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Quantifying and Communicating Uncertainty in Spatial Advice: A Practitioner's Guide

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Abstract

Proper communication of uncertainty in scientific advice is crucial, allowing decision-makers to weigh risks, consider alternative scenarios, and develop robust policies that recognise the boundaries of available evidence. When uncertainties are poorly communicated, policymakers take decisions based on incomplete information, potentially leading to unexpected outcomes and public loss of trust when predictions prove imprecise. The challenge of communicating scientific uncertainty to policymakers has become increasingly critical as marine conservation efforts expand into data-poor deep-sea environments. Deep-sea vulnerable marine ecosystems (VMEs) present unique challenges, with a very small portion of the deep seafloor visually observed, and critical knowledge gaps spanning taxonomic identification, ecosystem dynamics, and spatial distribution patterns. Recent adoption of methods which allow uncertainty quantification, coupled with policy integration mechanisms, offer promising pathways forward, though significant institutional and technical barriers persist in translating complex scientific uncertainties into actionable conservation advice.

This exploration of current frameworks and case studies reveals that effective reflection of uncertainty in policy requires fundamental changes in approach by both scientists and decision makers, away from traditional deterministic advice toward probabilistic, adaptive advisory and management frameworks that explicitly acknowledge knowledge limitations while maintaining scientific best practice. The synthesis of lessons from regional fisheries management organizations (RFMOs) and comparative deep-sea jurisdictions provides practical guidance for scientists and managers navigating the interface between deep-sea research and policy implementation.

Keywords: Uncertainty quantification, Precautionary approach, Vulnerable marine ecosystems (VMEs), Deep-sea fisheries management, Spatial conservation advice, Science-policy interface

Introduction

The established response to scientific uncertainty in advice is the precautionary approach, which mandates that a lack of full scientific certainty should not preclude the implementation of protective measures (United Nations, 1992). In fisheries management, this principle is highly operationalised through harvest control rules and advisory frameworks that systematically reduce levels of exploitation as estimates of stock size become more uncertain or fall below biological reference points (FAO, 1995). This link between uncertainty and management action is less established for spatial advice in the marine domain. Here, uncertainty pertains to the precise location, extent, and vulnerability of complex features like vulnerable marine ecosystems (VMEs) the distribution and nature of pressures acting upon them, and the uncertainty inherent in the trade-offs and consequences that management actions may entail (Auster *et al.,* 2011). This complexity suggests that spatial management frameworks would be better supported by communication and consideration of scientific advice that explicitly recognises the spatial distribution of uncertainty, rather than relying solely on point records, hard boundaries and deterministic maps, allowing managers to make risk-based decisions, by choosing an acceptable level of risk tolerance.

In the context of risk tolerance, Type 1 (erroneous rejection of a true hypothesis) and Type 2 (erroneous acceptance of a false hypothesis) errors represent fundamentally different conservation risks in relation to VMEs, with distinct policy implications (Neyman and Pearson, 1933). A Type 1 error represents a scenario where management actions unnecessarily restrict fishing activities, for instance establishing a closure to protect a predicted VME that does not actually exist, or applying protection measures based on outdated observations of communities that have since disappeared due to natural processes or unrecorded impacts. Conversely, a Type 2 error represents a failure to protect an actual VME, such as when sampling bias leads to VMEs being missed in unsampled regions, when detection methods fail to identify cryptic or less conspicuous VME indicator species, or when conservative definitional thresholds exclude moderately dense but still vulnerable aggregations from protection (van Denderen *et al.,* 2022). Whilst Type 1 errors impose economic costs on fishing industries and may undermine stakeholder confidence in scientific advice, Type 2 errors result in the irreversible loss of vulnerable deep-sea ecosystems that may require millennia to recover. This asymmetry in consequences fundamentally shapes how the precautionary approach is operationalised in deep-sea fisheries management, with most frameworks deliberately slanted towards accepting Type 1 errors to minimise the risk of Type 2 errors.

The treatment of scientific uncertainty in international fisheries management has evolved from a general principle to a specific, operational requirement. While foundational agreements like the UN Convention on the Law of the Sea (UNCLOS) established a general duty to protect the marine environment, subsequent instruments have become far more explicit. The 1995 UN Fish Stocks Agreement was a landmark, codifying the "precautionary approach" and making it a binding principle for managing fisheries. This concept was extended to spatial conservation through instruments such as UN General Assembly Resolution 61/105, which obligates states to protect deep-sea Vulnerable Marine Ecosystems (VMEs) where they are "known *or likely* to occur," demanding proactive management based on best available data (UNGA, 2006). This trend is most recently seen in the 2023 Biodiversity Beyond National Jurisdiction (BBNJ) Treaty, which enshrines the precautionary and ecosystem-based approaches as core obligations for the high seas, mandating the explicit consideration of uncertainty in environmental impact assessments (United Nations, 2023). High-level political commitments like Sustainable Development Goal 14 and the "30 by 30" conservation target of the Kunming-Montreal Global Biodiversity Framework further amplify this imperative. Achieving such ambitious goals requires states and regional organisations to act swiftly through precautionary designations in the face of incomplete scientific knowledge.

