



**Next-generation monitoring  
& mapping tools  
to assess marine  
ecosystems & biodiversity**

Deliverable D4.2

**Report on next generation observatories and  
autonomous systems**

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## Executive Summary

This Deliverable 4.2 – “Report on next generation observatories and autonomous systems” – examines the emerging landscape of next generation observatories and autonomous systems for marine biodiversity monitoring, as developed and tested within the NEMO-Tools project. As coastal and marine ecosystems face unprecedented pressures from climate change, pollution and a wide range of human activities, the need for scalable, cost-effective and technologically advanced monitoring solutions has never been more urgent. The report synthesizes advances in autonomous platforms, artificial intelligence and integrated data systems that collectively represent a shift in how we observe and assess marine ecosystems. The NEMO-Tools innovations enable broader spatial and temporal coverage while maintaining scientific rigour and supporting policy implementation under European frameworks such as the Marine Strategy Framework Directive (MSFD, 2008/56/EC) and the Water Framework Directive (WFD, 2000/60/EC).

Each technology is evaluated in terms of operational capabilities, integration potential, cost-effectiveness and limitations, with particular attention to how they can be combined into affordable, modular observatory designs. The report emphasizes that successful implementation of NEMO-Tools next generation observatories requires not only advanced hardware and sensors but also robust data integration frameworks, standardized protocols and engagement with diverse stakeholders, including citizen scientists. By coupling streamlined sampling strategies with cutting-edge analytical tools, marine monitoring programmes can achieve unprecedented spatial coverage and temporal resolution while remaining economically viable for resource-constrained institutions and national monitoring networks.

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## 1. Introduction: The Imperative for Innovation

### 1.1 Global Context and Environmental Challenges – revised / merged

Marine ecosystems worldwide are undergoing abrupt and accelerating change under intensifying anthropogenic pressures. Recent assessments indicate that global mean temperature has already exceeded 1.5 °C above pre-industrial levels in some years, bringing the climate system into a range where multiple tipping elements may be triggered (Armstrong McKay et al., 2022). These changes manifest as shifts in ocean temperature, stratification, oxygen, nutrient dynamics and pH, with cascading biological consequences and growing uncertainty in ecosystem trajectories (Heinze et al., 2021).

Coastal and shelf ecosystems are particularly exposed. They experience some of the strongest trends and extremes in physical and biogeochemical conditions, while simultaneously concentrating human uses such as fisheries, aquaculture, tourism, shipping and coastal development (Lian et al., 2023; Duarte et al., 2020). Increased urbanization, industrialization and agricultural intensification drive cultural eutrophication, harmful algal blooms and hypoxia, further disrupting ecosystem functioning and stability.

Despite these pressures, coastal systems remain foundational for societal well-being and survival. They support food and water security, blue-economy activities and livelihoods, renewable energy and green/blue growth opportunities, and climate mitigation and adaptation through “blue carbon” processes and coastal protection (Duarte et al., 2020; UNEP, 2021). Marine biodiversity underpins these services by enhancing ecosystem resilience and recovery potential.

Its conservation and sustainable use have therefore been placed at the core of several policy frameworks. In the European Union, the Water Framework Directive (WFD, 2000/60/EC) and the Marine Strategy Framework Directive (MSFD, 2008/56/EC) require member states to achieve good ecological and environmental status through systematic observation of key variables, indicators and descriptors across coastal and marine waters (European Commission, 2000, 2008)..

However, traditional monitoring approaches, typically based on infrequent ship-based surveys, manual sample processing and fragmented data handling, struggle to keep pace with the speed, scale and complexity of ongoing environmental change. They are frequently constrained by high costs, vessel availability, staff capacity and a lack of interoperability among datasets (Muller-Karger et al., 2018). This implementation gap highlights the need for next generation observatories and autonomous systems, such as those developed in NEMO-Tools, that can deliver the spatial, temporal and thematic coverage required by modern marine governance.

## 1.2 Technological Evolution and Monitoring Capabilities

Recent technological advances have provided a suite of state-of-the-art tools for sampling, analysing and interpreting environmental and biological variability in the ocean. High-fidelity instruments routinely measure key physical and biogeochemical parameters such as temperature, conductivity, salinity, oxygen, pH and bio-essential elements. Remote sensing and autonomous vehicles are now routinely deployed to collect in situ data and to extend observations into regions that are difficult, dangerous or too costly to sample using traditional ship-based methods (Müller-Karger et al., 2018).

At the same time, high-throughput DNA and RNA sequencing technologies enable eDNA and metabarcoding approaches that complement classical taxonomy for quantifying biodiversity and tracking biocommunity responses to environmental change (Cordier et al., 2020; Bohan et al., 2022). Artificial intelligence and machine learning (AI/ML) tools have become indispensable for processing the enormous data volumes generated by these technologies, providing automated image and acoustic classification, anomaly detection and predictive modelling of ecosystem responses (Malde et al., 2020; Rubbens et al., 2023). Together, these developments lay the technological foundation for NEMO-Tools next generation observatories.

