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The use of emerging autonomous technologies for ocean monitoring: insights and legal challenges

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The critical role of biology Essential Ocean Variables (EOVs) in advancing our understanding of marine ecosystems underscores the need for sophisticated observation tools like Autonomous Underwater Vehicles (AUVs), Unmanned Aerial Vehicles (UAVs), Maritime Autonomous Vehicles (MAVs). However, the integration of these technologies in Marine Scientific Research (MSR) has surfaced significant legal and policy challenges. This study, informed by insights from forty-six experts across academia, oceanographic institutions, industry, and intergovernmental organizations, identifies six principal legal challenges relevant to the: operation and navigation of AUVs, data collection, security, environmental impact, animal tagging, and intellectual property rights. Effectively addressing these challenges requires a coordinated, multi-stakeholder approach among the scientific community, policymakers, and international bodies. States may promote an initiative to drive progress in ocean observation while laying the groundwork for advancements. To address the operational and regulatory complexities, States may coordinate collaboration through involvement of the Intergovernmental Oceanographic Commission (IOC), the International Maritime Organization (IMO), and the World Meteorological Organization (WMO), for example. Additionally, coordination with frameworks such as the BBNJ Agreement, UNCLOS, the Convention on Biological Diversity's Kunming-Montreal Global Biodiversity Framework (CBD KM-GBF), and regional organizations like the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) would ensure a comprehensive and inclusive approach.

KEYWORDS

marine biodiversity observation, emerging autonomous technologies, autonomous underwater vehicles (AUVs), regime interaction, Biology and Ecosystems Essential Ocean Variables (EOVs), ocean data, ocean governance, BBNJ

1 Introduction

The growing use of autonomous technologies to collect information about the ocean within national jurisdictions and in the high seas, from the surface to the ocean bottom, necessitates the emergence of a global governance system that addresses data ownership, privacy, intellectual property rights, and liability for technology-driven damage in marine environments (Khaskheli et al., 2023). The urgency of this issue is intensifying as it becomes clear that the diverse applications of ocean resources are rapidly increasing worldwide. However, there remains a significant gap in our understanding of how these applications, combined with the effects of climate change, impact the fundamental qualities of the ocean that initially render it appealing for investment and leisure activities (IPBES, 2019; Díaz et al., 2018; Garcia Rodrigues et al., 2022; Flandrin et al., 2024). Historically, the impetus for ocean observation has stemmed from the need to comprehend the physical, biological, and geochemical characteristics of the ocean. This understanding is crucial for addressing scientific inquiries and supporting various maritime activities, including navigation, energy production, material and food extraction, weather and ocean state forecasting, as well as assessments of historical climate and future scenario planning. The observation of physical and chemical ocean variables and processes, including currents, temperature, salt, oxygen, carbon dioxide, and nutrients, has advanced rapidly since World War II, leading to the establishment of well-established regional and global-scale monitoring systems. Despite biodiversity being closely linked to ecosystem functioning and resilience to stress, and societies worldwide relying on marine life in numerous ways (Mooney et al., 2020; Oliver et al., 2015), routine and large-scale observations of marine life-including its biological production, abundance, and biodiversity-have not yet been fully operationalized.

Oceanographic knowledge and observation of ocean variables is the foundation for the development and implementation of many local and national strategies and international frameworks such as the United Nations Convention on the Law of the Sea (UNCLOS), the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement and the Kunming-Montreal Global Biodiversity Framework (CBD, 2022, Decision 15/4). The UNCLOS is the international cornerstone legal framework for the sustainable use and management of ocean resources, informed by ongoing scientific observation and research.

The UNCLOS establishes the foundational international legal framework for ocean governance, but it has limitations with respect to emerging maritime technologies. One gap are Autonomous Underwater Vehicles (AUVs), Unmanned Aerial Vehicles (UAVs), and Maritime Autonomous Vehicles (MAVs) (Chang et al., 2020). Article 20 of UNCLOS refers to the obligation of submarines and other underwater vehicles to navigate on the surface and show their flag while exercising the right of innocent passage through the territorial sea. Although the phrase "underwater vehicles" ostensibly encompasses a broad category of submersible technologies, it leaves considerable ambiguity regarding the legal classification of AUVs. There is no treatment of UAVs. It is unclear whether these entities should be treated as ships, vehicles, equipment, or devices under international law.

Marine scientific research and operations rely on advancements in ocean observation technologies for the collection of data across vast areas and depths of the ocean. Although UNCLOS mandates that all States protect and preserve the marine environment, it lacks adequate mechanisms to tackle threats other than pollution in areas beyond national jurisdiction (Humphries and Harden-Davies, 2020). The BBNJ Agreement addresses this deficiency by introducing a broad range of measures designed to protect marine biodiversity. These include the establishment of marine protected areas, rigorous environmental impact assessments, and enhanced sustainable management of marine resources, thereby offering a more comprehensive and effective framework for the conservation of marine ecosystems in the high seas. The BBNJ Agreement represents a significant advancement ma from earlier multilateral environmental agreements by prioritizing a systems-oriented framework and fostering enhanced international cooperation toward common environmental goals (Kim, 2024; Santos et al., 2022). Although the BBNJ Agreement has not yet entered into force, it underscores its jurisdiction over living organisms in both the high seas and the Area including the ocean floor (Friedman, 2024). By 12 July 2025, the BBNJ Agreement had been ratified by 51 parties and will enter into force 120 days after the 60th ratification is deposited, while remaining open for signature until 20 September 2025.The Kunming-Montreal Global Biodiversity Framework (KM-GBF) was adopted at the 15th Conference of Parties to the UN Convention on Biological Diversity. The KM-GBF supports efforts to meet Sustainable Development Goals, and specifically promotes the conservation, restoration, and sustainable utilization of biodiversity (Hughes and Grumbine, 2023). The four overarching goals of the GBF are to i) halt human-induced extinction of species, ii) the sustainable use and management of biodiversity, iii) equitable sharing of benefits, and iv) the implementation and financial resources (CBD, 2022). These goals are supported by 23 targets which are grouped into i) 'reducing threats to biodiversity' (targets 1-8), ii) 'meeting people's needs through sustainable use and benefit-sharing' (target 9-13) and iii) 'tools and solutions for implementation and mainstreaming' (targets 14-23) (Danielsen et al., 2024). Among the targets are the conservation of 30% of land, oceans, and inland waters; the restoration of 30% of degraded ecosystems; a 50% reduction in the introduction of invasive species; and a $500 billion annual reduction in environmentally harmful subsidies (CBD, 2022). The GBF tasks national governments to report progress towards the targets and goals through a monitoring framework containing headline indicators.

