye, and Korolovoe); (b) Government of Poland (26–33°N, Hayes-Kane Transform Fault, ~10,000 km², encompassing Lost City and Broken Spur); (c) IFREMER (France, south of the Azores). The absence of publicly available non-contiguous block geometries is a known limitation discussed in Section 4.4.

OSPAR MPA boundaries (n = 9 in ABNJ) were sourced from the OSPAR Commission 2021 Status Report and the OSPAR MPA database (<https://mpa.ospar.org>). Ecological sensitivity zones were derived from the functional trait clusters of Boschen-Rose et al. (2021) for 158 benthic invertebrate taxa from northern MAR habitats. Plume dispersal envelopes were based on MuñozRoyo et al. (2022) and Morato et al. (2022). Cold-water coral distributions followed Mortensen et al. (2008) from MAR-ECO expedition data.

2.3 Vulnerability Classification Framework

A four-tier vulnerability classification (HIGH, MEDIUM, LOW, INACTIVE) was developed for each of the 23 MAR vent fields by integrating five ecological criteria drawn from Van Dover et al. (2018), Boschen-Rose et al. (2021), and Chapman et al. (2024). Each criterion was scored on an ordinal three-point scale (1 = low concern; 2 = moderate; 3 = high) and the composite vulnerability score V computed as a weighted linear combination ($V = 0.20 \cdot R + 0.25 \cdot E + 0.20 \cdot F + 0.20 \cdot C + 0.15 \cdot P$; full criterion definitions and weighting rationale provided in Supplementary Material), where R = taxonomic richness, E = endemism and uniqueness, F = functional trait sensitivity, C = population connectivity (inverted,

so isolation scores highest), and P = recovery potential (inverted, so slow recovery scores highest). Weights were assigned a priori based on conservation biology principles: endemism/uniqueness received the highest weight (0.25) reflecting its primacy in irreversibility assessments (Van Dover et al., 2018), with the remaining criteria weighted equally at 0.20 except recovery potential (0.15) which was downweighted to avoid double-counting with irreversibility already captured in E . Tier thresholds were: HIGH ($V \geq 2.5$), MEDIUM ($1.5 \leq V < 2.5$), LOW ($V < 1.5$, active systems), and INACTIVE (predominantly inactive deposits flagged for data deficiency irrespective of V). Criterion definitions and category boundaries are summarised in Table 1; complete per-field scores are reported in Supplementary Table S1. External comparison against the sensitivity rankings of Boschen-Rose et al. (2021) was conducted for the 12 fields common to both studies. Tier-level agreement was 11 of 12 (91.7%), corresponding to Cohen's $\kappa = 0.85$ with a wide 95% confidence interval (0.64–1.00) reflecting the small sample size. The single discordance occurred at Moytirra, classified as MEDIUM in both frameworks but at the upper end of that tier by Boschen-Rose et al. (2021). Given the modest sample size, this agreement metric should be interpreted as indicative rather than definitive.

2.4 Atlantic Biodiversity Risk Index

A Biodiversity Risk Index (BRI) was computed for the extended Atlantic domain using a hexagonal spatial grid generated with the Uber H3 library at resolution 3 (~82 km cell diameter), yielding 1,847 cells over the study domain (70°N–60°S, 100°W–20°E). The BRI for each grid cell is a weighted composite of three spatially explicit components: a species-richness proxy derived from log-transformed and min-max

normalised OBIS benthic invertebrate occurrence counts (Echinodermata, Cnidaria, Mollusca, Polychaeta, Crustacea, Porifera; accessed January 2025); a habitat sensitivity score (assigned from V/3 for cells containing confirmed chemosynthetic habitats, or from CBD EBSA and NEAFC/NAFO VME categorical assignments for remaining cells); and a chemosynthetic habitat proximity weight derived from a 500-km distance-decay function based on documented larval dispersal and plume advection distances at MAR vent systems (Morato et al., 2022; Boschen-Rose et al., 2021). Component weights of 0.40 (richness), 0.35 (habitat sensitivity), and 0.25 (proximity) were assigned a priori on the basis of expert judgement: the richness term is the most direct of the three available proxies, habitat sensitivity reflects categorical knowledge from the published EBSA/VME literature, and proximity captures a structural modifier rather than a primary signal. All components were normalised independently to [0,1] before weighted summation, yielding a BRI on the same interval. The robustness of regional patterns to this weighting choice is addressed in Section 2.6. The full mathematical formulation, the OBIS query specification, the H3 grid construction parameters, and the categorical EBSA/VME assignment rules are provided in this section and are fully reproducible from the description given.

2.5 Spatial Overlay Analysis

Five categories of spatial overlay were computed: (a) point-in-polygon tests for each vent field within ISA contract areas and OSPAR MPA boundaries; (b) congruence analysis of HIGHvulnerability field distribution relative to all governance categories; (c) polygon intersection between plume dispersal envelopes and cold-water coral distributions with area quantification (Haversine-based polygon area); (d) minimum great-circle distance from each vent field to the nearest OSPAR MPA boundary vertex; and (e)

ISA contract area overlap with BRI quantile classes ($BRI \geq 0.75$, $BRI \geq 0.85$). All spatial operations were implemented in JavaScript using Haversine great-circle distance calculations on WGS 84 coordinates. Outputs were cross-checked by manual inspection against the georeferenced positions reported in the original literature (Section 2.2); discrepancies of more than 5 km between sources were resolved by selecting the most recent peerreviewed coordinate.

2.6 Weight Sensitivity Analysis

The a priori weight assignments in the vulnerability framework (Section 2.3) and BRI (Section 2.4) represent defensible but subjective choices. To assess the robustness of classification outcomes to uncertainty in these weights, a Monte Carlo sensitivity analysis was conducted for both components. For the vulnerability framework, 10,000 random weight sets were generated by perturbing each of the five baseline weights (R: 0.20; E: 0.25; F: 0.20; C: 0.20; P: 0.15) independently by up to $\pm 25\%$ relative to their baseline value (uniform distribution), followed by renormalisation to sum to 1.00. For each weight set and each of the 23 vent fields, the composite V score was recomputed and the tier classification (HIGH/MEDIUM/LOW) recorded. The proportion of simulations in which each field was classified as HIGH (%HIGH) was computed as a stability metric. The analysis was also extended to Moytirra, the highest-scoring MEDIUM field ($V = 2.25$ at baseline), to confirm the buffer between tiers. All calculations were implemented in Python 3.11. For the BRI, a parallel weight sensitivity test was conducted over the three BRI component weights (SR: 0.40; HS: 0.35; CP: 0.25) using 5,000 random perturbations ($\pm 25\%$), assessing whether the five Atlantic high-risk regions identified in Section 3.4 remain consistently at $BRI \geq 0.75$ irrespective of weight configuration.