## 2. Observatory as a “System of Systems”

A next generation observatory is not a single instrument or station, but a system of systems built from interoperable components. In the NEMO-Tools framework, a marine observatory (Figure 1) typically comprises:

1. Fixed stations (buoys, moorings, cabled nodes, hydrophone arrays) that deliver continuous time series of core physical, biogeochemical and acoustic variables.
2. Mobile autonomous platforms (UAV, ASV, AUV/UUV, ROV, drifters) that provide spatial context, targeted habitat surveys and event-driven sampling.
3. Remote-sensing assets (satellites, aerial and drone platforms) that offer synoptic mapping of surface conditions and shallow habitats.
4. Analytics and data-handling infrastructure (AI/ML services, harmonised workflows, FAIR-compliant data systems) that convert heterogeneous data streams into coherent indicators suitable for MSFD/WFD reporting and broader ecosystem assessments (Lindstrom et al., 2012; Pereira et al., 2013; Muller-Karger et al., 2018; Wilkinson et al., 2016).

The defining feature of such observatories is therefore not only the hardware, but the ability to transform multi-source observations into decision-ready products. This requires standardized metadata, interoperable data formats, reproducible analysis pipelines and transparent documentation of uncertainty (Wilkinson et al., 2016). NEMO-Tools develops and tests concrete building blocks for this system-of-systems

approach, including acoustic–optical ROV protocols, AI-assisted image analysis pipelines, low-cost passive acoustic nodes and remote-sensing workflows for macroalgal forests.

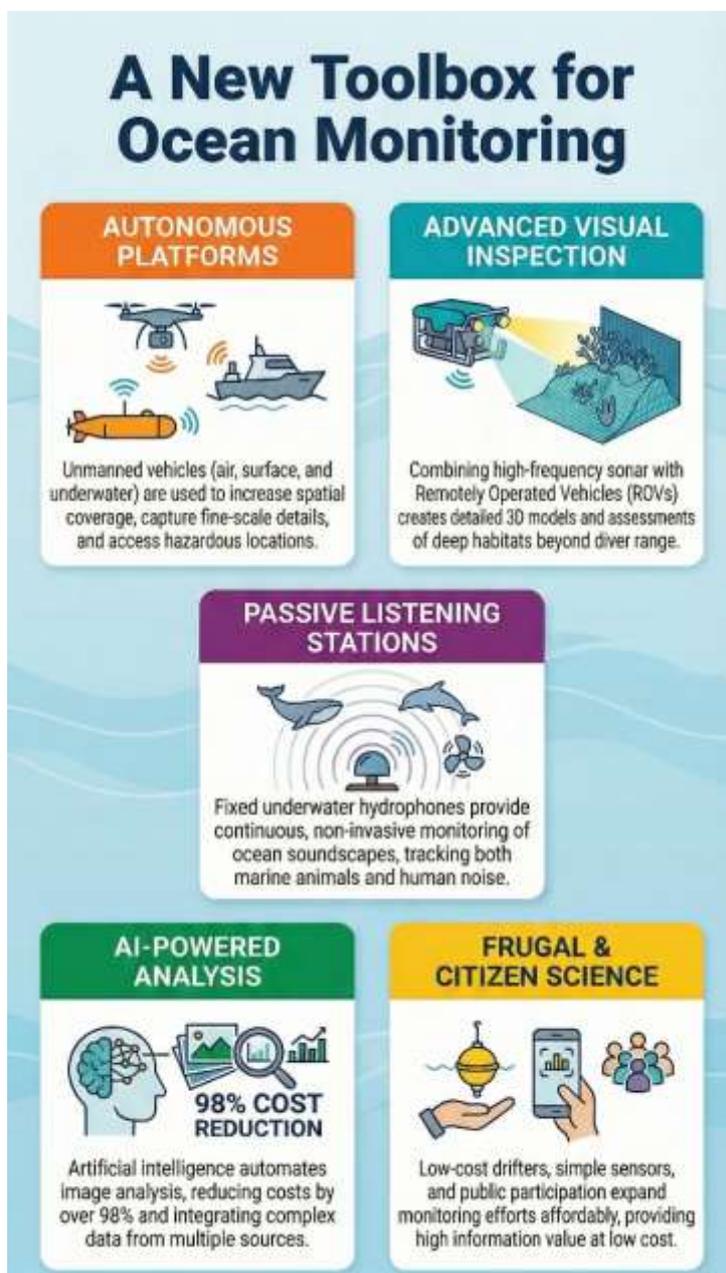


Figure 1. A graphical summary of NEMO-Tools toolbox

## 3. Next Generation Autonomous Platforms and Observatories Results

### 3.1 Remotely Operated Underwater Vehicles

#### 3.1.1 Optical Integration Protocol

An innovative acoustic-optical protocol has been developed that combines high-frequency side-scan sonar mapping with targeted ROV surveys, quantitative image analysis, and 3D photogrammetry. The workflow is designed for the mesophotic zone (approximately 25-60 meters depth), where SCUBA-based monitoring becomes difficult or unsafe and where many coralligenous and gorgonian assemblages remain virtually unmapped.