In order for these ocean governance frameworks to function, for example to evaluate progress toward targets, information about biodiversity and the environment needs to be collected and summarized. Among the strategies to collect information, governments, researchers, and the private sector look to the development and deployment of advanced ocean observation technologies. Information collected supports the implementation of international agreements and reflects a commitment to science-based policy development. These technologies are designed to provide multiple required and complementary observations (Chai et al., 2020; Lin and Yang, 2020; Oliver et al., 2015; Whitt et al., 2020).

Many high-quality and labor-intensive measurements are collected by technologies mounted on ships, and many of these systems are operated manually. Increasingly, automated and remote technologies are enabling the collection of observations across broader areas and over extended periods. These platforms include moored buoys, drifters, unmanned surface vehicles, Argo floats, underwater gliders, cabled seafloor observatories, AUVs, and hadal landers, all equipped with water samplers, cameras and other optical imaging devices, passive and active acoustic sensors, and chemical sensors. Additionally, UAVs may carry samplers, and they, as well as satellite-mounted sensors can observe the ocean surface across large areas, concurrently measuring multiple different parameters. Among the various autonomous ocean observing platforms, Argo floats exemplify the potential of autonomous platforms. Since 2000, thousands of autonomous profiling floats equipped with a wide array of biogeochemical sensors have been measuring key water properties such as temperature, salinity, and pressure across the world's oceans. These measurements have significantly enhanced our understanding of ocean circulation, heat content, and the ocean's role in regulating the climate system (Chai et al., 2020).

These platforms and sensors play a crucial role in measuring the Essential Ocean Variables (EOVs) developed by the Global Ocean Observing System (GOOS) to enhance coordination across different observational systems and networks. EOVs encompass physics- and biochemistry-related metrics such as sea ice, temperature, currents, salinity, heat flux, ocean bottom pressure, oxygen, nutrients, and carbon, as well as key biology and ecosystems variables. Despite the progress in measuring physical and chemical EOVs, direct measurements of biology and ecosystems variables remain limited (Boss et al., 2018; Muller-Karger et al., 2018). Research and management often estimate biology and ecosystems characteristics indirectly, using proxies and models based on observations of physical and chemical variables, such as temperature, salinity, chlorophyll, and oxygen levels. However, emerging technologies specifically designed to monitor biology and ecosystems EOVs are increasingly being integrated into autonomous platforms, enabling direct measurements of metrics such as species abundance, distribution patterns, and ecosystem interactions (Muller-Karger et al., 2018; Whitt et al., 2020). These autonomous platforms also have the potential to guide restoration interventions in deep-sea environments beyond areas of national jurisdictions by giving information on the location and migration patterns of animals (Aguzzi et al., 2024). There is indeed at present a market and technology development opportunity to improve such observational capacities for more effective management and sustainable use of marine resources (Estes et al., 2021a, 2021b; Miloslavich et al., 2022).

Table 1 lists some relevant Biology and Ecosystems EOVs, along with some of the technologies used to measure elements of each (the list of approaches is only a sample, as a comprehensive review of technologies and methods for each biology and ecosystems Essential Ocean Variable is beyond the scope of this manuscript). AUV and UAV platforms can provide information on many of these EOVs in remote, hard-to-access ocean regions, and can collect real-time or delayed data over extended periods (Ganie et al., 2025; Boss et al., 2022). The amount of data collected through these technologies and sensors mounted on automated platforms is large. Integrating, processing, and analyzing these big and diverse datasets would all benefit from the development and wide implementation of standards to facilitate data interoperability and forecasting solutions for effective and timely decision-making (Estes et al., 2021a, 2021b; Freestone et al., 2024).

2 Setting the scene

Effective coordination is crucial for advancing the adoption of new technologies and their widespread application. To fully harness the potential of autonomous observations, establishing new standards and best practices is essential, with a particular focus on improving the interoperability of sensors, systems, and data in autonomous vehicles (Whitt et al., 2020). What are the current legal challenges associated with the use of autonomous underwater technologies for the observation of marine biodiversity, and what may be expected as possible solutions and additional challenges in the future?