2.7 Cartographic Outputs

The integrated cartographic outputs of DEEPMAP are presented in Figures 1–3. Figure 1 maps the Mid-Atlantic Ridge axis trace, the 23 confirmed hydrothermal vent fields classified by vulnerability tier, the three active ISA SMS exploration contract polygons, the nine OSPAR Marine Protected Areas in Areas Beyond National Jurisdiction, and the Azores EEZ moratorium zone established under Portugal's Lei 36/2025. Figure 2 presents the Atlantic-scale Biodiversity Risk Index on a hexagonal H3 grid at resolution 3 (~82 km cell diameter, $n = 1,847$ cells), with the five peak BRI regions explicitly identified. Figure 3 reports the Monte Carlo weight sensitivity analysis underpinning the vulnerability classification. All maps use the WGS 84 datum (EPSG:4326) and were rendered with coastline geometry from Natural Earth 50 m physical vector data. Vent field positions were compiled from InterRidge v3.4 (Beaulieu and Szafranski, 2020) augmented with three post-v3.4 discoveries documented in the primary literature (Puy des Folles, Schmidt Ocean Institute 2023; Korolovoe, Sudarikov et al., 2021; and the expanded Steinahóll complex, Devey et al., 2021). A companion open-access interactive implementation of the cartographic synthesis described here has been archived under a permanent DOI [citation withheld for double-anonymized review; full DOI provided on Title Page].

3. Results

3.1 Vent Field Database and Vulnerability Classification

The compiled database includes 23 confirmed hydrothermal vent fields on the MAR between 63°06'N (Steinahóll, Reykjanes Ridge; 250–350 m) and 8°18'S (Nibelungen; 2,915 m). Of these, 15 are active high-temperature, 2 diffuse-flow

(Steinahóll, Saldanha), 2 sporadic or mixed activity (Irinovskoye, parts of Pobeda), and 3 predominantly inactive (Zenith-Victory, Krasnov, Semenov 1–5) with the latter three flagged as INACTIVE irrespective of computed V . Median inter-field distance along the ridge axis is ~180 km; the largest gap (~1,800 km) separates Red Lion (4°49'S) from Nibelungen (8°18'S). The three post-2020 database additions emphasise the incompleteness of the MAR inventory: Puy des Folles was the first new vent discovery in its latitude band in over four decades, underlining that governance frameworks are being built on a dataset still actively expanding.

Application of the vulnerability framework yielded six HIGH, thirteen MEDIUM, two LOW, and three INACTIVE classifications (see Supplementary Table S1 for complete per-criterion scores). The six HIGH fields each follow ecologically distinct pathways to maximum risk. Lucky Strike ($V = 2.80$) derives its score from the combination of maximum taxonomic richness ($R = 3$; >600 documented species, the most extensively characterised vent ecosystem on Earth), globally unique status as the primary larval source for the northern MAR connectivity corridor ($E = 3$), the sensitivity of its Bathymodiolus azoricus-dominated community to thermal and chemical perturbation ($F = 3$), and century-scale recovery potential ($P = 3$) given the decadal timescales documented for even partial recovery at experimentally disturbed vent sites (Mullineaux et al., 2012). Lost City achieves the same composite score ($V = 2.80$) through a qualitatively different profile: moderate macrofaunal richness ($R = 2$; dominated by archaeal and bacterial mats with limited macro-invertebrate diversity) offset by globally unique status — the only active alkalinehosted hydrothermal system described anywhere on Earth ($E = 3$), complete population isolation as an off-axis, fluid-isolated system ($C = 3$), and irreversible loss potential anchored in carbonate

chimney ages of up to 120,000 years (U/Th; Ludwig et al., 2006) that document ecological continuity spanning glacial cycles ($P = 3$). Rainbow ($V = 2.65$) and Logatchev ($V = 2.65$) score identically through different combinations: Rainbow's maximum uniqueness ($E = 3$; ultramafic chemistry with no analogue on the MAR north of the equator) and sink population dynamics ($C = 3$) versus Logatchev's exceptional species richness across five sub-fields ($R = 3$), including the only MAR site where *Rimicaris exoculata* and *Mirocaris fortunata* co-occur ($E = 3$). Menez Gwen ($V = 2.60$) and TAG ($V = 2.55$) complete the HIGH tier through a combination of unique geological context (Menez Gwen's Azores hotspot position, $E = 3$; shallowest SMS field on the MAR at ~850 m, accentuating plume exposure risk) and isolation combined with irreversibility (TAG: $C = 3$, $P = 3$; the primary commercial extraction target on the MAR with ODP-drilled mounds whose recovery would be measured in centuries).

3.2 Spatial Overlay: The Congruence Paradox Quantified

Spatial overlay reveals a striking governance asymmetry. Of the 23 MAR vent fields, 10 (43.5%) fall within ISA exploration contract boundaries: eight within the Russian Yuzhmorgeologiya contract (Logatchev, Irinovskoye, Semenov, Krasnov, Zenith-Victory, Pobeda, Korolovoe, and Ashadze) and two within the Polish contract (Lost City and Broken Spur). Conversely, OSPAR MPA coverage is negligible: only Rainbow (4.3%) falls within a formal MPA boundary. The nine OSPAR MPAs in the study area provide water-column and habitat protection that benefits larval connectivity — the Charlie-Gibbs South (324,000 km²) and NACES (595,196 km²) MPAs encompass important deep-water habitat — but no active high-temperature vent field other than Rainbow receives territorial protection. The minimum distance from non-MPA

vent fields to the nearest OSPAR MPA boundary ranges from <50 km (Lucky Strike to the MAR North of Azores MPA) to over 2,000 km for the four equatorial fields (Turtle Pits, Comfortless Cove, Red Lion, Nibelungen), which exist in an entirely unprotected spatial vacuum with no REMP, no APEI designation, and no national EEZ claim.

The plume analysis identifies two ecologically critical overlap zones. The 130-km conservative plume dispersal envelope from potential mining at Rainbow or Lucky Strike intersects documented *Lophelia pertusa* and gorgonian occurrence zones on Azores seamounts (Mortensen et al., 2008), yielding an estimated ~8,500 km² of cold-water coral habitat at risk from sediment loading and metal exposure — consistent with the modelling of Morato et al. (2022), who quantified significant coral community impacts from SMS mining plumes originating at this cluster. The 110-km envelope from the Logatchev/Semenov cluster similarly overlaps with coral distributions in the northern equatorial region.

