

## Article

# From Detection to Legal Knowledge: Environmental DNA Monitoring, Epistemic Due Diligence, and the Future of Marine Biodiversity Governance

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## Abstract

International marine environmental law increasingly depends on scientific information, but the legal consequences of new monitoring technologies remain underexplored. This article asks when environmental DNA (eDNA) monitoring may affect what states knew or ought reasonably to have known about marine biodiversity risks and consequently the application of due-diligence obligations. Drawing on Articles 192, 194, and 204–206 of the United Nations Convention on the Law of the Sea (UNCLOS), relevant jurisprudence of the International Court of Justice (ICJ) and the International Tribunal for the Law of the Sea (ITLOS), and the agreement under the UNCLOS on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ agreement), it uses “epistemic due diligence” as an analytical label for the informational dimension of existing duties of prevention, vigilance, monitoring, and assessment rather than as a new freestanding obligation. The article argues that scientific maturity, accessibility, and standardization can alter the factual baseline against which constructive knowledge and methodological adequacy are assessed. The analysis focuses primarily on water-derived (aqueous) eDNA, for which marine monitoring practices and standardization are most developed. Sediment-derived eDNA is considered a distinct matrix whose greater persistence and temporal integration require separate interpretive caution. eDNA monitoring results cannot constitute automatic legal knowledge because transport, degradation, contamination, sampling design, and reference-database limitations constrain inference. To discipline this assessment, the article proposes a five-factor eDNA knowledge test based on reasonable detectability, scientific maturity, accessibility and capacity, environmental gravity, and corroboration, organized in two stages: adequacy of the monitoring method and evidentiary evaluation/institutional response. The framework identifies the legally defensible space between environmental ignorance and what states ought reasonably to know.

Academic Editor: Beatriz  
Morales-Nin

Received: 7 September 2026  
Revised: 24 September 2026  
Accepted: 29 September 2026  
Published: 30 September 2026

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**Keywords:** environmental DNA; eDNA; UNCLOS; BBNJ agreement; due diligence; constructive knowledge; marine biodiversity; environmental monitoring

## 1. Introduction

Environmental DNA is beginning to alter the informational landscape. Organisms continuously release genetic material through mucus, skin cells, feces, gametes, tissue, and other biological material. Genetic material collected from environmental samples can

consequently reveal the presence of organisms without requiring the organisms themselves to be captured or visually observed. During the last decade, eDNA has developed from an emerging conservation technique into an increasingly prominent biodiversity-monitoring methodology [1–6].

Marine applications are particularly extensive. eDNA has been proposed or tested for fisheries monitoring, marine protected areas, invasive-species surveillance, threatened-species detection, ecosystem assessment, marine environmental impact assessment, and biodiversity monitoring in remote ocean regions [7–11]. Research has also demonstrated its capacity to identify temporal ecological change. Berry et al. [12], for instance, showed that molecular monitoring could identify seasonal biodiversity patterns and ecosystem responses to an anomalous marine heat wave, while Djurhuus et al. [13] demonstrated the capacity of eDNA to reveal seasonal shifts within marine communities.

The significance of these developments is not merely technical. Environmental monitoring is constitutive of governance because methods of observation influence which ecological conditions become visible to regulators. Kristensen, Pauwelussen and Bush [14], examining eDNA monitoring in North Sea offshore wind parks, show how choices concerning sampling and inscription shape which forms of biodiversity enter governance. Fisher's [15] account of epistemic responsibility in environmental law makes a complementary legal point: environmental institutions inevitably make choices about what knowledge counts and how environmental problems become cognizable. If technological change affects which environmental facts can reasonably be identified, it may also affect which facts states can reasonably be expected to know.

That question matters, because knowledge and foreseeability are central, though not uniform conditions in the operation of due diligence. Contemporary accounts treat due diligence as a context-sensitive standard of conduct. Its content depends upon the relevant primary rule, the seriousness and foreseeability of risk, state capacity, and the availability of reasonable preventive measures [16–21]. Monnheimer's analysis is particularly important because it places constructive knowledge within the due-diligence standard and argues that states may be expected to acquire knowledge of reasonably assessable threats ([19], pp. 116–141). Lanovoy [21] similarly identifies knowledge of risk as an essential condition of due diligence and notes that constructive knowledge may require proactive risk assessment rather than purely subjective awareness [22–24].

Recent jurisprudence has made this informational dimension explicit. The Seabed Disputes Chamber of the International Tribunal for the Law of the Sea (ITLOS) described due diligence as a “variable concept” responsive to scientific and technological knowledge and the gravity of risk ([25], p. 117). The International Court of Justice (ICJ) has likewise linked environmental diligence to vigilance, assessment, and scientific information, including in *Pulp Mills on the River Uruguay* and its 2025 Climate Change Advisory Opinion [26–27]. These authorities do not create a duty to use every available technology—they establish that the reasonableness of state conduct can evolve with risk, knowledge, and technical capability.

The United Nations Convention on the Law of the Sea (UNCLOS) is especially important because it links environmental protection with environmental knowledge. Article 192 requires states to protect and preserve the marine environment; Article 194 requires measures to prevent, reduce, and control marine pollution and to protect rare or fragile ecosystems and threatened species; Articles 204–205 address monitoring and reporting, and Article 206 requires assessment where planned activities may cause substantial pollution or significant and harmful changes to the marine environment. These provisions make information acquisition legally relevant without creating a general duty of environmental omniscience.

These provisions create what this article describes as an epistemic architecture of marine environmental protection. The convention does not impose a general obligation of environmental omniscience. It does, however, create legally structured practices through which environmental risks are to be observed, evaluated, and incorporated into regulatory decision-making. Monitoring under the UNCLOS is therefore more than bureaucratic reporting ancillary to substantive protection. It forms part of the process through which risks become legally cognizable [28].

The agreement under the UNCLOS on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ agreement) intensifies this relationship. In force since 17 January 2026, it elaborates procedures for area-based management tools, environmental impact assessment, capacity-building, and scientific cooperation. Its relevance here is institutional: it creates settings in which the adequacy, accessibility, and circulation of biodiversity information can affect environmental decision-making [29].