To address these questions, subject matter experts were invited via email to take part in semi-structured interviews between March and December 2024. The invitation included information about the purpose and scope of the study, its connection to the Future of the Ocean Program of the Sasakawa Global Ocean Institute at the World Maritime University, and details about the program's technology pillar, which aims to develop a roadmap for leveraging ocean observation technologies to address the Triple Planetary Crisis. A sample of forty-six (46) subject matter experts on marine science, ocean technology and ocean governance and policy were utilized for this study. The participants provided written informed consent to participate in this study. The respondents represent a wide geographical distribution, reflecting the international nature of marine science, ocean data, ocean technology and policy. Participants are affiliated with institutions based in the United Kingdom, the United States, Germany, Australia, Canada, Sweden, France, Finland, Chile, Turkey, Japan, Croatia, Norway, Argentina, Portugal, Colombia, Malaysia, Greece, Cyprus, and Israel. In terms of institutional affiliation, respondents were categorized according to the nature and function of their organization. The largest group comprises individuals affiliated with academia and research institutions, followed by those working in industry and national oceanographic/meteorological and fisheries organizations (Table 2).

During the interviews, respondents were asked to identify key legal, data governance and technological barriers affecting the observation of marine biodiversity and to reflect on obstacles that hinder the effective use of such data by policymakers. Two key questions led the discussions under this area: (i) Are there any legal or regulatory challenges that impact the collection and use of ocean observation data? (ii) What are the challenges in ensuring that policymakers understand and effectively use ocean data.

TABLE 1 Sample technologies for collecting data on elements of select Biology and Ecosystems EOVs.

Biology and Ecosystems EOVs	Platforms	Sensors
Phytoplankton Biomass and Diversity	BioGeoChemical (BGC) Argo Floats, gliders, other Autonomous Underwater Vehicles (AUVs), moorings, Unmanned Airborne Vehicles (UAVs)	Optical/bio-optical sensors (fluorescence, radiance, irradiance, LiDAR, cameras, etc.), environmental DNA (eDNA), samplers
Zooplankton Biomass and Diversity	AUVs, moorings, UAVs	Passive and active acoustic sensors [quantitative echosounders and Acoustic Doppler Current Profilers (ADCP)], Optical Plankton Counters (OPCs), cameras, eDNA
Fish Abundance and Distribution	AUVs, moorings	Passive and active acoustics, acoustic tag monitoring for tracking, imaging and video cameras and other systems, physiological sensors, environmental biologging sensors, Baited Remote Underwater Video Systems (BRUVs), eDNA
Sea Turtle Abundance and Distribution	AUVs	Imaging cameras, physiological sensors, environmental biologging sensors acoustic tag monitoring for tracking, other tracking, eDNA
Marine Mammal Abundance and Distribution	Drones (UAVs), AUVs, moorings	Passive acoustics, physiological sensors, environmental biologging sensors, acoustic tag monitoring for tracking, eDNA
Seabird Abundance and Distribution	Drones (UAVs), camera traps	Imaging, video cameras, physiology sensors, GPS trackers, eDNA
Coral Cover and Composition	AUVs, Drones (UAVs)	Imaging, video cameras, bio-optics, biogeochemical sensors (pH, carbon dioxide, nutrients), bio-optics, eDNA
Seagrass Cover and Composition	AUVs, Drones (UAVs)	Imaging, video cameras, bio-optics, biogeochemical sensors (pH, carbon dioxide, nutrients), bio-optics, eDNA, passive and active acoustics
Mangrove Cover and Composition	Drones (UAVs), camera traps	Imaging, video cameras, bio-optics, biogeochemical sensors (pH, carbon dioxide, nutrients), bio-optics, LiDAR (Light Detection and Ranging), eDNA
Macroalgal Canopy Cover and Composition	Drones (UAVs), AUVs	Imaging, video cameras, bio-optics, biogeochemical sensors (pH, carbon dioxide, nutrients), bio-optics, LiDAR (Light Detection and Ranging), active and passive acoustics systems, eDNA

A comprehensive review of platforms, sensors, and methods for each biology and ecosystems Essential Ocean Variable is beyond the scope of this manuscript.
Source: Authors.

3 Findings

The subsections below detail the six key patterns that emerged from the interview responses, highlighting the legal challenges associated with the operation and navigation of AUVs, UAVs, data collection, security, environmental issues, animal tagging, and intellectual property rights.

TABLE 2 Institutional affiliations of the respondents.

Field	Number of respondents
Academia and Research Institution	18
Industry	8
National Organization (Oceanography, Fisheries, Meteorological)	9
Navy	2
Intergovernmental Organization	2
Marine Observation Network	6
Global Research Program	1

Source: Authors.

3.1 Challenges relevant to the operation and navigation of emerging autonomous technologies

Evolving and fragmented legal frameworks affect the use of autonomous platforms including AUVs and UAVs. Regulations typically lag behind technological advancements, especially with the introduction of autonomous sensors and the collection of acoustic, optical, imaging, environmental DNA data, and the use of artificial intelligence (AI) in sampling design and on-board data processing.

According to the participants, autonomous platforms present unique challenges because existing international laws, particularly UNCLOS, were not crafted with these technologies in mind. Current laws, especially those governing Exclusive Economic Zones (EEZs), were not formulated to handle the complexities introduced by the deployment of AUVs. The utilization of automated underwater technologies, such as gliders, or UAV platforms such as drones, is not adequately addressed by existing frameworks, which were designed primarily for ship-based research. The introduction of autonomous vehicles into sensitive areas like the EEZs exacerbates jurisdictional issues as territorial boundaries are governed by different laws. This leads to a fragmented regulatory environment, where some nations impose stricter controls on AUV and UAV operations, while others allow more freedom for innovation, navigation, and data collection.

Navigating the legal landscape for autonomous equipment, particularly in coastal and harbor areas, poses significant challenges due to varying national frameworks. The combination of unclear communication regarding licensing, and differing national regulations, creates substantial operational challenges for autonomous data collection.