Combining the vulnerability classification with the governance overlay reveals a marked spatial co-occurrence pattern. Within the subset of six HIGH-vulnerability vent fields, each is associated with at least one of three governance categories: an active ISA exploration contract (Lost City, within the Polish contract; Logatchev, within the Russian contract), a documented commercial extraction interest outside formal contracts (TAG, the principal SMS target in unprotected ABNJ), or coverage by the Portuguese Lei 36/2025 moratorium as the principal operative protection layer (Menez Gwen, Lucky Strike, and Rainbow within the Azores EEZ). No HIGH-vulnerability MAR vent field within the present dataset is simultaneously outside ISA contracts, outside identified commercial-interest zones, and within a formally binding OSPAR MPA. Rainbow comes

closest to combined protection, being covered by both the OSPAR designation (2006) and the moratorium; however, the operational effectiveness of that MPA depends on ISA contractor compliance and flag state enforcement, a jurisdictional question that current governance frameworks have not yet fully resolved. The six HIGH-vulnerability fields and their primary policy implications are summarised in Table 2.

3.3 Atlantic-Scale Biodiversity Risk Index

The BRI map indicates a spatially structured pattern across the Atlantic basin (Figure 2). Cells with $BRI \geq 0.85$ cluster in five regions that recur across the analyses presented here. First, the northern MAR Azores cluster (37–47°N) shows the highest BRI values of the entire basin, driven by the convergence of HIGH-vulnerability vent fields ($SR = 3$, $HS \geq 0.87$), documented *Lophelia pertusa* habitat on adjacent seamounts, and the densest OBIS benthic invertebrate records in the Atlantic deep. This region is protected by the moratorium but remains subject to ISA contract and commercial interest pressure. Second, the equatorial Atlantic cluster centred on Ascension Island (~8°S) and the St. Peter and Paul Archipelago (~1°N), where unique endemic faunas associated with intertropical convergence zone productivity and documented hydrothermal activity generate elevated BRI values in an area with no EEZ-based governance protection and no OSPAR jurisdiction. Third, the Rio Grande Rise (~30°S), where the combination of cobalt-rich crust mineral interest, documented SMS mineralisation, and the highest benthic invertebrate species richness per unit area in the South Atlantic (driven by the Rise's heterogeneous substrate mosaic) produces BRI values consistently ≥ 0.80 — and where Brazil has designated a mineral province without an accompanying REMP or ecological baseline programme. Fourth, the South MAR / Drake

Passage cluster (~38–55°S), which coincides with confirmed ISA contract interest in Southern Ocean polymetallic deposits and hosts unique sub-Antarctic chemosynthetic communities at the East Scotia Ridge (~57°S). Fifth, the East Scotia Ridge itself, with the highest latitude confirmed active SMS systems (Copley et al., 2011), uniquely cold-adapted vent faunas, and no governance framework of any kind.

Across the three ISA contract polygons combined, approximately 71% of the contracted area falls within $BRI \geq 0.75$ cells and 34% within $BRI \geq 0.85$ cells. These figures are subject to the limitations of the polygon representation discussed in Section 4.4 but suggest that the spatial cooccurrence observed at the field scale on the MAR is not unique to that ridge and may apply at the basin scale.

3.4 Weight Sensitivity Analysis

The Monte Carlo sensitivity analysis (10,000 perturbations, $\pm 25\%$ per weight) was used to test how the field-level classification responds to changes in the weighting choices. For the vulnerability framework, four of the six HIGH-classified fields — Lucky Strike (V range: 2.7252–2.865), Lost City (2.718–2.865), Rainbow (2.544–2.739), and Logatchev (2.554–2.740) — are classified as HIGH in 100% of simulations, their minimum simulated V score remaining above the 2.5 threshold under all 10,000 tested weight configurations. Menez Gwen (V range: 2.4922–2.702) is classified as HIGH in 99.9% of simulations, dropping below the threshold only in 0.1% of extreme configurations that simultaneously minimise the weights on E and P — its two maximum-scoring criteria. TAG (V range: 2.446–2.654) shows the highest sensitivity, classified as HIGH in 93.6% of simulations; it drops below 2.5 only when the weights on C and P — its strongest criteria — are both simultaneously reduced by more than 20%

relative to baseline. Critically, the highest-scoring MEDIUM field (Moytirra; V range: 2.094–2.392) is classified as HIGH in 0% of simulations: there is no weight configuration within the tested perturbation space that elevates any MEDIUM field into the HIGH tier, confirming a genuine ecological discontinuity between the six HIGH fields and the remaining active-field population.

The spatial co-occurrence pattern is consequently stable to weight perturbations of this magnitude. Across all 10,000 weight configurations tested, a minimum of five fields (Lucky Strike, Lost City, Rainbow, Logatchev, and Menez Gwen) are classified as HIGH, and each of these falls within an ISA contract area, an identified commercial interest zone, or under coverage of the Portuguese moratorium as the principal operative protection. TAG is additionally classified as HIGH in 93.6% of configurations; in the remaining 6.4% (configurations that simultaneously down-weight C and P) TAG is reclassified as MEDIUM but the broader co-occurrence pattern among the five most stable HIGH fields is preserved. The main result of Section 3.2 is therefore not driven by a particular choice of weights within the tested range.

4. Discussion

4.1 Why ecological vulnerability and commercial interest co-occur on the MAR

The spatial co-occurrence observed in Section 3 has a plausible mechanistic basis: SMS deposits and high-diversity chemosynthetic ecosystems share the same geological and geochemical drivers, so their spatial distributions are not independent. SMS deposits form preferentially where metalliferous fluids are expressed at the seafloor in tectonically active, high-temperature settings with focused fluid flux. These are also the conditions that sustain diverse, chemically

adapted vent communities. The high species richness reported for Lucky Strike, the alkaline serpentinisation-driven ecosystem at Lost City, and the ultramafic-hosted ore deposits at Rainbow can therefore be understood as different expressions of related volcanic-tectonic processes rather than as independent phenomena. At the site scale, the SMS deposit and its associated ecosystem occupy the same substrate and the same three-dimensional space, which has implications for the kinds of spatial management measures available.

This co-location has implications for spatial planning, which is the conventional regulatory tool for managing competing ocean uses. In many multiple-use marine zones, ecologically sensitive and commercially valuable areas can in principle be separated by distance, depth, or time. At an SMS deposit, by contrast, the resource and the chemosynthetic community share the same substrate. A spatial plan that allocates the ore body to extraction also allocates the associated ecosystem to extraction, and the converse is also true. The governance discussion therefore shifts from a pure spatial-allocation question (where to mine, where not to mine) to a normative question regarding the conditions under which mining at sites of this ecological character would be compatible with the precautionary obligations under UNCLOS Articles 145 and 194. DEEPMAP makes the spatial component of that question explicit; the normative component remains a matter for state and ISA decision-making.