Despite these clear obligations and ambitious targets, recent analyses of Regional Fisheries Management Organisation (RFMO) impact assessments reveal critical gaps in uncertainty management (Kaikkonen *et al.*, 2024). Heavy reliance on fishery-dependent data creates ambiguity in data sources and methods, with only a subset of assessments adequately addressing species distribution model and habitat suitability model uncertainties. Most evaluations consider only direct impacts of fishing gear on seafloor communities, and not cumulative impacts from climate change, resource extraction or other human activities.

This review aims to provide a comprehensive framework for understanding, communicating and working with uncertainty in deep-sea VME conservation advice. First, it systematically describes the main sources of uncertainty that must be identified and addressed in any scientific advice on VME protection, organising these within a Pressure-State-Response (PSR) framework to clarify how uncertainties propagate through the assessment process (OECD, 1993). Second, it examines recent methodological and technological advances in quantifying and communicating these uncertainties, including developments in ensemble modelling, probabilistic mapping approaches, and interactive visualisation platforms that enable more transparent uncertainty communication. Through this synthesis, the review then seeks to bridge the gap between theoretical uncertainty frameworks and their practical implementation in deep-sea fisheries governance, providing actionable guidance for scientists, managers, and institutions navigating the interface between incomplete knowledge and urgent conservation needs.

A Framework for Understanding VME Uncertainties

To effectively communicate scientific advice and subsequently protect deep-sea ecosystems through fisheries management decisions, it is necessary to deconstruct the multiple layers of uncertainty. The PSR framework provides one logical structure to categorise these knowledge gaps. In the context of VMEs, uncertainty in one component amplifies uncertainty in the others: imprecise knowledge of pressures (*e.g.*, fishing) makes it difficult to assess the true state of the ecosystem, which in turn impacts confidence in predictions of the ecosystem's response to management. This section systematically explores the key uncertainties within each component.

Pressure

Fishing Activity Detection and Spatial Representation: Fishing activity in many RFMO contexts is recorded through a combination of logbooks and Vessel Monitoring System (VMS) data, though not all fleets or fisheries operating within RFMO regulatory areas are subject to VMS requirements, limiting the spatial coverage and consistency of fishing activity records. Assessing fishing pressure on VMEs faces challenges in both detecting fishing activity and representing it spatially. VMS data typically records vessel positions, headings and speeds at intervals of one to two hours, requiring researchers to infer fishing activity based on speed thresholds that distinguish between fishing (typically 2–5 knots for bottom trawling) and steaming activities (Gerritsen and Lordan, 2011). These speed-based classifications introduce substantial uncertainty, as vessels may reduce speed for reasons unrelated to fishing, such as navigation around obstacles, weather conditions, or mechanical issues, whilst conversely, fishing may occur at atypical speeds depending on gear type, target species, or seabed conditions (Hintzen *et al.*, 2012). This detection uncertainty is compounded by challenges in spatial representation, as the temporal resolution of VMS data limits the scale at which fishing activity can be accurately mapped. A VMS position report indicates that a vessel was present at a point in space and time but reveals nothing about where it travelled in the preceding and subsequent periods. The optimal scale for representing VMS-derived fishing activity is the product of average fishing speed and average interval between reports. Gridding at finer scales risks vessels fishing across grid cells without detection, underestimating impacts. Conversely, gridding at larger scales may create an erroneous perception of overlaps between fishing activity and actual VME locations (Amoroso *et al*., 2018). Moreover, this information indicates the vessel's position rather than the actual location where the fishing gear contacted the seafloor. In deep-sea fisheries, given a typical trawl warp length required is two to three times the water depth, the net may be operating several kilometres away from the vessel's recorded position.

Linking VMS Data to Gear Information: A limitation in VMS-based impact assessment stems from the difficulty of reliably linking vessel position data to information specifying the fishing gear being deployed. VMS data alone provides vessel location and speed but lacks details about gear type, size, or operational characteristics - information essential for calculating swept areas and impact intensities. This data integration challenge has significantly constrained spatial fishing advice, for example limiting the International Council for the Exploration of the Seas (ICES) ability to deliver comprehensive VME impact assessments to the North East Atlantic Fisheries Commission (NEAFC) in recent years (ICES, 2024). While the "ICES VMS & Logbooks data call" (ICES, 2026) attempts to standardise the linking of positional data with gear specifications, implementation remains inconsistent and coverage incomplete (ICES, 2025). The increasing use of Automatic Identification System (AIS) data has enabled large-scale analyses of apparent fishing activity, but these approaches face challenges in quantifying fishing activity and linking positional data to gear specifications, particularly in offshore areas (ICES, 2019; Hintzen *et al*., 2025). Whilst AIS-based studies can identify broad patterns of vessel activity and distinguish between mobile and static fishing operations, they cannot differentiate between specific gear types (*e.g.*, beam trawls versus seines), meaning that impact assessments may significantly misrepresent actual benthic disturbance compared to logbook-linked VMS data which provide precise gear-specific information.