An aspect brought into the discussion is that the Argo program of robotic floats deployed to gather global ocean data. The program is guided by consultation with the Intergovernmental Oceanographic Commission (IOC) and Resolution EC-XLI.4 provides *Guidelines for the Implementation of Resolution XX-6 of the IOC Assembly regarding the deployment of profiling floats in the high seas* within the framework of the Argo Program. According to the guidelines, coastal States must be informed in advance, through appropriate channels, of all deployments of profiling floats that might drift into waters under their jurisdiction. An entity designated as responsible for Argo Program floats deployed in the high seas has the responsibility to transmit this information through the Argo Information Centre to the Argo focal points designated by the International Oceanographic Commission (IOC) Member States. However, while the Argo notification scheme under the IOC addresses the drift of floats into national jurisdictions, it does not adequately cover their deployment (i.e. selection of location). Such inadequacies may introduce inefficiencies in an operational system that demands flexibility, particularly for deployments needed on short notice or for *ad-hoc* research opportunities. The complexity is further compounded during unpredictable events, such as hurricanes, where long-term planning (often six months or more) for marine research operations is impractical.

One of the subject matter experts interviewed stated that: *'If a glider or an Argo float enters an exclusive economic zone (EEZ), there are challenges. In the case of Argo, I believe they have to turn off some of the payloads, depending on the nation, as some countries are not willing to allow technology into their EEZ to collect information. Some of that information can be sensitive; for instance, they might not care about temperature data, but when it comes to marine life, nutrients, pollution, and so on, they may be more protective'.*

The integration of AI exacerbates the legal complexities. Current regulatory frameworks were designed for remotely operated vehicles, where human operators maintained control and were responsible for navigation and decision-making. In these cases, data collected within an EEZ is generally understood to be under the purview of the coastal State, which may exert control or at least have a say in the collection, archival, release and publication, and usage of that data. AUVs and UAVs, however, can independently navigate, collect data, and perform preprogrammed tasks, raising critical concerns about liability, accountability, safety, and sovereignty. For example, if an AI-operated platform malfunctions or violates airspace or maritime regulations, determining responsibility-whether it lies with the manufacturer, operator, or AI system itself-becomes an intricate issue.

3.2 Challenges for data collection for marine scientific research

Article 246 of the UNCLOS mandates that coastal States must give their consent for Marine Scientific Research (MSR) projects initiated by other nations or international organizations to expand scientific knowledge of the marine environment for the collective benefit of humanity. Therefore, coastal States are required to implement regulations that ensure that their consent for such research is not unduly delayed or unjustly withheld (Part III, Art. 246). Nonetheless, the interviewees noted that in some countries, the imposition of complex, time-consuming application processes, requiring renewal every year or even every six months, poses a severe challenge to the continuity and predictability of long-term scientific projects. In many cases, the burdensome nature of these processes can disincentive research efforts, particularly in many states where access to permits is slow, expensive, or unpredictable. Securing permits is often just the first hurdle; the actual process of conducting fieldwork and sample collection can be prohibitively expensive and fraught with additional requirements and challenges (Chang Y. et al., 2022). In some regions, there are mandates requiring foreign researchers to collaborate with local institutions. While this can foster beneficial partnerships, it also adds another layer of complexity, especially in cases where local institutions lack transparency. The context of local rights and participation is now further formalized in the CARE principles (GIDA, 2018).

Some member states are wary of research vessels entering and operating in their jurisdiction. This leads to delays or denied permissions; delays can be so long that the vessel leaves before approval is granted. There is also concern about mapping nearshore areas for national security reasons. In some nations, the administrative and procedural hurdles are so extensive that no one is willing to grant permission for mapping, or to release downgraded, lower-resolution datasets for global use.

The experts interviewed noted that there are significant legal questions concerning the operational limits within different maritime zones. In particular, maritime zones that are contested or disputed present complex legal challenges. For example, in regions such as the South China Sea, where competing claims over maritime boundaries exist, further complicate MSR, resulting in conflicting understandings of where data collection is permissible (Chang Y.-C. et al., 2022). This situation is further complicated when collaboration occurs with civilian institutions, such as National Oceanographic Centers that operate under the protection of Sovereign immunity.

The lack of a standardized global process for data collection permits contributes to various inconsistencies and confusion. These sovereignty issues highlight a broader tension in global data governance, particularly when comparing attitudes between regions. In much of the industrialized world, there is a growing acceptance of widespread data collection, which is now viewed as routine. This normalization of data collection underscores the cultural and regulatory differences between developed and developing states. Almost everywhere data are closely tied to notions of national wealth, pride, and sovereignty.

Outside the area of national jurisdiction, the participants noted that they had not experienced challenges in the field of ocean observation and that no permits or formalities had been requested. According to Article 257 of UNCLOS, States, regardless of their geographical location, as well as competent international organizations, are entitled to conduct MSR in the water column beyond the boundaries of the EEZ, taking into account environmental stewardship. However, it was noted that there is currently significant discourse surrounding the BBNJ agreement and marine genetic resources (MGRs), particularly regarding the collection of biological and water samples, the latter of which can be classified as biological due to the presence of environmental DNA (eDNA). The application of relevant legislation can lead to complexities, as any water sample containing eDNA may be treated as a biological sample. This classification introduces challenges, especially in the context of the collection, transportation, and transboundary movement of such samples, including those from the high seas.