The terminology used here is deliberately limited. The proposition that due diligence may require information acquisition has antecedents in scholarship on constructive knowledge and due diligence [19–21,28], while recent work develops a “duty to know” in marine environmental governance [30]. This article uses “epistemic due diligence” only to isolate the information-acquisition dimension of existing primary obligations. It does not propose a new freestanding duty: its contribution is to ask how the growing maturity of eDNA-based monitoring changes the reasonableness of ignorance in a specific regulatory context.

Against this background, the central research question is: To what extent may scientifically mature and reasonably accessible eDNA monitoring affect what states ought reasonably to know about marine biodiversity risks and thereby influence the application of due-diligence obligations under international law? The literature has established that due diligence may require information acquisition, but it has not supplied a technology-specific account of when improved biodiversity detectability changes constructive knowledge, methodological adequacy, or the evidentiary threshold for further inquiry. This article fills that gap by translating the emerging duty-to-know logic into a five-factor, application-specific test for eDNA. It does not claim that the UNCLOS or the BBNJ agreement mandates universal eDNA deployment—it asks when omission of a mature monitoring method becomes legally relevant.

The article advances three arguments. First, existing duties of prevention, monitoring, assessment, and vigilance may require reasonable steps to acquire information material to a legally relevant risk. Second, the validation, standardization, and accessibility of monitoring methods can affect the factual benchmark against which that reasonableness is assessed. Third, technological detectability is not legal knowledge: scientific uncertainty, capacity, and evidentiary context require a structured assessment. The proposed five-factor eDNA knowledge test addresses reasonable detectability, scientific maturity, accessibility and capacity, environmental gravity, and corroboration.

Methodologically, the article adopts a doctrinal and normative approach to international marine environmental law. It interprets the UNCLOS and the BBNJ agreement in light of relevant international jurisprudence, with particular attention to the relationships between due diligence, monitoring, EIA, scientific information, and constructive knowledge. The legal analysis is then tested against peer-reviewed eDNA literature and emerging technical standards to identify when a monitoring method is sufficiently mature and accessible to become relevant to reasonableness. The article does not treat scientific publications as sources of legal obligation. They are used to establish the factual conditions of detectability, reliability, and practicability against which technology-neutral legal standards operate. The proposed eDNA knowledge test is therefore an interpretive

framework derived from existing legal duties rather than an empirical model or a claim of new customary law. The scientific discussion is deliberately centered on water-derived eDNA because the legal argument concerns methods approaching routine monitoring and because ISO 17805:2026 [31] is confined to eDNA sampled from water. Sediment-derived eDNA is not excluded from the framework, but it is treated as a distinct evidentiary matrix rather than assumed to be interchangeable with aqueous samples.

## 2. Environmental DNA and the Changing Ecology of Marine Knowledge

### 2.1. Capabilities, Governance, and Scientific Limits

Environmental DNA is commonly understood as genetic material recovered directly from environmental samples rather than from organisms specifically collected for genetic analysis [1–2]. In aquatic ecosystems, organisms continually leave biological traces in the surrounding environment. Those traces can be captured from water or sediment and analyzed using species-specific assays or community-level approaches such as metabarcoding.

This article therefore distinguishes water-derived eDNA from sediment-derived eDNA. Sediments can retain extracellular and particle-bound DNA for longer periods than the water column and may integrate biological signals over a broader temporal window. That persistence can be valuable for reconstructing biodiversity or detecting taxa whose aqueous signal is intermittent, but it also complicates temporal attribution: a positive sediment detection may reflect past deposition, resuspension, vertical mixing, or transported material rather than the contemporaneous presence of a living organism at the sampling site. Recovery can also vary with sediment type, DNA adsorption, degradation conditions, extraction efficiency, and PCR inhibition. These matrix-specific uncertainties reinforce the general ecological caution identified by Barnes and Turner [32]. They also explain why ISO 17805:2026, which standardizes sampling, capture, and preservation from water, cannot presently be treated as a maturity benchmark for sediment sampling [31].

The eDNA knowledge test remains compatible with sediment-derived evidence, but its factors must be applied matrix-specifically. Under reasonable detectability and scientific maturity, the authority should ask whether the sediment protocol is validated for the target taxon, substrate, and temporal question. Accessibility and environmental gravity operate in the same manner as for aqueous eDNA. At stage 2, corroboration becomes especially important where legal significance depends on current presence, recent harm, or spatial attribution: sediment detections may warrant follow-up through replicate cores, water-column eDNA, conventional surveys, habitat evidence, or other independent observations before stronger constructive-knowledge or causation inferences are drawn. Accordingly, the framework extends to sediment-derived eDNA as a structured trigger for inquiry, but the present article does not claim that water and sediment methods have reached equivalent levels of standardization or regulatory maturity.

The technological significance of eDNA derives principally from its capacity to complement conventional biodiversity observation. Traditional marine monitoring remains indispensable, and may provide information unavailable through eDNA, including direct measures of organism size, age, behavior, condition, or certain forms of abundance, yet conventional approaches also have recognized limitations. Visual surveys are constrained by visibility, depth, and observer effort. Trawling is invasive and selective. Vessel surveys are expensive and cannot continuously cover large marine regions. Identification may require specialist taxonomic expertise. Rare or cryptic species may therefore remain undetected even where monitoring programs formally exist.

Molecular detection changes this relationship between presence and observation. Kelly et al. [7] demonstrated early that seawater eDNA could recover information concerning marine vertebrate communities. Later research substantially extended both the taxonomic range and the spatial scale at which such methods can operate. Deiner et al. [3] described metabarcoding as a potentially transformative method for surveying animal and plant communities, while Miya [5] reviewed its growing importance for monitoring marine fish communities. Gilbey et al. [8] examined practical applications to fisheries management and ecosystem monitoring and emphasized that eDNA could contribute meaningfully to science-based marine management while also highlighting the need for methodological caution.

The value of eDNA is especially evident when the management question concerns detection rather than comprehensive ecological description. Rare species, early-stage biological invasions, and endangered organisms may be particularly difficult to identify using conventional sampling alone. In those settings, the sensitivity of eDNA surveying can substantially change the probability that a relevant biological fact becomes known.

This distinction is legally important. Environmental governance often operates not upon complete ecological knowledge, but upon thresholds of information sufficient to trigger additional assessment or precaution. If a monitoring technique increases the probability that an ecologically significant condition is detected before irreversible harm occurs, its contribution to law cannot be assessed solely by asking whether it provides definitive proof. It may instead alter when further investigation becomes reasonable.