Inferring Seafloor Disturbance: Translating vessel activity into benthic impact relies on multiple uncertain parameters that interact in complex ways. The actual impact of a trawl upon the seabed depends on gear-specific parameters like the effective width and weight of doors and ground gear, which vary with substrate, currents, and operational techniques (Clark *et al*., 2016). The spread of trawl gears is dynamically influenced by both the speed the gear is towed through the water, how the net has been rigged by the fisher, and the depth at which it is being fished (ICES, 2019). The choice of speed thresholds used to classify VMS pings as "fishing" versus "steaming" directly affects swept area calculations, as swept area is calculated as the product of gear width and fishing speed. If speed thresholds are set too low, non-fishing activities may be misclassified as fishing, inflating impact estimates; conversely, if thresholds are too high, actual fishing at slower speeds may be missed, leading to underestimation of cumulative impacts. This methodological choice thus introduces systematic bias into impact assessments, with the direction and magnitude of bias varying depending on fishery-specific operational practices and environmental conditions. Estimating bottom contact time from VMS tracks compounds these uncertainties, as it requires assumptions about when gear deployment begins and ends relative to vessel position records, creating additional layers of uncertainty.

Static Gears: Static fishing gears such as longlines, gillnets, and traps present unique challenges for VMS-based activity detection that are fundamentally different from mobile gears. The deployment and retrieval speeds of static gears often fall within the same range as normal steaming speeds, making it impossible to distinguish gear operations from transit using speed-based classifications alone. Combined with the coarse temporal resolution of VMS data (one- to two hour intervals), this means that while it may be possible to infer locations where gears have been retrieved, the actual deployment and duration of operations remain largely unobserved, in contrast to experiences with AIS data in small-scale fisheries (*e.g.* Mendo *et al*., 2023). This fundamental limitation prevents the derivation of "soak times" (the duration that gear remains fishing on the seabed) from VMS data, information that is required for assessing cumulative impact on benthic communities. The degree to which VME indicator species are vulnerable to damage from static gears is also variable and not well parameterised (Dias *et al*., 2020).

Historical and Cumulative Pressure: Assessing the cumulative impact of fishing over time presents additional methodological challenges that are particularly acute for deep-sea VME assessments. Reconstructions of historical fishing effort rely on incomplete and often spatially imprecise logbook data from previous decades, with data quality and spatial resolution declining markedly for earlier time periods (NAFO, 2009). High-seas fisheries that were once highly productive, for example the Grand Bank cod stocks that straddle the Canadian EEZ and Northwest Atlantic Fisheries Organisation (NAFO) regulatory area boundary, may have been under moratoria for decades, creating significant gaps in our understanding of historical fishing footprints. Areas that appear pristine in contemporary VMS data may have experienced intensive trawling historically. This temporal uncertainty means that current "baseline" conditions for many deep-sea areas may already reflect heavily degraded states, while areas with limited recent fishing activity may have experienced significant impacts that are absent from contemporary management assessments (Pitcher and Lam, 2010). The inability to account for this legacy of disturbance introduces systematic bias into impact assessments, potentially underestimating the true cumulative pressure on VME communities and overestimating their current resilience to additional fishing impacts.

A further source of historical uncertainty lies in the spatial precision of pre-VMS logbook records themselves. Prior to mandatory VMS implementation, fishing positions were typically recorded by skippers at the point of departure or return to port, or estimated from memory, rather than captured continuously during fishing operations. Where positions were recorded at sea, they were commonly rounded to the nearest degree or half-degree of latitude and longitude - a spatial imprecision of up to 55 km - rendering fine-scale reconstruction of historical fishing footprints impossible (Jennings and Lee, 2012). This positional uncertainty is particularly acute for deep-sea fisheries that expanded rapidly during the 1970s and 1980s, precisely the period for which establishing pre-disturbance baselines would be most valuable for contemporary assessments.

State

Characteristics of Vulnerable Marine Ecosystems: Although international guidelines for identifying VMEs have been established (FAO, 2009), their interpretation and implementation varies across organisations. Key definitional elements - what constitutes a VME, which taxa qualify as "VME indicators," and required density thresholds to represent an "encounter" - are applied inconsistently between jurisdictions (Watling and Auster, 2021). Beyond habitat-forming organisms like corals and sponges, criteria such as "other locations that support species aggregations" remain poorly defined, with limited guidance for identifying features like seamount spawning aggregations or deep-sea nursery areas. The qualitative nature of many VME descriptors (*e.g.*, "significant concentrations," "essential fish habitat") introduces subjective interpretation that varies between scientists, institutions and regulatory frameworks, creating inconsistency in protection across regions.