The CCZ APEI network offers a useful contrast. In the CCZ, the ISA distributed nine reference areas across a comparatively uniform nodule field. The CCZ is ecologically valuable but the spatial distribution of biodiversity there is more dispersed than at the discrete vent fields considered here, with no single site presenting the combination of features associated with Lost City

or Lucky Strike. The APEI model is well suited to the CCZ because trade-offs between commercial and ecological values are more easily separated spatially. On the MAR, those trade-offs are less easily separated, which is why the APEI approach requires careful adaptation to the vent-field context. The strongest APEI candidate — Lost City — is already within a formal ISA exploration contract despite containing no commercially extractable SMS deposit. Its inclusion in the Polish contract boundary was not a governance decision: it was a consequence of drawing a bounding rectangle around the Hayes-Kane Transform Fault zone that happened to capture an off-axis alkaline system with no extractive value. Addressing this situation requires more than an APEI recommendation: it may require contract boundary review, which is a more demanding administrative undertaking that the ISA and the Government of Poland could consider as part of the northern MAR REMP process.

4.2 The Portuguese Moratorium: Architecture, Not Symbol

The long-term value of Portugal's Lei 36/2025 will depend in part on the scientific programme that accompanies it. A moratorium that expires in 2050 without an updated ecological baseline for the Azores vent fields, without validated plume dispersal models calibrated to local current regimes, and without the spatial evidence base that can support its legal defence (should that prove necessary) would rest on a thinner evidential foundation than the precautionary principle alone provides. The peer-reviewed evidence base relevant to such a defence is most efficiently built during the moratorium period rather than after.

The vulnerability scores reported here for Lucky Strike, Menez Gwen, and Rainbow ($V = 2.80, 2.60, \text{ and } 2.65$ respectively) provide one quantitative input into precautionary-protection

arguments under Lei 36/2025. The plume–coral overlap analysis indicates that the cold-water coral habitat area potentially intersected by plumes originating from mining at these fields is non-trivial (on the order of 10^3 km^2 under the modelling assumptions of Morato et al., 2022); this extends the environmental rationale for the moratorium beyond the vent fields themselves to surrounding seamount ecosystems, with potential implications for transboundary plume impacts from any future mining in adjacent ABNJ areas. The cartographic outputs of DEEPMAP are intended to be readable in the governance contexts where these spatial arguments are typically discussed, including ISA expert meetings, OSPAR working groups, and parliamentary briefings.

Whether Portugal's Lei 36/2025 functions as an international template will depend in part on its articulation with multilateral frameworks. Portugal is an OSPAR contracting party (the Azores host three of the nine OSPAR ABNJ MPAs), an EU member state, and a UNCLOS party, which creates institutional pathways for translating the precautionary logic of the moratorium into OSPAR recommendations, EU Blue Economy instruments, and BBNJ area-based management tools. Recent precautionary statements by states and the scientific community (Jones et al., 2025; Van Dover et al., 2018) suggest some political and scientific receptivity to comparable measures elsewhere. DEEPMAP contributes a spatial-evidence layer that may support such discussions where they take place.

4.3 DEEPMAP in Comparative Context

Several existing spatial platforms address portions of the governance challenge identified here. The InterRidge Global Database (Beaulieu and Szafranski, 2020) is the authoritative source for vent field locations but presents raw data without

vulnerability assessment or governance overlay. The ISA's GeoSpatial Information System exists but is not publicly accessible and does not integrate ecological data. The OSPAR MPA database (<https://mpa.ospar.org>) maps MPA boundaries but does not display ecological vulnerability or mining pressure. The Ocean Biodiversity Information System (OBIS) provides occurrence records but no spatially explicit risk assessment tailored to SMS governance. The present synthesis differs from these existing resources in three respects: it places data from several primary sources in a single SMS-governance frame; it applies an explicit multi-criterion vulnerability score (with the caveats discussed in Section 4.4) rather than presenting raw occurrence data; and it presents results in cartographic formats intended for non-specialist policy readers in addition to expert data users. The synthesis is not intended to replace the authoritative databases on which it draws.

The closest comparator in the SMS context is the spatial analysis of Dunn et al. (2018) for the CCZ, which similarly integrated ecological and geological data to support APEI development. However, the MAR presents challenges that the CCZ analysis did not face: geologically and ecologically heterogeneous discrete vent fields rather than a continuous nodule field, tightly coupled mineral-ecology relationships at the site scale, and a governance landscape complicated by overlapping national jurisdictions and an incomplete international regulatory framework. These differences motivate the site-specific multi-criterion approach used here, which is complementary to the statistical habitat-modelling approach that has been applied successfully in the CCZ context.

4.4 Limitations

Several limitations should be acknowledged. First, ISA contract boundaries are represented as bounding rectangles derived from published coordinate ranges, rather than the actual noncontiguous block geometries, which are not publicly available. The bounding-rectangle representation will overestimate contracted area; we estimate the magnitude of overestimation at roughly 20–40% based on comparison with the small number of partially disclosed block configurations in the literature, but the true value is uncertain. Greater ISA transparency on block geometries would refine this analysis. Second, in cells without confirmed chemosynthetic habitats, the BRI habitat-sensitivity term is derived from qualitative categorical assignments based on EBSA and VME literature rather than from quantitative biodiversity surveys. These categorical assignments are best understood as informed estimates carrying non-trivial uncertainty. Future iterations could incorporate topographically constrained habitat distribution models based on bathymetric data such as GEBCO. Third, the vulnerability framework draws on published literature, which introduces a data-availability bias: fields with extensive monitoring records (e.g., Lucky Strike, with multi-decadal MoMAR-D coverage) are scored with greater confidence than fields without a published ecological baseline (e.g., Korolovoe, Irinovskoye). The direction of this bias is most plausibly toward underestimating the vulnerability of data-poor fields, but the magnitude is hard to quantify in the absence of baseline surveys for those sites. Fourth, neither the vulnerability framework nor the BRI incorporates explicit temporal dynamics. Seasonal current variability, inter-annual productivity cycles, and future climate trajectories are likely to affect plume dispersal and species distributions on the decadal-to-centennial timescales relevant to longterm SMS governance, and these effects are not represented in the static snapshot presented

here. The weight sensitivity analysis (Section 3.4) addresses one class of uncertainty (subjectivity in the weighting choices); the remaining three limitations indicate priorities for future data collection and modelling rather than reasons to disregard the present results.

5. Conclusions and Policy Recommendations

The analysis presented here illustrates that spatially integrated, evidence-based cartographic synthesis is feasible for SMS mining governance in the Atlantic, and may be useful as a complement to the ecological and legal analyses already in the literature. Within the present dataset, each of the six HIGH-vulnerability MAR vent fields falls within at least one of three governance categories of interest (ISA contract, commercial-interest target, or moratorium-only protection). Because the resource and the ecosystem share the same substrate at the site scale, the spatial overlap is unlikely to be resolved by spatial separation alone; this points to the relevance of precautionary management approaches grounded in best available science. The Atlantic-scale BRI suggests a similar pattern in five regions beyond the MAR where ecological sensitivity and commercial interest appear to converge.