The potential value of eDNA extends beyond individual species detection. Metabarcoding allows environmental samples to be screened for multiple taxa simultaneously and can consequently contribute to community-level biodiversity assessment. Berry et al. [12] demonstrated that repeated molecular sampling could detect seasonal marine biodiversity patterns and ecological responses to climate anomalies. Djurhuus et al. [13] similarly identified temporal community shifts through marine eDNA.

These applications suggest that environmental DNA may eventually function not simply as an occasional investigative technique, but as part of continuing environmental infrastructure. That possibility is reflected in the growing literature on protected areas. eDNA has been proposed as a means of improving monitoring within marine protected area networks, particularly where existing methods are spatially fragmented or taxonomically selective. Recent work by Zhang et al. [11], for example, used eDNA metabarcoding to assess multiple biological groups in a marine protected area and detected substantial fish, phytoplankton, and invertebrate diversity.

The relationship with environmental impact assessment is similarly developing. Hinz et al. [9] specifically evaluated eDNA for marine EIA and concluded that it already possesses substantial potential as a complementary method, particularly for detecting rare, endangered or invasive species. Coston-Guarini et al. [33] subsequently developed a simulation framework for examining when eDNA may be suitable for aquatic and marine EIA. These studies are particularly relevant to international environmental law because EIA is not simply a scientific exercise. It is a legal process through which environmental uncertainty is translated into decisions concerning whether and under what conditions activities may proceed. [34–37]

The distinction between environmental monitoring and governance consequently becomes increasingly difficult to maintain. Monitoring determines which risks appear in the evidentiary record. That record influences whether an EIA is required, what alternatives are considered, whether precautionary measures are adopted, and how environmental conditions attached to authorization are formulated.

Kristensen et al. [14] make this governance dimension explicit. Their analysis of North Sea offshore wind monitoring shows that the design of eDNA monitoring is not

neutral: decisions concerning what can be detected influence what forms of biodiversity become visible to future governance. From a legal perspective, that observation has a complementary implication. If regulatory institutions deliberately select methods that make certain significant environmental effects difficult or impossible to detect, the adequacy of the monitoring system itself may become part of the due-diligence inquiry.

The case for legal relevance must nevertheless begin with the scientific limits of eDNA. A persuasive legal analysis cannot treat molecular detection as synonymous with direct ecological observation.

One important problem concerns the ecology of DNA after it leaves an organism. Barnes and Turner [32] emphasize that origin, state, transport, and degradation affect the interpretation of environmental DNA. In marine environments, currents may transport genetic material away from the organism that produced it. Environmental conditions such as temperature, salinity, microbial activity, and ultraviolet radiation can affect persistence and degradation. A positive detection at one sampling point therefore does not always establish that a living organism occupied precisely that point at the moment of sampling.

Contamination provides another challenge. Because molecular techniques can be extremely sensitive, DNA introduced during sampling, filtration, laboratory processing, or sequencing may produce false-positive detections. Sepulveda et al. [38] consequently emphasize contamination control as a central requirement of rigorous aquatic eDNA research. Conversely, non-detection cannot automatically prove biological absence. Low DNA concentration, inadequate sampling effort, PCR inhibition, primer mismatch, and stochastic amplification can generate false negatives [6,39].

Quantification is also problematic. Although relationships between eDNA concentration and biomass have been demonstrated under some circumstances, those relationships are context-dependent. Rourke et al. [40] note both the promise and continuing limitations of using eDNA to estimate fish biomass. The number of sequence reads cannot ordinarily be treated as a straightforward census of organisms without accounting for shedding, degradation, transport, laboratory procedures, and species-specific biology.

Taxonomic identification creates a related dependence upon reference databases. If species lack reliable reference sequences, environmental DNA may be recovered without precise assignment. Shea et al. [41], reviewing marine metabarcoding studies, identify broader problems concerning metadata, interoperability, accessibility, and consistency. These deficiencies affect not merely scientific reproducibility, but also future legal use, because evidentiary reliability depends upon transparent methods and the capacity for independent review.

These limitations establish a crucial distinction that should inform the remainder of the analysis. Scientific uncertainty does not make eDNA legally irrelevant, but neither does scientific sensitivity make eDNA legally conclusive. Different legal decisions require different evidentiary thresholds. Evidence insufficient to establish causation or responsibility may nevertheless be more than sufficient to trigger additional monitoring, precaution, or EIA.

This graduated understanding of evidence is essential. It avoids the false choice between treating eDNA as determinative proof and dismissing it because it contains uncertainty.

## 2.2. Standardization and Technological Maturity

A monitoring method becomes increasingly important to law as it moves from experimental possibility toward standardized professional practice. The distinction matters because due diligence is assessed by reference to reasonableness rather than technological perfection.

For many years, one obstacle to routine eDNA adoption was methodological heterogeneity. Takahashi et al. [6], reviewing more than 400 aquatic eDNA studies, observed substantial diversification in sampling, preservation, extraction, replication, and analytical methods despite efforts at standardization. Shea et al. [41] identified similar variation in marine metabarcoding and emphasized the importance of data accessibility and reusable metadata. These concerns limit comparability and complicate any argument that a single eDNA method can already represent a universal monitoring benchmark.

The regulatory trajectory is nevertheless changing. ISO 17805:2026 [31], published in July 2026, establishes an international standard for sampling, capture, and preservation of environmental DNA from water. It addresses contamination avoidance, sample integrity, filtration, preservation, equipment, and metadata. The standard deliberately does not prescribe every aspect of eDNA analysis and does not cover sediment, passive sampling, or sampling design. Its importance should therefore not be exaggerated. It does, however, demonstrate that at least part of the eDNA workflow has matured sufficiently to support international standardization. [42–45]

That development is highly relevant to an evolving due-diligence standard. If scientific maturity, recognized methodology, and international standards are relevant considerations when deciding whether state conduct was reasonable, standardization can reduce the strength of an argument that a particular technology was too experimental or uncertain to deserve regulatory consideration.

Technological maturity is therefore gradual rather than instantaneous. Methods may move from experimental research through validation and inter-laboratory comparison into professional practice and standardization. Due diligence need not identify a single moment at which innovation becomes a legal benchmark. It must remain capable of recognizing when a method has become sufficiently mature to affect the reasonableness of monitoring choices.