Identifying and Sampling VMEs: The ability to find and characterise VMEs is fundamentally limited by the challenges of operating in the deep seas. With less than 0.001% of the deep seafloor visually observed, current knowledge is based on a tiny and highly biased sample. Data collection is concentrated in areas accessible to research vessels or within existing fishing grounds, meaning vast, unexplored regions are entirely absent from models and assessments (Clark *et al*., 2010). Survey methods themselves introduce systematic bias, with different techniques (cameras, trawls, multibeam sonar) detecting different VME components and size classes, while operational capabilities, funding constraints, and logistical limitations determine survey timing and locations rather than optimal sampling design, further biasing results. The expense and complexity of deep-sea operations mean that many potential VME areas are sampled only once, providing no information on temporal variability or the persistence of observed communities. Furthermore, at-sea observer coverage is typically low and non-randomly distributed, with observer deployment concentrated on larger vessels or specific fleets (Ewell *et al*., 2020), meaning that bycatch records of VME indicator species from commercial fishing operations are likely to underrepresent true encounter rates and should be interpreted with caution when used as evidence of VME distribution (Morato *et al*., 2018). Observational data from commercial trawls raises the question of whether the VME an indicator organism was collected from still exists, and precisely where along the trawl path it was encountered, as specimens cannot be linked to specific locations within the towed track (Auster *et al*., 2011).

Taxonomic and Compositional Uncertainty: When potential VMEs are observed, correctly identifying their components presents additional challenges. Identification from imagery is often uncertain, as morphologically similar species can have very different vulnerabilities and ecological roles (Althaus *et al*., 2009). However, many of the traits that confer vulnerability - slow growth, longevity, and structural fragility - are shared across higher taxonomic levels such as family or class, meaning that identification uncertainty at the species level does not always compromise the ability to recognise a VME indicator and apply appropriate protection (Watling and Auster, 2021). Without physical voucher specimens, which are rarely collected due to the destructive nature of sampling and the fragility of many VME organisms, there is a risk of misclassifying communities and misjudging their conservation status. Even with correct taxonomic identification, the ecological roles and vulnerabilities of many deep-sea species remain unknown, making it difficult to assess the functional significance of observed communities or predict their responses to disturbance. This functional uncertainty extends to community-level properties, where the ecosystem services provided by different VME assemblages, their resilience to impact, and their recovery potential are largely unknown.

Assessing ecosystem state: Even where VMEs are successfully identified and sampled, quantifying their ecological condition and detecting change over time presents additional layers of uncertainty. Establishing meaningful baselines is severely hampered by the paucity of historical observations, meaning that current VME assessments often lack a reference point against which to measure change (Pitcher and Lam, 2010, Rossberg *et al*., 2017). Where repeat surveys do exist, distinguishing genuine ecological change from natural variability in community composition, abundance, and distribution requires long time series that are rarely available for deep-sea systems. The absence of standardised monitoring protocols across surveys and institutions further compounds this problem, as differences in methodology between sampling events can introduce artefactual apparent change that is indistinguishable from real ecological trends. These limitations mean that assessments of ecosystem state are typically snapshots rather than trajectories, providing limited ability to detect gradual degradation or assess whether management measures are delivering ecological recovery. A particular challenge that is actively debated within RFMOs and approached differently across jurisdictions lies in determining whether a VME has been degraded to the point of Significant Adverse Impact. Defining thresholds for ecosystem state requires both empirical data on reference conditions and agreement on acceptable levels of depletion, neither of which is straightforward for deep-sea systems (Hiddink *et al.*, 2023a). The resolution of the habitat and fishing effort data used in state assessments further influences outcomes, with coarser data tending to obscure localised impacts and potentially underestimate the extent of degradation (Hiddink *et al.*, 2023b). Some RFMOs have developed quantitative approaches to assess ecosystem state with explicit uncertainty, such as the Relative Benthic Status (RBS) method applied within the South Pacific Regional Fisheries Management Organisation (SPRFMO) to estimate the current status of VME indicator taxa relative to an unfished baseline (SPRFMO, 2024).

Response

Assessing Vulnerability and Recovery Potential: Fundamental uncertainty exists regarding the intrinsic vulnerability of deep-sea species and communities to different disturbance types and intensities. Recovery timescales remain largely unknown for most VME taxa, with estimates spanning orders of magnitude from decades to millennia (Strong *et al*., 2023). This temporal uncertainty is compounded by ecological uncertainty about whether disturbed communities will follow predictable recovery pathways or shift to alternative stable states, and whether recovery trajectories observed in one location or environmental context can be reliably extrapolated to other sites or future conditions (Schlacher *et al*., 2010). These uncertainties limit managers' ability to make proportionate decisions about protection levels and duration, as it becomes difficult to weigh the costs of closures against conservation benefits or set appropriate review timelines.

Effort Displacement and Spatial Response: Management responses, particularly area closures, create cascading uncertainties about how fishing effort redistribution will affect marine ecosystems. The spatial distribution of displaced fishing activity cannot be predicted with certainty, as it depends on complex interactions between vessel economics, resource availability, regulatory frameworks, and fisher behaviour patterns that vary across fleets and seasons. This displacement uncertainty is coupled with ecological uncertainty about the vulnerability of receiving areas to newly concentrated fishing pressure, creating the potential for unintended consequences where protecting one VME can inadvertently lead to impacts on previously unfished areas (Auster *et al*., 2011; Lohrer *et al.,* 2023). These uncertainties undermine the effectiveness of spatial management tools by making it impossible to predict whether a closure will simply shift impacts to adjacent vulnerable areas, potentially creating a cycle of sequential habitat degradation. Managers cannot assess the true net conservation benefit of spatial closures, as positive effects in protected areas may be offset by negative effects in receiving areas, forcing them to choose between small, targeted closures, which may simply displace effort and be difficult to enforce, and larger, comprehensive closures, which may be economically and politically challenging.