One of the experts interviewed stated: '*In the open ocean, challenges are becoming more apparent as people look at the use of genetic resources and resources associated with the seabed, which no one owns on the high seas. This isn't a new issue; similar regulatory thinking has been applied to high-seas fisheries. In response, regional fisheries management organizations have been established to bring countries together to set regulations around what is caught on the high seas and to implement conservation measures to minimize impacts on biodiversity.*'

This issue is also relevant to the concept of bio-banking, by which biological samples are preserved for future analysis. As scientific knowledge of genomes, including those of newly discovered species or species with incomplete genome sequences (Pastra et al., 2022), expands, concerns arise regarding the appropriate handling of samples collected today. Researchers may not fully anticipate all potential future uses of a sample at the time of collection. For instance, an eDNA sample collected for immediate analysis might later prove valuable for additional studies, such as those involving advanced techniques that may emerge years later. This uncertainty in the future utility of collected samples complicates regulatory frameworks and permitting processes. Given that the potential applications of stored samples are not always foreseeable, the legal and ethical complexities surrounding the long-term preservation and use of bio-banked materials present significant challenges for researchers and policymakers alike.

3.3 Security and military concerns

The split between MSR and Military Data Gathering (MDG) was underlined in the discussions. On the one hand, military organizations show reluctance to release high-resolution topographical and marine seabed data to civilian research communities and international initiatives. On the other hand, autonomous devices, like gliders and Argo floats, can potentially and inadvertently collect sensitive data. This issue continuously raises concerns about national security and privacy among interested parties and member states of the IOC and other international frameworks.

One expert stated: '*There are situations where ships are conducting bathymetric surveys, and it would be ideal to install measurement systems to gather water condition data. However, because these platforms are operated under defense-related programs, such as those by the Defense Department, we are often unable to place any equipment on them.*'

MDG operations, conducted by vessels with sovereign immunity, often face various complexities. Although these vessels have the right to proceed with their activities without interference under and within guidelines for freedom of navigation under UNCLOS, they must maintain transparent communication with other nations and naval forces. This ensures that their operations are clearly understood and avoids the perception that data are being collected without consent. Effective communication mitigates potential misunderstandings and diplomatic tensions, especially in areas where multiple jurisdictions and interests overlap. All parties are responsible for ensuring that MDG activities comply with international maritime laws and norms.

A subject matter noted that the broader legal challenges associated with implementing the BBNJ agreement underscore the intersection of international maritime law, sovereign rights, and geopolitical strategy. Throughout the BBNJ negotiation process, careful legal maneuvering was necessary to strike a balance that preserved sovereign immunity while advancing the overarching goals of the BBNJ. A separate dialogue occurs among states in the context of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), which functions under the Antarctic Treaty System (ATS). CCAMLR maintains communications and links with the various conventions and treaties developed under the umbrella of the United Nations.

The issue of data sharing under sovereign immunity is expected to resurface in future international discussions. This is likely to remain a point of contention within the framework of global maritime governance. While these agreements seek to enhance global cooperation in the conservation and sustainable use of marine biodiversity, the complex web of legal constructs and political interests will continue to present challenges in implementation.

3.4 Marine protected areas and indigenous people

The establishment of Marine Protected Areas (MPAs) sometimes imposes restrictions on data gathering to prevent disruption of sensitive ecosystems, even if the intent is focused on the use of an area or resources in it. International regulations are generally not applicable unless they are explicitly incorporated into domestic tribal or national policy through legislation or rules. Measures that restrict the collection of observations typically prevent the disturbance of an ecosystem or misuse of sensitive information. There often are legal restrictions designed to block the sharing of certain data for conservation reasons associated with different MPAs. Thus, a significant challenge in MSR exists in balancing environmental protection with the need for data collection. In some areas, there are also various environmental regulations surrounding the use of chemicals, like antifouling agents, in data collection devices, which present additional legal concerns. Ensuring minimal environmental impact while collecting ocean data remains a key regulatory hurdle.

An expert stated that: '*Another major challenge is that we have many marine protected areas. These areas are of great interest, yet there's a dilemma because you need to understand what's there in order to protect it effectively. However, accessing these areas requires being respectful of the ecosystems. We're working on how to manage this, trying to gather sufficient data without disturbing the ecosystems of the marine protected areas.*'

The issue of environmental justice becomes critical when considering the rights of Indigenous and local communities and the CARE principles (GIDA, 2018) seek to address these concerns. Many Indigenous populations have deep connections to their ocean spaces, which are integral to their livelihoods and identities. When large corporations or foreign entities use autonomous vehicles to explore or exploit natural resources, without explicit consent, it can disproportionately harm these communities by disrupting the ecosystems they depend on. In this context, national and tribal regulations should be respected and followed to protect sensitive ecosystems and the rights and livelihoods of Indigenous and local communities.

The capacity to conduct MSR has historically been and continues to be, unevenly distributed among states. This disparity stems from several factors, including variations in technological resources, infrastructure, funding, scientific expertise, and general policy and political contexts. Addressing this is an opportunity as there is a pressing global need for policymakers to safeguard the interests of vulnerable communities while allowing scientific research to continue responsibly.

An expert interviewed concluded that: *"I think we're going to see more legal challenges to data sharing or data access due to privacy concerns, particularly with GDPR-style legislation, and issues such as Indigenous rights or the rights of groups whose data is collected without their consent, which can actually harm them. For example, if data shows where fish are located, a large company could extract that resource more efficiently than the local fishing community, but the local community would suffer as a result."*

3.5 Tagging marine animals with sensors

Apart from the collection of data from AUVs, a few interviewed experts brought into the discussion the legal and ethical challenges related to the practice of tagging animals with animal-mounted sensors for scientific research. A notable aspect of this process is the inherent autonomy of the animals. Once tagged, researchers have no control over the movement of the animals or the areas they traverse. These tagged animals continue to collect data even when they enter the EEZ or territorial zones of other states, raising complex questions about the ownership and control of the data gathered. Currently, the scientific community engaged in animal tagging operates under the assumption that data collected through tagged animals is not subject to the same jurisdictional scrutiny as data collected by controlled platforms, such as autonomous vehicles or ship-based instruments. This stems from the fact that animals, as independent agents, are not bound by human-imposed borders or regulations. As a result, researchers routinely collect and analyze data without regard to the jurisdiction in which it was collected, largely ignoring the potential legal implications tied to the collection of both environmental and biological data as one or more animals equipped with sensors cross into a foreign EEZ. Despite the absence of explicit regulation or enforcement surrounding this aspect, the autonomy of tagged animals introduces an interesting tension between the scientific goal of data collection and the legal frameworks governing marine resources and sovereignty. This issue, while currently unaddressed in the ocean observing community and international MSR community, contrasts sharply with the regulations that govern other data collection methods.