Portugal's Lei 36/2025 moratorium provides an immediate precautionary response that may benefit from being accompanied by active environmental knowledge generation during the protected window, which is one of the use cases the DEEPMAP analysis is intended to support. The five recommendations below follow from the spatial evidence presented and from the limitations discussed in Section 4.4; they are offered as inputs to ongoing policy discussions rather than as definitive prescriptions.

Recommendation 1 — Consideration of APEI

designation for Lost City. With $V = 2.80$, no documented commercially extractable SMS deposit, and current location within the Polish ISA contract, Lost City is a strong candidate for consideration under any future ISA APEI framework on the MAR. Contract boundary review, in consultation with the Government of Poland, could be examined as part of the northern MAR REMP process. Complementary designations under the UNESCO World Heritage Convention or the IMO Particularly Sensitive Sea Area framework could also be explored.

Recommendation 2 — Potential replication of the Azores moratorium model. Portugal's Lei 36/2025 offers a legislative template that could be considered by other Atlantic coastal states whose EEZs include or border ecologically sensitive SMS provinces, such as Brazil (Rio Grande Rise), the United Kingdom (Ascension Island, East Scotia Ridge), South Africa and Namibia (Walvis Ridge), and Argentina (South MAR / Drake Passage). Coordinated action through OSPAR, the BBNJ Agreement's area-based management provisions, and bilateral Atlantic maritime cooperation frameworks could be one channel for such consideration.

Recommendation 3 — OSPAR MPA coverage for TAG and the equatorial MAR. Within the present dataset, TAG is the only HIGH-vulnerability MAR vent field that lies in unprotected ABNJ without any governance overlay. The OSPAR Commission could consider designating TAG as an ABNJ MPA under its existing network framework. A BBNJ high-seas area-based management tool may be appropriate for the equatorial MAR cluster (Turtle Pits, Comfortless Cove, Red Lion, Nibelungen), where four MEDIUM-vulnerability fields currently lie outside any formal governance overlay.

Recommendation 4 — Ecological baseline surveys as a condition of ISA contract renewal.

All three MAR contracts are subject to renewal review. The ISA could consider requiring up-to-date vent community characterisation, validated plume dispersal modelling, and submission of spatial data in formats compatible with the broader synthesis (such as the one presented here) as conditions for renewal. In the case of the Russian contract, this would be particularly relevant for Semenov 1–5, currently the largest reported SMS deposit on the MAR (~10 Mt) and one for which the published ecological baseline is sparse.

Recommendation 5 — Atlantic spatial transparency. Greater transparency on contract boundaries, APEI delineations, and ecological sensitivity assessments — published in open and machine-readable formats by the ISA, the OSPAR Commission, and Atlantic coastal states — would substantially improve the evidence base available to the public, to ISA member states, and to the scientific community. The present synthesis shows that integrating already-public data into a single open cartographic frame is technically straightforward; broader contributions of currently unpublished spatial information by competent bodies would extend this further. Such transparency is consistent with operationalising the ‘common heritage of humankind’ principle under UNCLOS.

Acknowledgements

This work was supported by the FLAD Atlantic Security Award, funded by the Luso-American Development Foundation (FLAD), in partnership with the Atlantic Centre and the Instituto da Defesa Nacional (IDN). The authors gratefully acknowledge this support, which enabled the development of the DEEPMAP framework and its contribution to Atlantic Ocean governance and deep-sea mining policy discussions.

Special thanks are due to Rear Admiral Nuno António de Noronha Bragança and to Francisco Santos Silva de Arantes e Oliveira for their support, encouragement, and valuable institutional engagement throughout this initiative. The authors also acknowledge CCMAR – Centre of Marine Sciences, Universidade do Algarve, for providing institutional support. Technology

This study received Portuguese national funds from FCT – Foundation for Science and through (DOI:10.54499/UIDB/04326/2020) 4499/LA/P/0101/2020) and the and projects UIDB/04326/2020 LA/P/0101/2020 (DOI:10.5 CEECINSTLA/00028/2022/CP2990/ CT0002 (<https://doi.org/10.54499/CEECINSTLA/00028/2022/CP2990/CT0002>).

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Figure Captions

Figure 1. Mid-Atlantic Ridge synthesis map showing the 23 confirmed hydrothermal vent fields classified by vulnerability tier (HIGH – red triangles, $n = 6$; MEDIUM – orange triangles, $n = 13$; LOW – green circles, $n = 2$; INACTIVE – grey squares, $n = 3$), the three active ISA SMS exploration contract polygons (red hatched: Russia, Poland, France/IFREMER), the nine OSPAR Marine Protected Areas in Areas Beyond National Jurisdiction (teal), the Azores EEZ moratorium zone established under Portugal’s Lei 36/2025 (blue ellipse), and the Mid-Atlantic Ridge axis trace (dashed red). Coastline geometry from Natural Earth 50 m physical vector data. WGS 84 (EPSG:4326).

Figure 2. Atlantic Biodiversity Risk Index (BRI) on a hexagonal H3 grid (resolution 3, ~82 km cell diameter; $n = 1,847$ cells). Colour scale: cream (BRI = 0) to dark red (BRI = 1.0). Blue triangles: confirmed hydrothermal vent field locations. Green polygons: ISA SMS exploration contract boundaries. Five peak BRI regions (BRI ≥ 0.85): (1) Northern MAR / Azores cluster (3747°N); (2) Equatorial Atlantic / Ascension Island (~0–8°S); (3) Rio Grande Rise (~30°S); (4) South MAR / Drake Passage (~38–55°S); (5) East Scotia Ridge (~57°S). ISA contract boundaries systematically coincide with BRI ≥ 0.75 across 71% of their combined area. Coastline geometry from Natural Earth 50 m physical vector data. WGS 84 (EPSG:4326).

Figure 3. Monte Carlo weight sensitivity analysis of the DEEPMAP vulnerability framework. Panel A: simulated range of the composite vulnerability score V for each of 20 active and recently inactive Mid-Atlantic Ridge hydrothermal vent fields under 10,000 random weight perturbations of $\pm 25\%$ relative to baseline values, with the HIGH ($V = 2.5$) and MEDIUM ($V = 1.5$) tier thresholds shown. Right-margin column reports the percentage of simulations classifying each

HIGH-tier field as HIGH. Panel B: classification stability bar chart for the six HIGH-tier fields plus Moytirra (the highest-scoring MEDIUM field). Lucky Strike, Lost City, Rainbow, and Logatchev are classified as HIGH in 100% of simulations; Menez Gwen in 99.9%; TAG in 93.6%; and no MEDIUM field reaches the HIGH tier under any tested weight configuration.