### 3. Legal Foundations: Monitoring, Knowledge, and Due Diligence

The UNCLOS provides the principal legal framework, but the relevant provisions perform different functions. Article 192 establishes the general duty to protect and preserve the marine environment; Article 194(1) requires necessary measures to prevent, reduce and control marine pollution; and Article 194(5) requires those measures to include protection of rare or fragile ecosystems and the habitats of depleted, threatened, or endangered species. These are obligations of due diligence rather than guarantees of environmental outcomes [20–21,28]. In *Pulp Mills on the River Uruguay*, the ICJ linked diligence to administrative vigilance and monitoring (*Pulp Mills* [26], p. 197), while the *South China Sea Arbitration* applied a due-diligence lens to Articles 192 and 194 in relation to fragile ecosystems and endangered species (*South China Sea Arbitration* [46], pp. 941–944, 956, 964, 971, 975).

Article 204 supplies the clearest express monitoring obligation, but its scope must not be overstated. Article 204(1) requires states, as far as practicable and directly or through competent international organizations, to observe, measure, evaluate, and analyze by recognized scientific methods the risks or effects of pollution of the marine environment. Article 204(2) requires surveillance of the effects of activities that states permit or undertake to determine whether they are likely to pollute. The provision is therefore prospective as well as retrospective and links legal monitoring to recognized scientific methods. Its “as far as practicable” qualification makes cost, infrastructure, geography, technological maturity, and capacity relevant to methodological reasonableness.

Crucially, Article 204 is not a general biodiversity-monitoring clause. Species distributions or biodiversity patterns fall within it only where they are relevant indicators of pollution risk or effect. Broader biodiversity monitoring requires another legal route:

Article 194(5), where pollution-control measures implicate vulnerable ecosystems or species, and Article 206, where planned activities may cause substantial pollution or “significant and harmful changes to the marine environment,” or a project-specific authorization, EIA, treaty, or institutional monitoring obligation. The argument here is therefore conditional: eDNA-based monitoring becomes legally relevant only where an existing primary rule already makes the biodiversity information material.

Within that legally defined context, methodological discretion is not unlimited. The Seabed Disputes Chamber described due diligence as a variable standard responsive to scientific and technological knowledge and the gravity of risk ([25], p. 117), and the ITLOS identified scientific and technological information, international rules and standards, risk, and urgency as relevant to diligence under Article 194 ([47], pp. 235, 239–241). These authorities do not mandate every new technique. They support scrutiny of whether the chosen method was reasonably capable of detecting the legally relevant risk.

Articles 205 and 206 reinforce this informational structure. Article 205 anticipates circulation of monitoring results beyond the originating administration. Article 206 requires assessment where planned activities under a state’s jurisdiction or control may cause substantial pollution or significant and harmful environmental change. Pulp Mills further recognized EIA as part of due diligence in a transboundary-risk setting and contemplated continuing monitoring where necessary ([26], pp. 204–205). The ICJ’s 2025 Climate Change Advisory Opinion adds that states must actively pursue scientific information necessary to evaluate the probability and seriousness of harm and that diligence may evolve with scientific and technological knowledge ([27], pp. 283–285).

The resulting proposition is modest. International law does not silently insert “eDNA” into the UNCLOS. Rather, where a primary obligation requires monitoring, assessment, or vigilance, the adequacy of the information-gathering method can become part of the due-diligence inquiry. A mature and proportionate method may therefore matter when it materially resolves an uncertainty central to the legal decision, while technological novelty, weak validation, disproportionate cost, or lack of access may justify non-use.

### *Epistemic Due Diligence and Constructive Knowledge*

“Epistemic due diligence” is used here only for the information-acquisition dimension of an existing duty of reasonable conduct. Its antecedents lie in work on constructive knowledge and due diligence [19–21,28], reinforced by the ICJ’s 2025 advisory opinion and the marine “duty to know” literature [27,30]. The label is analytical, not a new primary obligation.

For the present purposes, epistemic due diligence asks whether, given the applicable primary rule, a reasonably diligent authority would have taken additional steps to resolve an uncertainty material to its decision. It is parasitic on that primary rule, concerns conduct rather than perfect knowledge, and remains both risk-sensitive and capacity-sensitive. It therefore avoids two extremes: technological detectability cannot automatically impute knowledge, but a state should not be able to manufacture unforeseeability by unreasonably failing to investigate a risk that the applicable legal regime required it to assess.

This differs from the territorial inference considered in the Corfu Channel, the 1949 ICJ case concerning mines in Albanian territorial waters. The court did not treat territorial control as automatic proof of knowledge ([48], pp. 18–22). Here, the question is instead whether a monitoring or assessment duty required reasonable information acquisition. If a validated eDNA-based method is materially more capable of resolving a serious, decision-relevant biodiversity uncertainty, its unexplained omission may bear on constructive knowledge. If the method is experimental, inaccessible, or poorly suited to the setting, the omission carries little weight.

Technological maturity therefore changes the comparative reasonableness of monitoring choices rather than creating an automatic legal baseline. ISO 17805:2026, for example, standardizes important stages of aquatic eDNA sampling, capture, and preservation without mandating eDNA-based monitoring or validating every downstream analytical technique. Such standardization can weaken the argument that a method is too experimental to consider, but technical standards remain evidence of competent practice rather than treaty amendments.

Capacity is equally central. External cooperation cannot be treated as available merely because a regional laboratory exists. A cooperative pathway is realistically accessible only where the state can lawfully and institutionally use it, the facility can deliver competent analysis within the regulatory timetable, costs are proportionate, sample-export and data-sovereignty rules permit use, quality assurance and chain-of-custody requirements can be met, and domestic authorities may rely on the resulting analysis. UNCLOS cooperation provisions, the ICJ's emphasis on knowledge-sharing, and Part V of the BBNJ agreement make cooperation relevant, but they do not create a presumption of access. Failure to seek assistance becomes legally significant only where a concrete, reliable, and proportionate pathway was effectively available.

The analytical sequence is thus: technological capability → reasonable detectability → reasonable information acquisition → actual or constructive knowledge → foreseeability → required diligence → compliance or breach. None of these transitions is automatic. The sequence simply explains how a monitoring technology can alter the factual benchmark against which an existing legal standard of reasonable knowledge is applied.