3.6 Commercialization issues and intellectual property

UNCLOS does not distinguish between marine research for academic or commercial purposes; thus Article 143 of UNCLOS about MSR could be applied to both cases. However, the commercialization of ocean data, particularly genetic resources and seabed information, has historically raised concerns over intellectual property (IP) rights, national sovereignty issues, and in general, issues of poaching of biodiversity patrimony and associated nature contributions to people. As ocean data becomes a valuable asset, regulatory scrutiny increases, especially when multiple parties are involved in data collection. The lack of standardized licensing agreements complicates data sharing and usage, particularly for commercial purposes. Although there is substantial interest within the corporate sector to share data for the greater good, corporate legal counsel often advises against it, citing the risk of litigation.

One expert commented: *"I think the BBNJ agreement highlighted some of the challenges in collecting information from the high seas, especially when that information is used for commercial purposes. Generally, regulatory issues arise when people attempt to profit from the data or samples they collect. These regulatory challenges are less prominent when there is open sharing of observations or data. However, regulation becomes more complex when monetization is involved due to the commercial component."*

Another noted that: "Within MSR, you need explicit permission to collect any data that could have economic value. We encountered this when we wanted to collect samples from the seabed off the coast of South Africa to study mineral deposits. Since the seabed in that area also contains rich veins of diamonds, the South African government required that any samples we collected be inspected to determine whether they contained diamonds. When scientific research data has potential economic benefits, access to making *observations can be denied—this applies to areas like fisheries, seabed minerals, and oil exploration".*

The interviews highlighted IP concerns that can significantly restrict access to data, even when the data are generated through government funding or public resources. Despite being publicly funded, the data may remain inaccessible to broader scientific or public use due to proprietary claims. This creates a complex network of legal challenges, as the interests of intellectual property protection often conflict with the principles of open data sharing and transparency. In some cases, the legal barriers surrounding IP rights can appear insurmountable, impeding scientific progress and international collaboration. Addressing these challenges requires a delicate balance between protecting innovation and ensuring that publicly funded data remains accessible for broader societal benefit.

The consumption of data-its dissemination and public use-can be as problematic as the initial collection. Once data are made publicly available through publications or other platforms, it enters a broader arena of scrutiny, where questions of compliance with national and international legal frameworks come into sharper focus. The ethical implications of bypassing permission can undermine international cooperation, lead to reputational damage for researchers and institutions, and may even result in diplomatic tensions. Therefore, compliance with local regulations and transparent collaboration with national authorities is crucial to ensure the legitimacy and acceptance of scientific data, both at the time of collection and throughout its dissemination. Respondents emphasized the importance of developing licenses that ensure that data remains FAIR (Findable, Accessible, Interoperable, and Reusable) to facilitate its use while protecting the rights of data collectors.

4 Concluding remarks and the way forward

Measurements of EOVs for marine biodiversity (biology and ecosystems EOV) are crucial for advancing our understanding of marine ecosystems and their dynamics (Boss et al., 2022; Lindstrom et al., 2012; Miloslavich et al., 2018, 2022; Muller-Karger et al., 2018, 2025). These variables facilitate long-term operational monitoring, allowing their integration into models, supporting the development of policies and informing internationally agreed needs (Benson et al., 2018). AUVs and robotic platforms have significantly contributed to these measurements by providing high-resolution, continuous, and long-term monitoring capabilities allowing for the collection of crucial biological data that can address societal issues and inform efficiently both the scientific community and policymakers (Whitt et al., 2020). These advanced systems are essential to overcome the limitations of traditional observation methods by providing broad spatial coverage, frequent temporal sampling, and high-resolution measurements at depth for monitoring complex biogeochemical processes in the ocean (Chai et al., 2020). A cultural shift in data-sharing practices is essential for this purpose, ensuring that scientific data are first consistent with CARE principles, and then as possible by default open, accessible, and aligned with FAIR principles (Stall et al., 2019). Where specific details about the data and data themselves lead to issues of security or threat to marine life, data should be aggregated in a way where critical details are dithered and/or anonymized.

The increasing role of advanced technology in data collection and analysis presents significant challenges for policymakers as substantial hurdles emerge in terms of governance, ethical considerations and standards development. The findings of this study underscore the legal and policy-related challenges faced by ocean observation efforts, particularly in the use of AUVs and data collection for Marine Scientific Research (MSR), as identified by the respondents of the study (Figure 1). As technology outpaces legal frameworks, especially in the realm of autonomous systems and AI, there is a need for policymakers to assess these unique challenges posed by the utilization of unmanned technologies.

To overcome the legal challenges, the authors propose a number of recommendations, based on the issues identified by the forty-six (46) subject matter experts of the study. The evolving use of autonomous platforms and sensors for scientific research highlights the necessity of revisiting existing legal instruments to address the responsible deployment and navigation of these autonomous systems. The development of international guidelines and a roadmap for these technologies is required if their massive exploitation is to be achieved (Alexandropoulou et al., 2021; Pastra et al., 2023; Johansson, 2022; Johansson et al., 2023; Trivyza et al., 2024). Regional agreements that facilitate coordination, resource utilization and data-sharing could also contribute to their deployment, providing a legal basis for cross-border AUV and UAV operations.