Tables

Table 1. Vulnerability classification criteria, scoring protocol, and weights for the DEEPMAP vulnerability framework applied to all 23 Mid-Atlantic Ridge hydrothermal vent fields. Composite score $V = 0.20 \cdot R + 0.25 \cdot E + 0.20 \cdot F + 0.20 \cdot C + 0.15 \cdot P$. Tier thresholds: HIGH ≥ 2.5 ; MEDIUM 1.50–2.49; LOW < 1.50 (active fields).

Criterion	Score 1 — Low	Score 2 — Moderate	Score 3 — High	Weight
R — Taxonomic richness	<50 taxa documented	50–200 taxa	≥ 200 taxa	0.20
E — Endemism / uniqueness	Common assemblage; no endemic hotspot	Regional endemics; biogeographic distinctiveness	Globally unique system; no worldwide analogue	0.25
F — Functional trait sensitivity	Tolerant traits dominant (e.g. sulphide-oxidising bacteria)	Mixed sensitivity; variable trait composition	Sensitive traits dominant; specialist endemic invertebrates	0.20
C — Population connectivity (inverse)	Well-connected; multiple larval sources	Partially connected; limited exchange	Isolated or sink population; larvae self-recruiting only	0.20
P — Recovery potential (inverse)	Years to decades	Decades to century-scale	Century-scale or effectively irreversible	0.15

Table 2. The six HIGH-vulnerability Mid-Atlantic Ridge hydrothermal vent fields identified by the DEEPMAP framework: composite vulnerability scores (V), current governance status, principal ecological justification for the HIGH tier classification, and primary policy recommendation derived from the spatial overlay analysis (Section 3.2).

Field	V	Governance Status	Ecological Justification for HIGH Tier	Primary Policy Recommendation
Lucky Strike	2.80	Azores EEZ – Lei 36/2025; MoMAR-D/EMSO permanent observatory	R=3 (>600 spp.); E=3 (global biodiversity reference + larval hub); F=3 (sensitive <i>B. azoricus</i>); C=2; P=3 (century-scale recovery)	Moratorium maintenance; REMP reference site; permanent observatory status
Lost City	2.80	Polish ISA exploration contract (no SMS deposit present)	R=2; E=3 (globally unique alkaline system, no analogue); F=3 (carbonate chimneys $\geq 120,000$ yr; irreversible); C=3 (off-axis isolated); P=3	IMMEDIATE APEI designation; contract boundary renegotiation; UNESCO WHC co-nomination
Rainbow	2.65	OSPAR MPA (2006); Azores EEZ – Lei 36/2025	R=2; E=3 (ultramafic-hosted, geochemically unique); F=3; C=3 (sink population); P=2	Enforce MPA compliance; integrate into Portuguese extended shelf claim; plume EIA buffer zones
Logatchev 1–5	2.65	Russian ISA contract (Yuzhmorgeologiya)	R=3 (5 sub-fields; only MAR site with <i>R. exoculata</i> + <i>M. fortunata</i> coexistence); E=3; F=3; C=2; P=2	Mandatory ecological baseline update as contract renewal condition
Menez Gwen	2.60	Azores EEZ – Lei 36/2025	R=2; E=3 (Azores hotspot setting; shallowest SMS field ~850 m); F=3; C=2; P=3 (shallow depth = accentuated plume vulnerability)	REMP larval connectivity reference site; explicit plume buffer zone in Azores EEZ management plan
TAG	2.55	Unprotected ABNJ; high commercial interest; no ISA contract	R=2; E=2; F=3 (inactive mound coral/sponge communities); C=3 (isolated); P=3 (~4 Mt SMS target; ODP-drilled; century-scale recovery)	Urgent APEI consideration via REMP or BBNJ area-based management; precautionary moratorium on new exploration

Supplementary Material

Supplementary Table S1 — Complete Vulnerability Scoring for All 23 MAR Vent Fields

Criterion scores and composite vulnerability index ($V = 0.20 \cdot R + 0.25 \cdot E + 0.20 \cdot F + 0.20 \cdot C + 0.15 \cdot P$) for all 23 hydrothermal vent fields on the Mid-Atlantic Ridge included in DEEPMAP. Criteria: R = taxonomic richness; E = endemism / uniqueness; F = functional trait sensitivity; C = connectivity (inverted); P = recovery potential (inverted). Scale 1–3 per criterion. Tier thresholds: HIGH ≥ 2.5 ; MEDIUM 1.50–2.49; LOW < 1.50 (active); INACTIVE (predominantly inactive deposit, flagged irrespective of V). ISA: Russian contract = Yuzhmorgeologiya; Polish contract = Government of Poland.

Vent Field	Depth (m)	R	E	F	C	P	V	Tier	ISA Contract
Lucky Strike	1700	3	3	3	2	3	2.80	HIGH	—
Lost City	800	2	3	3	3	3	2.80	HIGH	Poland
Rainbow	2300	2	3	3	3	2	2.65	HIGH	—
Logatchev 1–5	3000	3	3	3	2	2	2.65	HIGH	Russia
Menez Gwen	850	2	3	3	2	3	2.60	HIGH	—
TAG	3600	2	2	3	3	3	2.55	HIGH	—
Moytirra	3030	1	3	2	3	2	2.25	MED	—
Ashadze 1 & 2	4200	2	2	2	2	2	2.00	MED	Russia
Snake Pit	3500	2	2	2	2	2	2.00	MED	—
Turtle Pits	3000	1	2	2	3	2	2.00	MED	—
Comfortless Cove	2996	1	2	2	3	2	2.00	MED	—
Red Lion	3050	1	2	2	3	2	2.00	MED	—
Nibelungen	2915	1	2	2	3	2	2.00	MED	—
Puy des Folles	3000	1	2	2	2	2	1.80	MED	—

Vent Field	Depth (m)	R	E	F	C	P	V	Tier	ISA Contract
Broken Spur	3100	1	2	2	2	2	1.80	MED	Poland
Pobeda 1–3	3500	1	2	2	2	2	1.80	MED	Russia
Irinovskoye	3100	1	1	2	2	2	1.55	MED	Russia
Koralovoe	3100	1	1	2	2	2	1.55	MED	Russia
Steinahóll	300	1	1	1	1	1	1.00	LOW	—
Saldanha	2200	1	2	1	1	1	1.25	LOW	—
Zenith-Victory	2800	1	1	1	2	3	—	INACTIVE	Russia
Krasnov	3700	1	1	2	2	3	—	INACTIVE	Russia
Semenov 1–5	2600	1	2	2	2	3	—	INACTIVE	Russia

Notes: For INACTIVE fields (Zenith-Victory, Krasnov, Semenov 1–5), V scores are computed for reference but the INACTIVE classification overrides the tier assignment. Moytirra’s E score of 3 reflects its status as the sole known vent field between the Azores and Iceland, harbouring a faunal assemblage entirely distinct from both the northern (Iceland/Norwegian) and southern (Azores) biogeographic provinces, with absence of *Bathymodiolus* and unique functional trait composition (Wheeler et al., 2013). Concordance with Boschen-Rose et al. (2021): 11/12 shared fields (91.7%; Cohen’s $\kappa = 0.85$, 95% CI 0.64–1.00); discordance at Moytirra (both MEDIUM, differing in sub-tier position).