#### 4. Environmental DNA and the BBNJ Agreement

The BBNJ agreement provides a particularly important setting because biodiversity beyond national jurisdiction is marked by major observational gaps. Its four pillars—marine genetic resources, area-based management tools (ABMTs), environmental impact assessment, and capacity-building and transfer of marine technology—depend heavily on the production and circulation of scientific information [49–51]. The obligations discussed here apply to parties and, where the agreement so provides, to activities under their jurisdiction or control. References to authorizing states, competent international organizations, and treaty bodies are used according to their distinct institutional roles rather than as interchangeable categories [52].

The agreement's EIA regime is the clearest entry point. It elaborates UNCLOS Article 206 through screening, scoping, impact prediction, mitigation, consultation, decision-making, monitoring, and review [53–55]. Baseline knowledge is therefore legally consequential: an assessment that systematically fails to detect the biodiversity feature most vulnerable to a proposed activity may be formally complete, yet methodologically inadequate. eDNA-based monitoring is relevant here only as a possible complementary method. The agreement does not mandate it, but omission may require explanation where a mature, proportionate, and substantially more sensitive method could resolve an uncertainty material to the assessment [9,33].

##### 4.1. EIA, Monitoring and Best-Available Science

The agreement repeatedly invokes best-available science and scientific information, but “best available” should not simply mean whatever information happens to exist. In data-poor areas, diligent implementation may require reasonable efforts to improve the baseline while remaining sensitive to capacity [49–50,56]. eDNA-based monitoring may contribute to that effort alongside acoustics, remote sensing, conventional sampling, and modeling. Its value is application-specific rather than substitutive [51].

Articles 35–37 create an adaptive post-authorization cycle for parties: surveillance of impacts of activities they permit or in which they engage, reporting of monitoring results, and review where significant adverse effects were not foreseen or authorization conditions are not met. The sequence—assessment, authorization, monitoring, new information, review, and adaptation—means that an eDNA detection need not prove causation or breach to justify further investigation. Its immediate legal significance may instead lie in triggering verification, additional monitoring, or reconsideration of an earlier assessment.

#### *4.2. Institutional Pathways, ABMTs, and Epistemic Equality*

The same logic extends to ABMTs and marine protected areas, where evidence of ecological significance, vulnerability, connectivity, and change informs designation and review. The scientific and technical body can translate evolving science into performance-based guidance, while the clearing-house mechanism can improve the institutional accessibility of relevant information [50,57]. Neither function converts technical guidance into an automatic legal obligation to use a particular technology.

Capacity-building is integral to this analysis because sequencing facilities, bioinformatic expertise, and reference libraries are unevenly distributed. Part V can support regional laboratories, field protocols, reference-library development, data stewardship, and quality-assurance networks [58], yet legal accessibility must remain effective rather than theoretical: affordable and timely access, legal permission to transfer samples or data, institutional entitlement to services, data-sovereignty safeguards, and domestic usability of results all matter. This capacity-sensitive approach avoids converting technological inequality into a presumption of fault while allowing genuinely usable cooperation to influence what is reasonably expected [59–60]. [61]

Accordingly, proposals for regional eDNA hubs, shared sequencing capacity, and interoperable reference libraries are policy pathways rather than treaty-prescribed eDNA duties. Their legal relevance is indirect: as cooperative mechanisms become genuinely accessible and reliable, they may alter the practicability and proportionality assessment for parties facing serious biodiversity risks.

## **5. Environmental DNA as Legal Evidence**

### *5.1. Evidentiary Functions and Inferential Limits*

Discussion of environmental DNA as “legal evidence” can easily become misleading because evidence performs different functions at different stages of governance. An eDNA result may inform ordinary environmental management, trigger further investigation, influence the adequacy of an EIA, justify precautionary measures, or later be presented before a court or tribunal. These functions require different degrees of scientific confidence. A tribunal deciding whether a state breached an international obligation after environmental harm had occurred may require substantially stronger evidence than an administrative authority deciding whether uncertainty warrants additional sampling before an activity is authorized. The legally appropriate question is therefore not whether eDNA is “reliable enough for law,” but reliable enough for which legal inference and for which decision.

Species presence provides perhaps the most intuitive use. Repeated detections generated through validated assays, contamination controls, and appropriate spatial sampling may offer strong evidence that biological material from a target species was present in the sampled environment. Even here, however, legal reasoning must account for transport: in marine environments, DNA can move, so a detection does not necessarily demonstrate that the organism occupied the precise sampling location or remained there

at the material time. Non-detection requires even greater caution. Rees et al. [39] and later reviews emphasize that false negatives can arise because DNA concentrations fall below detection thresholds, sampling occurs at unsuitable times or locations, primers perform poorly, or environmental conditions accelerate degradation. This has major implications for EIAs concerning endangered species, because where conventional or molecular sampling has limited statistical power, a conclusion of absence may itself be epistemically weak. The legal standard should therefore examine detection probability rather than merely recorded presence or absence.

The inferential distance becomes greater when eDNA is used to establish population abundance, environmental damage, or causation. Research increasingly explores relationships between environmental DNA concentration and biomass, but those relationships remain context-sensitive [40]. A decline in read abundance may reflect changes in biomass, but it may also arise from hydrodynamics, shedding rates, degradation, sampling design, or laboratory variation. Likewise, a difference in community composition before and after an industrial activity does not by itself prove that the activity caused the change, because marine ecosystems are affected by temperature, salinity, currents, seasonal migration, and other pressures. A legally disciplined use of eDNA must therefore preserve distinctions between biological presence, abundance, ecological change, legally significant harm, and causation. This inferential discipline is essential if eDNA is to retain credibility before international courts and tribunals.

### *5.2. Methodological Transparency, Precaution, and Proof*

Where eDNA detections or survey results become contentious evidence, methodological transparency will be central to probative weight. A tribunal or expert body may need to consider where and when samples were collected, how much water was sampled, whether replication was adequate, which contamination controls were used, how DNA was preserved and extracted, which primers or assays were employed, what reference database supported taxonomic assignment, which bioinformatic thresholds were applied, and whether raw or processed data remain available for independent scrutiny. Shea et al. [41] demonstrate why metadata and data accessibility are particularly important in marine metabarcoding. A result that cannot be independently examined should receive less evidentiary weight than one supported by transparent protocols, accessible sequence data, and reproducible analytical decisions. ISO 17805:2026 is potentially important in this respect. The standard does not resolve the entirety of the evidentiary chain, but its requirements concerning sampling, contamination avoidance, preservation, and metadata can provide a recognized benchmark for parts of the workflow. The emergence of such standards can therefore influence evidentiary weight without converting formal compliance into conclusive proof.