Cumulative and Interactive Effects: Anticipating how VME communities will respond to multiple, interacting stressors operating across different spatial and temporal scales. Climate change, ocean acidification and direct fishing impacts interact in complex, non-linear ways that challenge current predictive capacity and introduce substantial uncertainty into any projections of combined effects. The cumulative effects of these stressors on VME resilience, recovery potential, and ecosystem functioning remain highly uncertain, particularly under projected future ocean conditions where baseline environmental parameters will fall outside the range of historical variability (Puerta *et al*., 2020). This uncertainty extends to the effectiveness of current management measures under changing environmental conditions and the potential for threshold effects or tipping points in ecosystem responses (Stephenson *et al*., 2023). These uncertainties make it extremely difficult for managers to set appropriate management targets or assess whether current measures are sufficient, as they cannot reliably predict how VMEs will respond to the combination of fishing pressure and climate change. These conditions force managers to make decisions with limited understanding of the relationship between management actions and ecological outcomes, significantly impeding evidence-based policy development and pushing advisory frameworks toward precautionary recommendations that stakeholders often perceive as excessively conservative.

The uncertainties described above do not exist in isolation but interact to create systematic biases in our ability to identify and protect VMEs, whilst simultaneously constraining the range of management options available to fisheries managers. An understanding of both the directional nature of these biases and their impact on advisory frameworks is necessary to develop and implement appropriate precautionary measures (Kenny *et al.,* 2018). Table 1 provides a systematic overview of the key uncertainty sources and their likely impact on conservation outcomes, categorised by whether they tend towards Type 1 errors (protection of areas where VMEs may not occur) or Type 2 errors (failure to protect actual VMEs). This analysis reveals a fundamental asymmetry: inherent scientific and observational limitations create a strong underlying tendency towards Type 2 errors, systematically causing us to underestimate VME presence and distribution. However, the management implications of these uncertainties extend beyond simple error classification and create a systematic bias toward highly precautionary approaches.

Quantifying and Visualising Uncertainty

Faced with the sources of uncertainty outlined above, the scientific community has worked to develop a suite of technical and methodological innovations that can better quantify, communicate, and manage these knowledge gaps. This represents a fundamental shift away from deterministic advice toward a risk-based approach that explicitly acknowledges uncertainty whilst maintaining scientific rigour.

Quantification of Pressure

To address the uncertainty around fishing effort estimation, researchers have moved beyond simple speed-filter methods toward probabilistic approaches. Hidden Markov Models (HMMs) now assign probability distributions to vessel "fishing states" based on sequences of positional data, incorporating speed, turning angle, and temporal patterns for more nuanced activity classification (Le Guyader *et al*., 2017). These models provide confidence intervals around fishing effort estimates rather than deterministic classifications.

For issues with identifying static gear deployments, technological solutions are emerging through direct gear instrumentation. Acoustic pingers, depth sensors, and GPS loggers deployed on longlines and trap arrays provide ground-truth data on gear deployment locations and soak times, enabling validation of VMS-based inferences (Sala *et al*., 2023). However, these approaches remain limited by cost, technical complexity, and the need for industry cooperation.

Physical trawl footprint models have evolved from fixed assumptions to parameterised, probabilistic approaches that incorporate gear-specific variables, substrate interactions, and environmental conditions. Monte Carlo simulations have been used to generate uncertainty distributions around swept area estimates, allowing impact assessments to express confidence intervals rather than point estimates (Eigaard *et al*., 2016).

Assessment of State

Quantitative assessments of ecosystem state increasingly draw on meta-analyses of empirical studies to derive estimates of VME indicator depletion and recovery potential, though the uncertainty inherent in extrapolating values from disparate study systems to specific management contexts remains substantial (Hiddink *et al*., 2023a; 2023b). In relation to mitigating VME identification and sampling uncertainties, ensemble species distribution modelling has become the standard approach for habitat suitability assessment. Such models combine outputs from multiple algorithms such as Boosted Regression Trees and Random Forest, alongside Bayesian approaches that use Integrated Nested Laplace Approximations (INLA) as an efficient method for estimating posterior distributions within spatial models, to generate both habitat suitability predictions and explicit uncertainty maps showing model agreement and confidence levels (Rubbens *et al*., 2023).

Machine learning applications, particularly Convolutional Neural Networks (CNNs), now enable semi-automated analysis of seafloor imagery with built-in confidence scoring. These systems achieve classification accuracies up to 80% whilst providing uncertainty estimates for each taxonomic identification, directly addressing the taxonomic uncertainty challenges outlined above (Zurowietz *et al*., 2018).