The expansion of AI is accompanied by various legal questions regarding accountability, liability, and compliance with international law. Any evaluation of the international legal implications surrounding the use of autonomous platforms and sensors must begin with a clear conceptualization of the relevant terminology and levels of autonomy for determining the legal obligations and rights associated with the operation of these technologies (Klein et al., 2020; Johansson et al., 2023; Pastra et al., 2023).

The fragmented nature of regulations across EEZs, combined with differences in national permits for MSR, creates significant operational challenges for researchers. The approximately 180 maritime boundary disputes that exist across all continents compel a reassessment of the political dynamics of ocean space, highlighting the need for updated legal frameworks, international cooperation, and geopolitical considerations to address resource rights, and jurisdictional boundaries in an increasingly contested marine environment (Østhagen, 2021). The development of an internationally recognized, streamlined permitting process for MSR activities involving autonomous technologies in EEZs would be beneficial. This process should include detailed guidelines for application submissions, clear timelines for decision-making, and criteria for approval to ensure consistency and fairness in handling requests. Additionally, a comprehensive data-sharing framework should be integral to this process, obligating researchers to share data collected in EEZs with host nations and the international

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scientific community. This would enhance transparency, foster collaboration, and contribute to the global understanding of marine environments. Additionally, notification schemes for AUV and UAV deployments, similar to the Argo program, ensuring transparency and reducing potential conflicts, would also foster international cooperation, address jurisdictional concerns, and promote the responsible use of these technologies in shared marine environments. Such schemes should detail the operational areas, research objectives, and autonomous technology specifications, and provide regular updates to coastal States and relevant international bodies.

Another challenge relates to security concerns that present a major obstacle to the open sharing of oceanographic data, as defense-related operations often limit access to high-resolution datasets. However, selective declassification and broader access to certain comprehensive datasets could offer substantial benefits to the scientific community. For instance, data relevant to climate modeling, biodiversity research, and ocean health assessments could be made accessible without compromising national security priorities (Baker and Zall, 2020). By balancing security considerations with scientific needs, such initiatives could enhance global understanding of marine environments and inform sustainable management practices.

Expert participants underlined that environmental regulations, especially in MPAs, add layers of ethical and legal complexity to MSR. Traditional MPA management techniques have static boundaries, while marine biodiversity is not restricted by these divisions; thus, the spatial understanding of the ocean in international law would benefit by shifting from a static, territorial approach to a more dynamic ocean management framework (Westholm and Argüello, 2023). This transformation would emphasize the inherent interconnectedness and migratory nature of marine species and ecosystems, which are not confined by artificial human demarcations. This shift from "fixity to fluidity" would focus on "social practice rather than spatial regulation," encouraging cooperation between states and stakeholders in managing and conserving marine biodiversity across transboundary spaces (Jones, 2016; Westholm and Argüello, 2023). Dynamic ocean management involves adjusting spatially and temporally to the constantly evolving conditions of the ocean and its users through the integration of comprehensive capabilities in science, technology, management, law, and policy (Hobday et al., 2014). In this context, data collection from cutting-edge technologies for species movements and oceanographic changes in real-time is a foundational step for a dynamic ocean management approach.

Another topic raised in the discussions is linked to the issue of parachute science in marine research, where international scientists-often from higher-income states-conduct fieldwork in less developed states, leading to inequitable research practices (Stefanoudis et al., 2021). Researchers need to collaborate with Indigenous local communities to ensure that their rights and traditional knowledge systems are respected in MSR activities. This process should involve obtaining prior informed consent, co-developing research agendas, following CARE principles for Indigenous and local community data governance, contacting government funding bodies of the host nation, and ensuring that the outcomes of the research provide tangible benefits to the local communities.

The legal and ethical concerns of another type of MSR, which is the use of various animal tagging technologies to track marine species were discussed, as well. Bio-logging is another example of the way that technology outpaces the existing regulatory framework (Kraska et al., 2015). According to Kraska et al. (2015), bio-logging research is governed solely by the nation with jurisdiction over the waters where the tagging happens, while nations the animal crosses afterwards do not have the same regulatory rights. However, bio-logging highlights the need for regulatory clarity, especially as international agreements like the BBNJ come into effect. The development of international guidelines for the deployment and use of animal-mounted sensors could ensure respect for jurisdictional boundaries and data privacy. The establishment of a legal framework that clearly defines data ownership and sharing protocols when tagged animals cross into foreign waters, could also balance the scientific value of the data with respect for national jurisdictional rights.

Lastly, issues related to IP rights and the commercialization of ocean data amplify legal and policy-making hurdles. The commercialization of ocean data, particularly around genetic resources and seabed minerals, introduces concerns over IP rights. Current frameworks are often insufficient to address the nuanced ownership and sharing of data generated from these valuable resources, creating tension between private interests in exclusive rights and the broader public interest in open access. This lack of clear, standardized licensing frameworks complicates efforts to balance innovation with equitable access to data, posing risks of data monopolization by private entities or specific nations. Such monopolization can hinder collaborative research and potentially slow advancements in critical fields like marine conservation, biodiversity protection, and sustainable resource extraction. To navigate these challenges, a well-defined licensing approach is essential-one that accommodates the need for innovation incentives while ensuring that data remains accessible for scientific, environmental, and societal benefits.