Figures

Figure 1. Mid-Atlantic Ridge: hydrothermal vent fields, ISA SMS exploration contracts, and OSPAR Marine Protected Areas

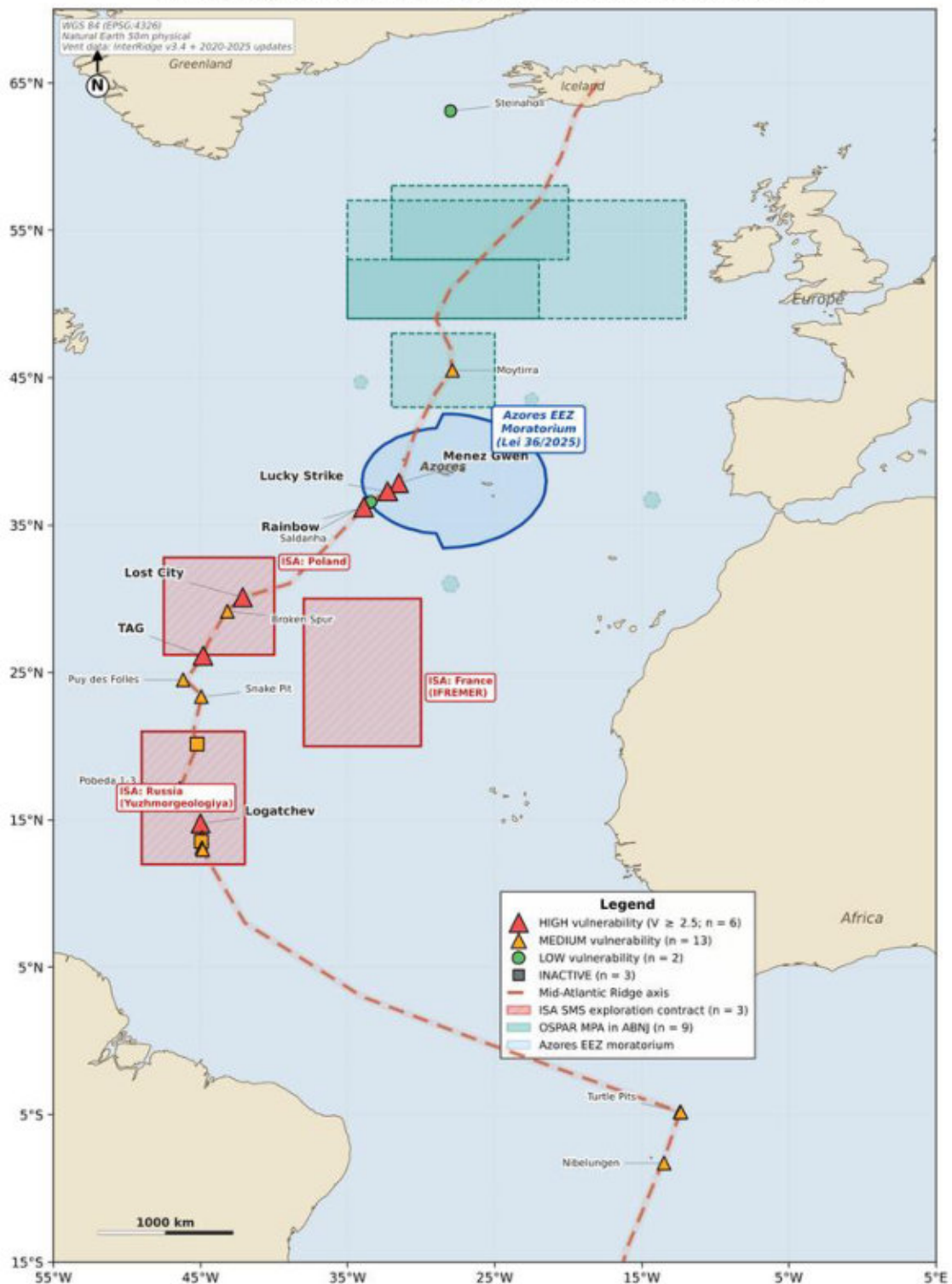


Figure 2. Atlantic Biodiversity Risk Index (BRI)
Hexagonal H3 grid (resolution 3, ~82 km cell diameter; n = 1,847 cells)