Environmental DNA (eDNA) techniques offer a promising approach to the spatial sampling limitations identified in the State framework. By detecting genetic material shed by VME indicator species, eDNA can screen vast areas more efficiently than traditional visual surveys, though it introduces new uncertainties around DNA transport and persistence in deep-sea environments (Gallego *et al*., 2024; Stefanni *et al*., 2022).

Visualisation and Communication

Advances in uncertainty quantification require effective communication tools to be operationally useful. Interactive decision support tools now allow managers to explore multi-layered uncertainty products, adjusting confidence thresholds and viewing how predictions change across different spatial scales (Rowden *et al*., 2019). These platforms can help distinguish between predicted VME likelihood and model confidence, enabling users to understand both the scientific prediction and the certainty associated with it.

Mapping techniques that simultaneously display both predicted habitat suitability and model uncertainty provide more nuanced information than simple presence/absence maps by showing the full range of scientific confidence. These bivariate visualisations help managers distinguish

Table 1. Sources of uncertainty in VME spatial advice and their error bias.

Source of Uncertainty	Description	Likely Error Bias
Data Collection and Observation		
Sampling Bias	VME data is collected non-randomly, concentrating on fished areas, seamounts, or along ship tracks, rather than being representative of the entire management area.	**Type 2.** Systematic failure to identify VMEs in extensive unsampled regions results in underestimated distributions and inadequate protection of undetected habitats.
Detection Probability	Survey methods have inherent biases. Cameras are good for large, erect fauna but often miss small, cryptic, or encrusting VME indicator species. Trawls only sample what they can catch.	**Type 2.** The presence and density of less-conspicuous VME indicator taxa are consistently underestimated, meaning areas that qualify for protection might be missed.
Taxonomic Uncertainty	Species are often identified from low-resolution imagery, making it difficult to distinguish between a vulnerable VME indicator and a morphologically similar, non-vulnerable species. However, as vulnerability traits such as slow growth and structural fragility are frequently shared across higher taxonomic levels, misidentification at species level does not always compromise VME recognition.	**Leans toward Type 2**, though the conservation consequence of taxonomic uncertainty is moderated where vulnerability is conserved at family or class level. The greater risk remains failing to recognise a true VME indicator where morphological similarity leads to misclassification as a non-vulnerable taxon.
Temporal Mismatch	Management advice is based on historical observations. A VME observed 30 years ago may no longer be present due to natural change or unrecorded fishing impacts.	**Type 1.** An area is protected based on a historical record of a VME that no longer exists, leading to an unnecessary restriction on human activities.
Modelling and Prediction		
Model Extrapolation	A habitat suitability model is applied to a new geographic region or to environmental conditions outside the range of the data it was trained on, where its predictive power is unknown.	**Both.** The model could dramatically overpredict suitable habitat (Type 1) or completely fail to identify suitable conditions because the ecological relationships are different (Type 2). This introduces high, but not directionally biased, error.
Predictor Variable Error	The environmental data layers used in models (e.g., bathymetry, substrate maps) have their own errors and are often at a coarse resolution that smooths over smaller VME habitats like pinnacles or canyons.	**Leans toward Type 2.** The smoothing effect of coarse environmental data is more likely to cause models to miss small, suitable habitat features than to create false ones, leading to an under-prediction of VME locations.
Definition and Application		
Definitional Ambiguity	The thresholds for what constitutes a "VME" (e.g., density of indicator species) are often qualitative or inconsistently applied, creating uncertainty about which observed aggregations qualify for protection.	A *conservative* definition (low threshold) intentionally invites **Type 1 errors** to be precautionary. A *permissive* definition (high threshold) leads to **Type 2 errors** by failing to protect moderately dense but still vulnerable areas.
Spatial Discretisation	The process of converting a continuous probability map from a model into a discrete polygon for a management closure. Boundaries are often simplified and buffered for practical enforcement.	**Type 1.** To ensure the high-probability core is protected and to create manageable boundaries, polygons are almost always drawn larger than the predicted VME footprint. This deliberately protects non-VME habitat, a precautionary Type 1 error.

between areas of high predicted suitability with low confidence (requiring additional research) and areas of moderate suitability with high confidence (suitable for immediate management action).

Evolving Policy and Management Frameworks

Whilst technical advances have improved uncertainty quantification and communication, they reveal a critical distinction between what can and cannot be solved through better methods. These solutions make uncertainties more explicit and manageable for decision-making, but they cannot eliminate the underlying knowledge gaps about VME distribution and vulnerability. The fundamental challenge of translating inherent scientific uncertainty into precautionary yet practical management policies remain. Resolving this requires institutional and policy innovation rather than purely technical solutions, representing a shift from asking "how certain are we?" to "how do we act responsibly given what we don't know?"

These methodological advances enable scientists to provide advice with explicit confidence levels and probabilistic outcomes rather than deterministic statements. The question becomes: how should management frameworks respond to this more nuanced scientific input?

The value of uncertainty quantification tools depends on their integration into decision-making processes. This section examines how policy frameworks have evolved to incorporate explicit uncertainty into management actions. High-level agreements like the 2023 BBNJ Treaty have made precautionary and ecosystem-based approaches binding obligations, requiring explicit consideration of uncertainty in all management decisions.