Perhaps the most important legal distinction is between *ex ante* and *ex post* decision-making. An eDNA signal need not be sufficient to prove state responsibility in order to justify precaution before authorization. Suppose a validated assay repeatedly detects genetic material from a critically endangered species near a proposed seabed activity, while hydrodynamic uncertainty prevents investigators from establishing the organism's precise location with adjudicative certainty. The signal may nevertheless provide more than enough reason to delay authorization and conduct additional surveys. This reflects a broader principle of environmental governance: the evidence required to justify further investigation should generally be lower than the evidence required to impose final legal responsibility for environmental harm. Treating those standards as identical would undermine precaution because authorities could intervene only when facts were already sufficiently established for adjudication.

## 6. Limits: Why Technological Detectability Cannot Become Automatic Legal Knowledge

Technological possibility must not be converted into automatic legal obligation. States cannot monitor every organism or environmental change continuously, and the existence of a new technique does not make non-use negligent. Treating every technically discoverable fact as known would create epistemic strict liability, and allowing authorities to rely only on information they chose to collect would permit strategic ignorance. Due diligence lies between these extremes and remains contextual, risk-sensitive, and capacity-sensitive.

Scientific maturity and application-specific reliability provide the first limitation. A validated species-specific assay cannot be equated with an experimental metabarcoding workflow whose coverage and error rates remain uncertain. Reproducibility, quality assurance, reference-database adequacy, and suitability for the ecological question determine whether a method can reasonably inform regulation.

Accessibility provides the second limitation. Cost, infrastructure, expertise, and timing matter, and due diligence does not require impossible measures. At the same time, capacity cannot operate as an automatic excuse where serious or irreversible harm is at stake and proportionate assistance is effectively available. The relevant inquiry is practical accessibility in the circumstances, not technological availability in the abstract.

Reference databases create a third limitation. Environmental DNA cannot reliably identify organisms for which adequate genetic references do not exist, so regions with poor taxonomic coverage may remain less visible even where sampling and sequencing are technically sophisticated. This creates an epistemic asymmetry in biodiversity governance: species in heavily studied regions are more likely to be represented in reference libraries and therefore more readily detected and protected through molecular monitoring. International capacity-building should consequently include not only sequencing infrastructure but also reference-library development, taxonomic research, and locally usable analytical expertise.

Digital environmental governance generates a further challenge: information overload. If automated sensors and molecular monitoring continuously generate data, governments may possess far more environmental information than officials can meaningfully assess. Constructive knowledge cannot therefore be based upon theoretical accessibility alone. An obscure dataset stored in a repository and never communicated to a competent authority differs significantly from repeated scientific warnings officially submitted during an EIA or licensing process. Legal salience should depend upon relevance, credibility, institutional accessibility, repetition, seriousness of the identified risk, and connection with the decision under review. Constructive knowledge must remain realistic enough to guide administration rather than becoming a fictional presumption that states know everything available online.

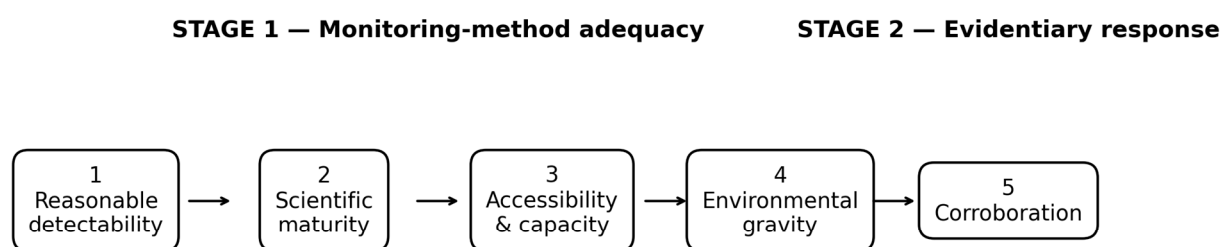
## 7. The eDNA Knowledge Test

The analysis above demonstrates that neither technological possibility nor actual possession of information provides a satisfactory test. The eDNA knowledge test is therefore offered as a structured interpretive framework, not as a rule deduced in its entirety from positive law. Its components have different pedigrees. Environmental gravity, capacity sensitivity, and responsiveness to scientific and technological development are strongly anchored in treaty text and international jurisprudence. Reasonable detectability and scientific maturity translate those legal requirements into technology-specific questions using the scientific characteristics of eDNA-based monitoring. Corroboration is primarily an evidentiary and normative criterion developed here to calibrate what legal

consequence should follow from an eDNA signal. The framework thus combines legal principles, scientific best practice, and an explicit normative synthesis rather than claiming that all five factors are directly prescribed by treaty or case law.

### 7.1. A Two-Stage Framework

Stage 1 asks whether the monitoring method was adequate for the legally relevant uncertainty. The first factor, reasonable detectability, asks whether the particular species or ecological characteristic relevant to the decision could have been detected with sufficient reliability under prevailing environmental conditions and an appropriate sampling design. This criterion is science-derived, but legally functional: it operationalizes the requirement that monitoring or assessment methods be capable of addressing the risk that the applicable primary rule makes material. If detectability is low, non-use of eDNA-based monitoring carries little weight. The structure and sequence of the five-factor test are summarized in Figure 1.



Scientific detectability → reasonable information acquisition → legally relevant knowledge / response

**Figure 1.** The five-factor eDNA knowledge test: from scientific detectability to legally relevant knowledge.

The second stage 1 factor is scientific maturity. A decision-maker should examine validation, replication, characterized error rates, acceptance within the relevant scientific community, quality-control standards, and applicable technical standards. The legal foundation is the dynamic character of due diligence and its responsiveness to scientific and technological knowledge. The operational content is supplied by eDNA science. ISO 17805:2026 strengthens maturity for specified stages of aquatic eDNA sampling and preservation, but does not validate every downstream inference. The existence of a water-sampling standard should not be used to infer equivalent maturity for sediment protocols, which require matrix-specific validation.

The third stage 1 factor is reasonable accessibility and capacity. Capacity sensitivity has a direct due-diligence foundation, while the accessibility inquiry is applied here to eDNA practice. Cost, infrastructure, expertise, laboratory access, time, and concrete cooperation pathways matter. External capacity counts only if it is effectively accessible under the legal, financial, temporal, data-governance, and institutional conditions described above. Resources are assessed relative to risk, but due diligence does not require impossible measures.