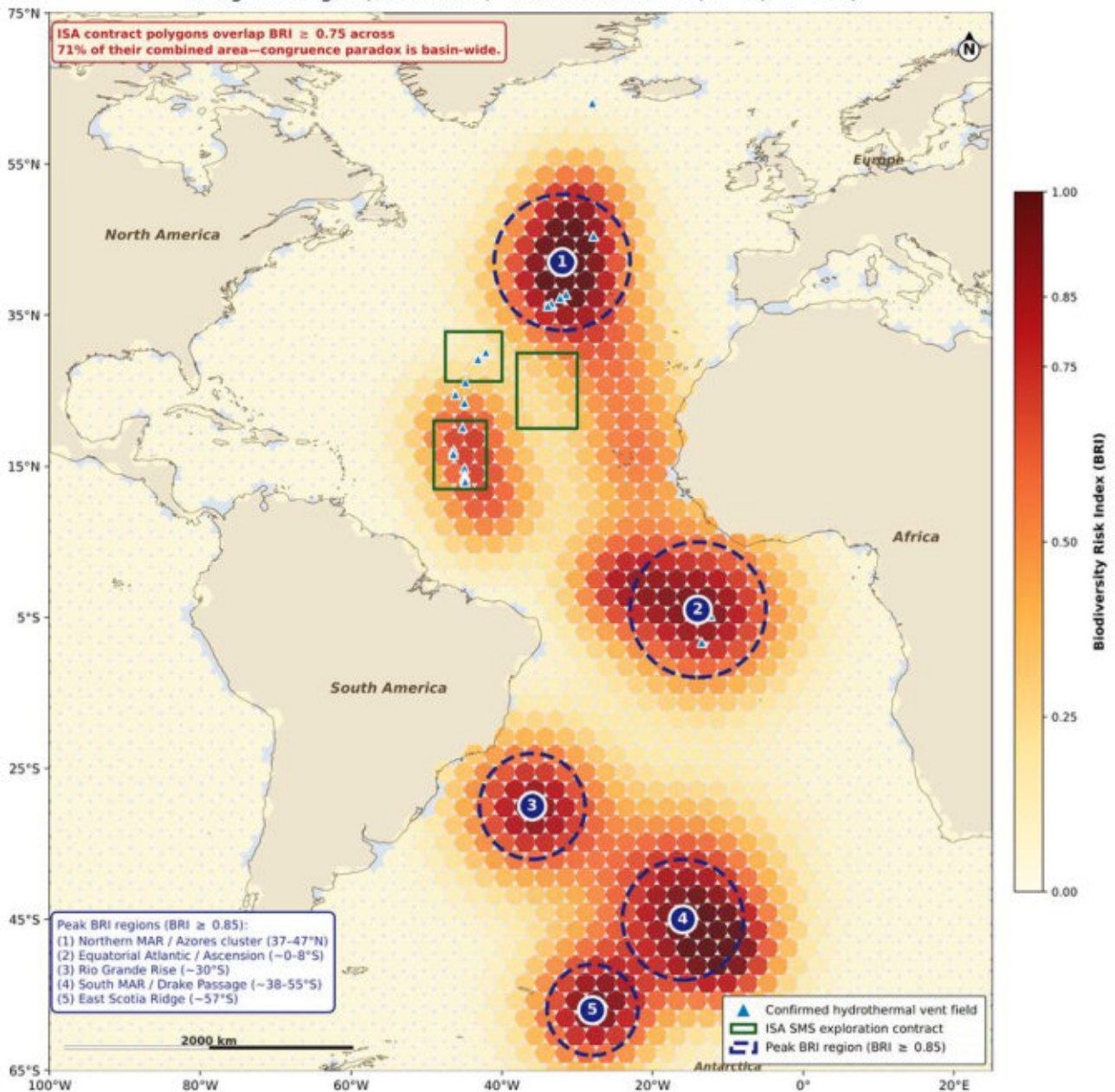
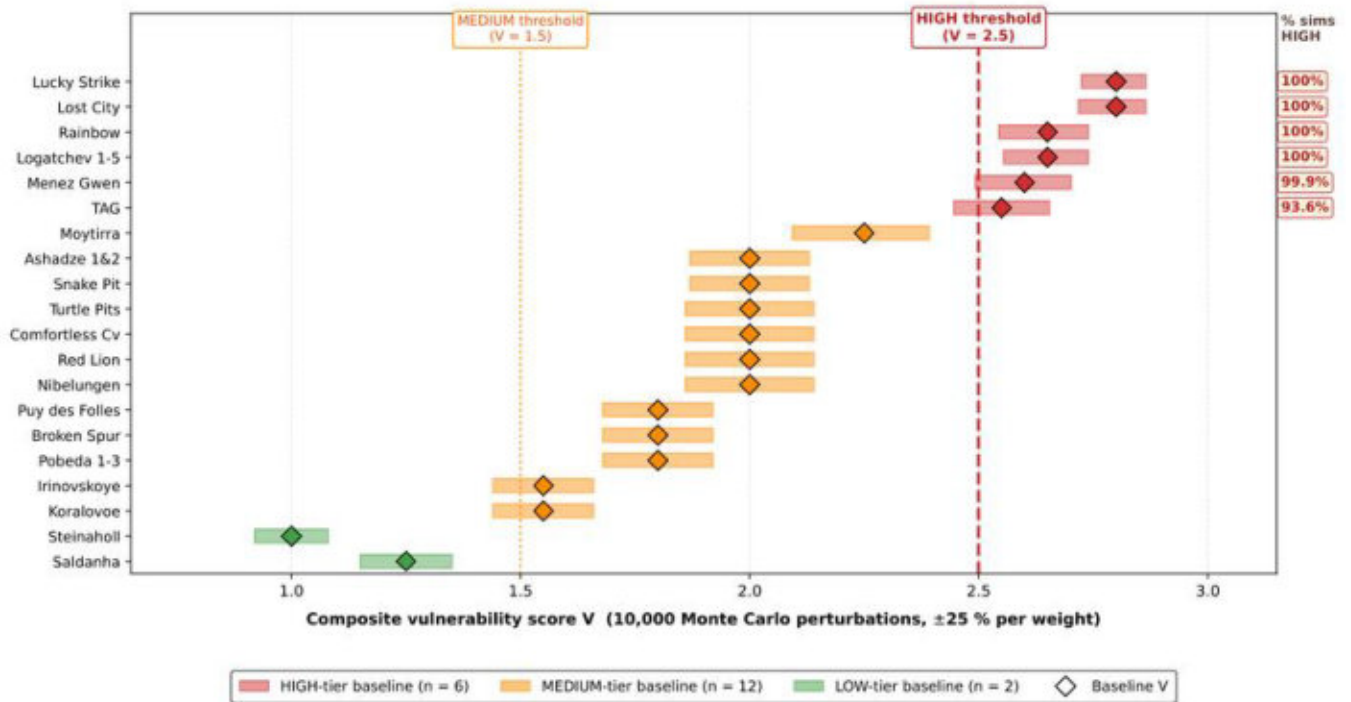
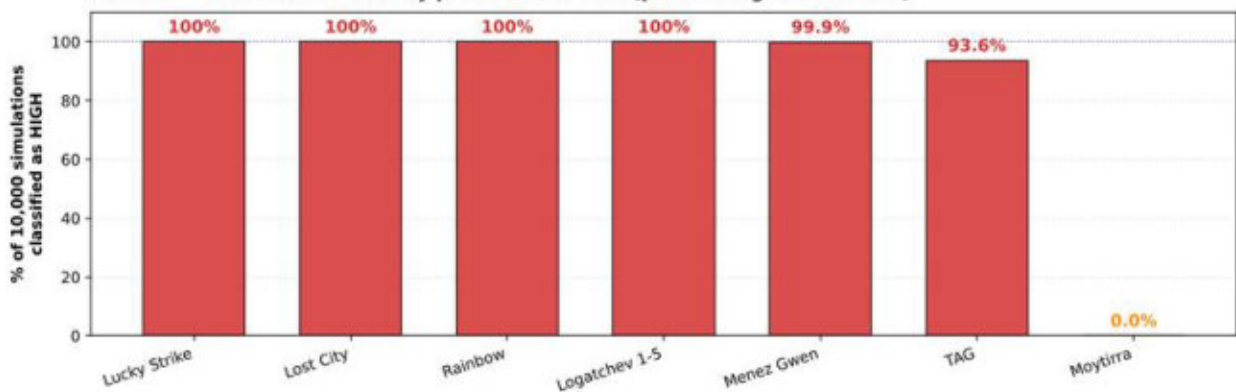


Figure 3. Monte Carlo Weight Sensitivity Analysis of the DEEPMAP Vulnerability Framework
Panel A – Weight sensitivity: V-score range per vent field



Panel B – Classification stability per HIGH-tier field (plus the highest MEDIUM)



Key finding: Moytirra (the highest-scoring MEDIUM field) is classified as HIGH in 0 % of simulations. No weight configuration within the ±25 % perturbation space elevates any MEDIUM field into the HIGH tier.