Addressing these legal and regulatory challenges requires coordinated efforts involving both the scientific and policy communities, as well as international organizations and treaty bodies. To ensure that ocean observation advances responsibly and transparently, fostering global cooperation while respecting national sovereignty and environmental stewardship, a structured, multi-stakeholder process is essential. A potential pathway could involve a collaborative initiative of states under the joint auspices of the United Nations General Assembly. The effort would be in the spirit of the Decade of Ocean Science for Sustainable Development (2021–2030), but the impacts would advance ocean observation much beyond 2030.

Given the operational and regulatory aspects, a scenario could be the initiative among states under the coordination of the Intergovernmental Oceanographic Commission (IOC), International Maritime Organization (IMO) and the World

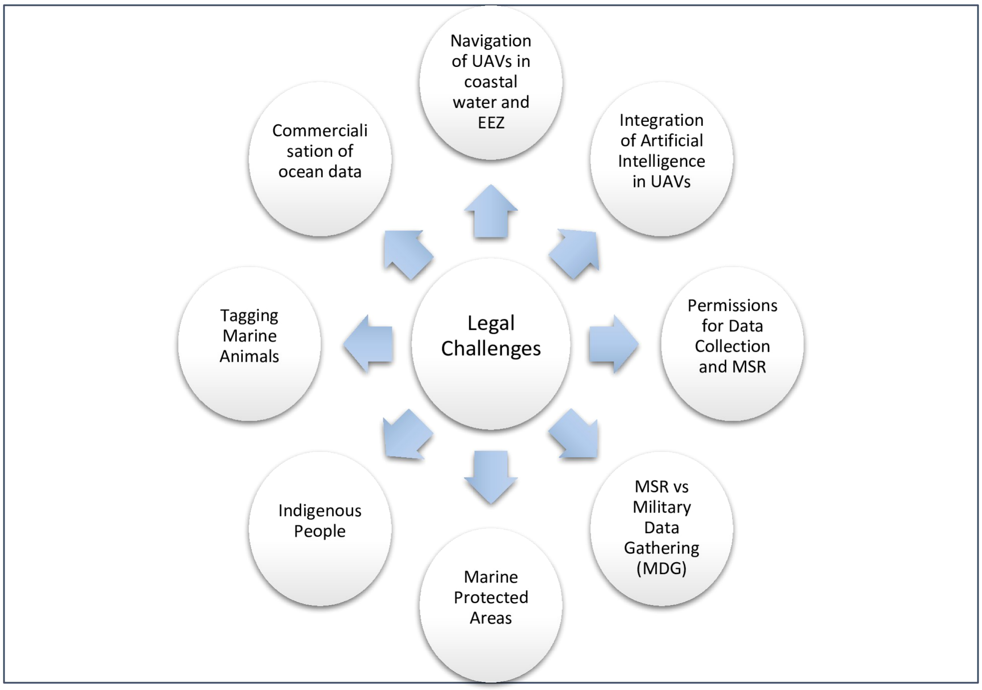

FIGURE 1
Legal challenges for the observation of marine biodiversity. Source: Authors.

Meteorological Organization (WMO), with input from relevant frameworks such as the BBNJ Agreement, UNCLOS, the Convention on Biological Diversity's Kunming-Montreal Global Biodiversity Framework (CBD KM-GBF), and regional bodies like the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). This approach would ensure that both scientific and operational perspectives are integrated. UNEP and the CBD could provide complementary expertise on environmental and biodiversity issues. To facilitate this, a dedicated forum or working group could be established, for example in coordination with the Group on Earth Observations Biodiversity Observation Network (GEO BON), to bring together key stakeholders, including states, researchers, industry representatives, and intergovernmental organizations, to develop harmonized governance frameworks. Such efforts would support the recovery of declining populations and prevent further declines in currently healthy populations, and enhance international cooperation and governance in the sustainable management of ocean resources and ecosystems (Harrison et al., 2018).

The development of a global biological ocean observing system is swiftly becoming a reality, driven by rapid advancements in technology. Innovations in automation and miniaturization are paving the way for larger-scale and more detailed scientific research, leading to observation programs that are data-rich, cost-efficient, and environmentally sustainable (Bax et al., 2019). Despite significant advancements in existing ocean observing systems, their development has been hindered by insufficient funding and limited collaboration among current stakeholders; thus, it will be crucial for GOOS, the Marine Biodiversity Observation Network (MBON), and others to continue actively engaging end users from various sectors, identify potential users in areas such as commerce, national defense, climate change, and renewable energy, and foster collaboration among stakeholders with shared interests (Lin and Yang, 2020).

Collaboration in ocean observation will be enhanced through various frameworks, including GOOS Regional Alliances, global networks, national systems, and well-established national ocean observation programs (Moltmann et al., 2019). Increased scientific collaboration, *in situ* monitoring, remote sensing and the use of deep submergence vehicles in the abyssal ocean, located at depths between 3,000 and 6,000 meters, primarily in areas beyond national jurisdiction, have the potential to fundamentally transform our understanding of global ocean processes (Marlow et al., 2022). The integration of new technologies and collaborative efforts promises to improve the capacity to monitor changes in ocean systems, offering crucial data to address pressing environmental challenges.

In this context, policies, blueprints, and regulations will provide a unified framework for action that can give stakeholders guidance and confidence in the use of ocean robotic systems and acknowledge that technology-policy interface developments are keeping pace with innovation (Johansson et al., 2023; Pastra et al., 2022; Pastra et al., 2023). In summary, while there are regulations and laws at both national and international levels, they need to be re-evaluated to accommodate new technologies, address legal challenges, and enhance the efficiency of biodiversity decision-making.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the studies involving humans in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

AP: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. TJ: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. JS: Writing – review & editing. FM: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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