The fourth stage 1 factor is environmental gravity. International jurisprudence directly supports a more demanding standard of diligence where the probability or consequences of harm are serious. Gravity therefore acts as an intensity multiplier: it cannot cure non-detectability or scientific immaturity, but it can justify greater expenditure,

additional sampling, or a stronger explanation for choosing a materially weaker monitoring method where threatened harm is severe or irreversible.

Stage 2 begins only after the monitoring-method inquiry. Its central factor is corroboration, which evaluates the evidentiary significance of the information produced and the institutional response it reasonably warrants. Corroboration is not a treaty-prescribed element of due diligence. It is the author's normative synthesis of evidentiary caution and scientific best practice. Repeated detections, independent laboratories, habitat evidence, conventional observations, and other ecological indicators can strengthen a signal. Weak corroboration may justify verification or continued monitoring, stronger corroboration may justify precaution, EIA review, or a stronger constructive-knowledge inference, while proof of causation or state responsibility may still require more. Where sediment persistence makes contemporaneity uncertain, corroboration should carry greater weight before a detection supports inferences about current presence or recent environmental change.

The two stages are sequential, but connected. Stage 1 asks whether a diligent authority should reasonably have used or considered an eDNA-based method: reasonable detectability and scientific maturity operate as gateway considerations, accessibility and capacity test practical feasibility, and environmental gravity adjusts the intensity of the expected effort. Stage 2 asks what should follow from the information actually obtained or credibly presented: corroboration calibrates evidentiary weight and the proportional institutional response. This separation prevents two errors: treating a scientifically available method as automatically mandatory, and treating a single molecular detection as automatically conclusive legal knowledge.

The framework remains application-specific and does not generate a universal threshold at which constructive knowledge arises. Terms such as “reasonable,” “accessible,” “grave,” and “sufficiently corroborated” still require legal and scientific judgment. Its function is narrower: to make the reasons for monitoring and evidentiary choices explicit and to expose inconsistent treatment of technological possibility, capacity, and uncertainty. The legal and scientific foundations of the five factors are summarized in Table 1, while their interaction and indicative consequences are set out in Table 2.

**Table 1.** Legal and scientific foundations of the eDNA knowledge test.

| Factor                     | Stage | Primary Legal Foundation                                                                                                                                                             | Scientific/Evidentiary Foundation                                                                                    | Status and Function                                                                                       |
|----------------------------|-------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Reasonable detectability   | 1     | UNCLOS Arts. 204 and 206 where their respective triggers are met; methodological adequacy within due diligence/EIA                                                                   | Sampling design, assay sensitivity, transport, degradation, false-negative risk                                      | Science-derived operational criterion translating legal adequacy into a target-specific question; gateway |
| Scientific maturity        | 1     | Seabed Disputes Chamber [25] (p. 117); ITLOS Climate Change Advisory Opinion [47] (pp. 239–241); ICJ Climate Change Advisory Opinion [27] (pp. 283–284)                              | Validation, reproducibility, error characterization, QA/QC, ISO 17805:2026 where applicable                          | Mixed legal/scientific criterion; gateway                                                                 |
| Accessibility and capacity | 1     | UNCLOS practicability and capacity-sensitive due diligence; ICJ Climate Change Advisory Opinion [27], including cooperation and differentiated capabilities; BBNJ Part V for Parties | Cost, infrastructure, expertise, timing, legal entitlement, data governance, effective access to external facilities | Legally grounded feasibility criterion operationalized for eDNA; proportionality                          |

|                       |   |                                                                                                                                               |                                                                                                                        |                                                                                                   |
|-----------------------|---|-----------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Environmental gravity | 1 | Risk-sensitive due diligence in the Seabed Disputes Chamber [25] and ITLOS Climate Change Advisory Opinion [47]; relevant primary obligations | Conservation status, irreversibility, ecosystem fragility, probability/severity of harm                                | Directly law-grounded intensity multiplier                                                        |
| Corroboration         | 2 | No freestanding treaty requirement; informed by evidentiary caution, precaution and reasoned decision-making                                  | Replication, independent laboratories, conventional observations, habitat/model evidence, metadata and reproducibility | Author's normative/evidentiary criterion; calibrates legal consequence and institutional response |

**Table 2.** Decision matrix for the two-stage eDNA knowledge test.

| Factor                     | Function in the Test                 | Priority/Interaction                                                                          | Indicative Consequence                                                                       |
|----------------------------|--------------------------------------|-----------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|
| Reasonable detectability   | Stage 1: gateway                     | Must be plausible for the specific target and setting; gravity cannot cure non-detectability. | If low: eDNA omission carries little or no weight.                                           |
| Scientific maturity        | Stage 1: gateway                     | Validation and quality controls must be adequate at the material time.                        | If low: no expectation to use the method as a regulatory benchmark.                          |
| Accessibility and capacity | Stage 1: feasibility/proportionality | Assessed relative to resources, cooperation options and environmental gravity.                | Higher gravity can justify greater cost or external assistance, but not impossible measures. |
| Environmental gravity      | Stage 1: intensity multiplier        | Raises the level of vigilance and the justification required for weaker monitoring choices.   | High gravity strengthens the case for additional investigation or precaution.                |
| Corroboration              | Stage 2: evidentiary calibrator      | Determines how far the signal can support action or constructive-knowledge inferences.        | Weak: verify/monitor; strong: precaution, EIA review, heightened diligence.                  |

Regulatory practice already illustrates the transition from experimental science to environmental assessment. Lee et al. [62] document public-agency adoption of eDNA and identify the U.S. Bureau of Ocean Energy Management (BOEM), which developed inter-agency expertise and accepted eDNA data in offshore-energy review. The BOEM's Empire Wind documentation combines eDNA sampling with trawl and video surveys, using conventional observations to independently validate the molecular approach. This does not establish an international duty to use eDNA. It shows that regulatory acceptance can strengthen evidence of scientific maturity while the method remains complementary, quality-controlled, and context-specific.