The ICES approach exemplifies direct uncertainty communication in its VME assessment frameworks, combining habitat suitability predictions with confidence indices that separate scientific uncertainty assessment from management risk decisions (Morato *et al*., 2018; van Denderen *et al*., 2022). Different RFMOs have developed distinct approaches: CCAMLR uses precautionary encounter protocols where small VME bycatch (10 kg) triggers immediate local closures, effectively using fishing fleets as sampling tools (CCAMLR, 2024). SPRFMO relies on large model-based closures with higher encounter thresholds as backup protection (SPRFMO, 2022). GFCM has institutionalised uncertainty through adaptive management, establishing "Fisheries Restricted Areas" with regular review cycles that update rules based on new scientific information (GFCM, 2024). NAFO has developed a complementary suite of uncertainty communication tools within its VME assessment framework, using kernel density estimation (KDE) alongside species distribution models rather than relying on either approach alone (Kenchington *et al*., 2019). Model uncertainty is communicated explicitly through additional output layers, including the frequency of presence across cross-validation runs and the average probability of the dominant prediction class, providing managers with a direct visual representation of spatial confidence (Murillo *et al*., 2024, 2025; NAFO, 2024). Extrapolation areas, where models are applied beyond the environmental conditions of their training data, are also identified and mapped to flag predictions of unknown reliability (Mesgaran *et al*., 2014).

The diversity of these approaches reflects both the flexibility inherent in the precautionary principle and the genuine scientific uncertainty about which combination of encounter protocols, model-based closures, and adaptive review cycles best achieves VME protection in practice - a question that remains unresolved and argues for continued cross-RFMO learning and comparisons.

Roles of RFMOs and Advisory Bodies

The principles for effective communication require institutional support to be realised. Advisory bodies serve as the link between scientists, policymakers, and stakeholders, making them well-positioned to implement these approaches. Success requires three elements: maintaining technical consistency and quality, improving communication interfaces, and supporting adaptive governance.

Advisory bodies can foster common standards through several mechanisms: convening expert workshops to establish shared best practices for uncertainty quantification, providing clear guidance that requests explicit uncertainty assessments (using confidence indices or pedigree matrices), and commissioning comparative studies of different modelling approaches to build collective understanding of their strengths and weaknesses.

Advisory bodies act as "knowledge-brokers" between scientists and managers in policy systems (Pielke Jr, 2007). This exchange involves documenting all data, stakeholder input and scientific advice, including minority and dissenting views; facilitating structured discussions where policymakers can directly engage with scientific uncertainty; and developing communication tools, such as interactive formats that allow scientists and managers to explore risk scenarios together. For example, NAFO has developed an approach to bridge the science-policy gap through its Joint Commission-Scientific Council Working Group on Ecosystem Approach Framework to Fisheries Management (WG-EAFFM). This institutional mechanism demonstrates a practical way in which RFMOs can create structured opportunities for scientists and managers to address uncertainty in VME protection. The working group brings together fishery managers, scientists, and advisors from contracting parties in informal sessions where scientific advice can be explored before formal policy recommendations are developed.

The informal dialogue format used by WG-EAFFM effectively communicates spatial uncertainties in VME assessment and protection. During these sessions, scientists explain confidence intervals around habitat suitability models, discuss sampling bias in VME data, and describe directional biases. This transparency helps managers understand both what the science indicates and why precautionary measures are necessary given asymmetric risks. Since its inception in 2012, the working group has developed capacity to handle increasingly complex uncertainty frameworks, moving from basic vulnerability assessments to comprehensive treatments of encounter protocols, model extrapolation risks, and adaptive management cycles that acknowledge the provisional nature of spatial protection measures.

WG-EAFFM's structure recognises that effective uncertainty communication requires both technical translation and policy development. When discussions move from informal sessions to formal recommendations, the Scientific Council maintains representation whilst scientists remain within their national delegations. This structure preserves the understanding developed during informal exchanges when developing policy recommendations for the Commission. The working group's success in advancing VME protection measures how institutional mechanisms can translate complex scientific uncertainties into conservation policies that acknowledge their limitations whilst maintaining precautionary effectiveness. However, the NAFO WG-EAFFM model is not universally replicated across RFMOs, and many bodies lack equivalent fora for informal science-policy dialogue. Where such mechanisms do exist in other organisations - for example, the South Pacific Working Group (SPACWG) within SPRFMO, which brings together managers, scientists, fishing bodies, and environmental NGOs to discuss science feeding into the Scientific Committee - they fulfil a similar bridging function. In organisations where no such intermediate forum exists and scientific advice moves directly to formal deliberation, the nuances of uncertainty are less likely to be understood and incorporated into management decisions, representing a governance gap that warrants attention.

A Practitioner's Guide to Spatial Uncertainty

Table 2 translates the principles discussed in this review into practical recommendations for scientists, managers, and institutions working at the science-policy interface.