### 7.2. Application: The South China Sea Arbitration as a Counterfactual Stress Test

The South China Sea Arbitration provides a useful real-world stress test even though eDNA was not at issue in the proceedings. The tribunal interpreted Articles 192 and 194 through due diligence and found failures relating to destructive harvesting and protection of fragile ecosystems and endangered species (South China Sea Arbitration [46], paras 941–944, 956, 964, 971, 975). The case is therefore not authority for an eDNA obligation. It is useful because it shows how knowledge of ecological harm, the adequacy of state vigilance, and the quality of environmental evidence can become legally material under Part XII [63].

Applied counterfactually, the five factors clarify what a tribunal should ask if a comparable dispute arose today. First, reasonable detectability would require proof that the relevant species, community, or ecological signal could have been detected in the affected

waters through an appropriately designed eDNA program. Second, scientific maturity would turn on validated assays or metabarcoding workflows, error controls, and standards applicable at the material time. Third, accessibility would examine whether the responsible authorities possessed, could procure, or could reasonably access the necessary sampling and analytical capacity. Fourth, environmental gravity would be high where destructive activity threatened rare species or fragile reef ecosystems. Fifth, corroboration would ask whether molecular detections aligned with habitat evidence, visual observations, fisheries information, or repeated independent samples. A strong showing across these factors would not prove that the state knew a species was present, still less that a particular activity caused its decline. It could, however, support the narrower conclusion that reliance on insensitive monitoring, without explanation or follow-up, was inconsistent with reasonable vigilance.

This counterfactual also demonstrates the test's limiting function. If no validated assay existed, reference databases were inadequate, currents made spatial inference highly uncertain, or the relevant state lacked realistic access to molecular capacity, omission of eDNA-based monitoring would carry little weight. Conversely, where conventional surveys were known to have low detection probability and a validated, affordable assay could materially resolve uncertainty concerning irreversible harm, failure even to consider the method would require stronger justification. The test thus evaluates the reasonableness of information acquisition rather than retroactively converting technological possibility into knowledge.

A shorter hypothetical illustrates the weighting structure. State A authorizes an off-shore seabed project where conventional surveys have not recorded a critically endangered migratory species, but researchers submit repeated eDNA detections using a validated species-specific assay. Detectability and maturity are gateway questions: if hydrodynamics, sampling design or assay performance make the signal unreliable, the case for follow-up weakens. If those gateways are satisfied, accessibility is assessed in context. A regional laboratory able lawfully to analyze samples within the licensing timetable at proportionate cost may be relevant even where state A lacks domestic sequencing capacity. Environmental gravity can intensify the diligence reasonably expected, while corroboration determines the response. Repeated, independently processed detections consistent with habitat or migration evidence may justify targeted verification, reconsideration of the biodiversity baseline, or adjustment of authorization without automatically proving species presence, causation, or state responsibility.

## 8. Wider Implications for Marine Biodiversity Governance

The wider implication is a shift toward anticipatory governance. Sensitive monitoring can move intervention earlier for invasive species, threatened populations, and fragile ecosystems by improving the informational basis for precaution before irreversible harm. Monitoring design is therefore a governance choice as well as a technical one: sampling frequency, spatial coverage, and detection thresholds determine which risks enter the administrative record, and a formally complete EIA may remain deficient if its observation strategy cannot detect the harm it purports to assess [14].

The appropriate response is performance-based standardization rather than technological lock-in. Institutions should require methods that are sufficiently sensitive, transparent, reproducible, and appropriate to the environmental question while allowing eDNA-based monitoring to complement visual surveys, acoustics, remote sensing, and future tools. Results used in EIAs, area-based management tools, or adjudication also require adequate metadata, interoperability, and independent review [41]. BBNJ institutions can help make these expectations portable without turning a single protocol into permanent law.

Environmental knowledge should also be treated as graduated rather than binary. An isolated signal may justify verification, repeated detections may support investigation, corroborated evidence may alter an EIA or justify precaution, and proof of causation or state responsibility may demand substantially more. This graduated approach preserves capacity sensitivity while allowing technological progress to narrow environmental blind spots.

For sustainability governance, the practical consequence is that eDNA should be treated as part of a socioecological decision system rather than as a laboratory technique operating outside policy. Earlier and more sensitive detection can affect where protected areas are proposed, whether offshore projects are redesigned, when precautionary restrictions are adopted, and how scarce monitoring resources are allocated. These decisions also distribute costs and benefits among regulators, developers, coastal communities, and states with unequal scientific capacity. The eDNA knowledge test therefore has a governance function: it makes explicit why a particular monitoring choice is proportionate to the ecological risk, technically credible, and institutionally feasible. This transparency can improve the legitimacy and reviewability of marine decisions even where the underlying science remains uncertain.

## 9. Conclusions

International marine environmental law depends on the capacity of institutions to identify legally relevant ecological risks. UNCLOS Articles 192 and 194 establish substantive environmental obligations, while Articles 204–206 connect protection with scientific observation, reporting, and assessment. International jurisprudence confirms that due diligence is dynamic and responsive to risk, scientific knowledge, and technological development.

The BBNJ agreement deepens this informational architecture through EIA, monitoring, reporting, review, and scientific cooperation. Its implementation will therefore depend not simply on the existence of biodiversity data but on whether relevant information is generated, accessible, and capable of informing institutional decisions.

Environmental DNA is an instructive case because eDNA-based monitoring can reveal species and biodiversity patterns that conventional methods may overlook, yet transport, degradation, contamination, sampling design, reference databases, and abundance inference constrain what detections prove. These limitations preclude any simple rule of universal use.

The appropriate inquiry is contextual. A mature, reasonably accessible method that can materially resolve a serious, legally relevant uncertainty may affect whether information acquisition was reasonably diligent. The two-stage eDNA knowledge test structures that inquiry: stage 1 addresses monitoring-method adequacy through detectability, maturity, accessibility/capacity and environmental gravity, and stage 2 addresses corroboration and the institutional response warranted by the evidence.

The framework does not convert technological availability into automatic legal knowledge. Its broader significance is technology-neutral: as molecular tools, autonomous sensors, satellite observation, and other systems expand environmental detectability, legal institutions will increasingly need to distinguish excusable uncertainty from unreasonable failures to investigate. The central question is not whether technology replaces legal judgment, but how legal judgment should respond when technology changes what a diligent authority could reasonably have known.

**Funding:** This research received no external funding.

**Data Availability Statement:** The original contributions presented in this study are included in the article. Further inquiries can be directed to the author.

**Conflicts of Interest:** The author declares no conflicts of interest.

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