Conclusions

Scientific and observational limitations in the deep seas create a strong tendency towards Type 2 errors – a failure to protect VMEs. Precautionary advisory frameworks and management actions counter this underestimation by introducing Type 1 errors as a risk-averse strategy to ensure conservation goals are met. While states and RFMOs operate under the precautionary approach, they have implemented it differently for VME protection, ranging from highly risk-averse encounter protocols to large-scale predictive models to adaptive management cycles.

Uncertainty communication in deep-sea VME conservation represents one of the most challenging interfaces between marine science and policy. Extreme data limitations, technological constraints, and institutional complexity create advisory challenges that exceed those in other marine systems. Success requires shifts from deterministic advice toward probabilistic, adaptive frameworks that acknowledge knowledge limitations whilst maintaining scientific credibility. Effective approaches combine sophisticated uncertainty quantification with clear communication strategies, precautionary policy frameworks, and stakeholder engagement that acknowledges both scientific and value uncertainties.

These challenges extend beyond deep-sea conservation into virtually all domains where scientific advice informs spatial decision-making. The Pressure-State-Response uncertainty framework applies equally to offshore renewable energy development, marine spatial planning, and coastal management. VME protection is distinguished not by the nature of these uncertainties, but by extreme data limitations and irreversibility of impacts that make precautionary approaches particularly critical.

The communication strategies, stakeholder engagement principles, and adaptive management frameworks outlined here provide transferable guidance for any spatial advice context where scientific uncertainty must be translated into policy decisions. Success will depend on continued investment in methodological development, capacity building across the science-policy interface, and institutional innovations that embrace uncertainty as inherent to complex marine systems rather than as a barrier to conservation action. The challenge is not to eliminate uncertainty, but to communicate and manage it effectively.

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Table 2. Recommendations for scientists, managers, and institutions working with uncertainty at the science-policy interface.

Scientists: Communicating Uncertainty Effectively	
Principle	**Action**
Quantify Uncertainty	Move beyond stating that 'more research is needed' by quantifying and presenting uncertainty explicitly across all components of the assessment. For pressure, this means expressing fishing effort and swept area estimates with confidence intervals derived from probabilistic approaches such as Hidden Markov Models or Monte Carlo simulations, rather than deterministic classifications. For state, uncertainty can be communicated through ensemble modelling, Bayesian approaches, cross-validation outputs, or other methods appropriate to the data and context, generating uncertainty maps alongside habitat suitability predictions and presenting results with confidence intervals rather than point estimates.
Visualise the Unknown	Maps showing what is not known can be as valuable as maps showing what is predicted. Use bivariate maps to display both VME likelihood and model confidence, and interactive platforms that allow managers to explore how different risk thresholds affect management options.
Be Explicit About Bias	Clearly explain directional biases in your data and methods, and if sampling limitations mean your assessment is more likely to miss VMEs, state this directly by including a summary table in advisory notes that explains each major uncertainty source and its likely effect on conservation outcomes.
Use Structured Frameworks	Organise advice using logical frameworks like Pressure-State-Response to break complex problems into understandable components by structuring assessment reports around the PSR framework and linking fishing pressure uncertainties to ecosystem state uncertainties and response uncertainties.
Managers and Policymakers: Operating Under Uncertainty	
Request Better Advice	Do not accept deterministic advice without uncertainty information. When setting terms of reference for scientific advice, explicitly request uncertainty quantification such as confidence maps, probability scores, and risk scenarios. The NAFO WG-EAFFM model provides a practical example, where informal dialogue sessions are structured specifically to allow managers to interrogate the uncertainty behind scientific advice before formal recommendations are developed.
Embrace Risk-Based Frameworks	Focus on choosing acceptable risk levels rather than seeking single "correct" answers by adopting management frameworks that allow explicit risk tolerance selection, such as protecting all areas with >60% chance of being a VME whilst acknowledging associated uncertainties.
Institutionalise Adaptability	Treat management measures as experiments to learn from rather than permanent solutions by building mandatory review cycles (every 3-5 years) into text of area closures and spatial measures, creating formal processes for incorporating new data and adapting management as uncertainty reduces.
Create Spaces for Dialogue	Effective policies benefit from co-development through informal discussion between scientists and managers before formal decisions, so support joint working groups like the NAFO WG-EAFFM model that bring scientists, managers, and stakeholders together to explore scientific advice nuances.
Institutions: Building capacity for effective science-policy communication	
Standardise	Ensure the processes behind the advice are transparent and repeatable, without prescribing specific scientific methods. Establish and adopt common standards for uncertainty reporting in scientific advice, such as requiring confidence indices.
Document	Ensure information flows freely and is well-documented by transparently recording and presenting all scientific input, including minority opinions and dissenting views, and developing and maintaining interactive data and advice portals.
Invest in the Interface	Dedicate resources to tools and people that facilitate communication by funding development of visualisation platforms and decision-support tools and supporting workshops and training that build communication capacity for scientists and uncertainty interpretation skills for managers.
Formalise	Translate high-level principles into clear operational rules for action under uncertainty by developing clear encounter protocols, model-based frameworks, and adaptive management cycles that provide precautionary pathways for decision-making when data is limited.

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