This protocol addresses multiple scientific gaps. Coralligenous bioconstructions host around 10 percent of known Mediterranean marine species and include several Red List taxa, yet many formations have been poorly studied and rarely monitored beyond SCUBA depth range. Standard side-scan sonar surveys offer spatial broad coverage but cannot reliably resolve community composition, while ROV campaigns are often descriptive and spatially restricted.

#### 3.1.2 Technical Components and Innovation

The protocol rests on five core technological components:

- A high-frequency side-scan sonar system (325 kHz) and processing chain for seabed mosaicking and habitat interpretation
- An observation-class ROV capable of 4K video, dual laser scaling, and stable flight
- A photogrammetry workflow to generate 3D models and orthomosaics for selected areas
- An analytical backbone combining image measurements with distance sampling methodology
- AI-assisted semi-automated image analysis through specialized software platforms

What is genuinely innovative is not the individual instruments but their integration and application. Side-scan sonar is used not just for background mapping but to design and optimize ROV effort, focusing dives on coralligenous rims, drop-offs, and mixed hard-soft interfaces. ROV imagery is fed into formal distance-sampling frameworks that model detection as a function of perpendicular distance and colony size, providing statistically robust density estimates with quantified uncertainty.

### 3.1.3 Operational Capabilities

The protocol offers several practical capabilities directly relevant to affordable biodiversity monitoring. It couples broad spatial coverage with high ecological resolution. Side-scan sonar provides full-coverage acoustic mapping over kilometers, distinguishing soft sediments, rocky outcrops, biogenic mounds, and seagrass patches, while ROV dives supply benthic assessment of coralligenous formations, colony-level data on gorgonian density, size structure and injury, alongside detailed records of marine litter.

The protocol generates quantitative indicators rather than just descriptions. For coralligenous formations, it provides data on substratum slope, basal living cover, coralline algae cover, and sedimentation levels. For gorgonians, outputs include density, height distributions, and injury categories, with detection bias accounted for. For marine litter, it provides densities, composition, biofouling stages, and interaction types with structuring species. The same imaging system can capture extent and density of fish nesting aggregations in previously unknown breeding sites.

### 3.1.4 Implementation Requirements

Personnel needs are modest but non-trivial: a skipper and deckhand for safe sonar and ROV operations; an acoustic operator and geomorphologist for sonar survey design, analysis and interpretation; an ROV pilot; and one or two benthic ecologists comfortable with image analysis and distance sampling workflows. This is not a citizen-science tool but an affordable professional solution where main cost drivers are vessel time and staff rather than bespoke high-end hardware.

### 3.1.5 Constraints and Future Directions

Technical bottlenecks include navigation limitations. Without acoustic tracking systems, ROV positions are approximated from surface GPS and cable geometry, which is adequate for transect-based density estimates but introduces uncertainty in fine-scale mapping. The side-scan sonar classification step is not fully automated and may require manual mapping in steep, heterogeneous sectors.

Operationally, the method is sensitive to sea state, currents, and visibility. Rough conditions and strong currents limit safe sonar towing and ROV flight, particularly along high-relief coralligenous habitat. There is also risk of physical disturbance to erect fauna if tether management or piloting is poor, and added risk in areas with substantial marine litter where entanglement hazards exist.

Development priorities include integrating low-cost acoustic tracking to improve ROV georeferencing, applying machine-learning approaches to coupled sonar-ROV datasets to reduce reliance on manual classification, and establishing regular temporal replication to turn one-off baselines into true monitoring time series. Over a

five to ten year horizon, the realistic vision is a mesophotic observatory network deploying this protocol across multiple protected sites, delivering harmonized indicators for coralligenous status, gorgonian populations, marine litter impacts, and key fish reproductive habitats.

## 3.2 Unmanned Aerial, Surface, and Underwater Vehicles

### 3.2.1 Platform Diversity and Monitoring Roles

Unmanned Aerial Vehicles (UAVs), Autonomous Surface Vehicles (ASVs) and Autonomous/Unmanned Underwater Vehicles (AUVs/UUVs) provide complementary capabilities for observing Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) across coastal and shelf seas (Pereira et al., 2013; Miloslavich et al., 2018; Muller-Karger et al., 2018). UAVs can map shallow-water habitats such as seagrass beds, macroalgal canopies and intertidal zones under favourable water clarity conditions, complementing satellite observations and diver-based surveys (Phinn et al., 2018; Lyons et al., 2020). Within NEMO-Tools, these platforms are conceived as mobile extensions of fixed observatories, designed to:

- increase spatial coverage around core sites,
- capture fine-scale heterogeneity in physical and biological fields,
- and enable access to remote or otherwise hazardous locations where traditional sampling is impractical or too costly.

Autonomous systems offer three core benefits for biodiversity monitoring: repeatability, coverage and risk reduction (reduced dependence on expensive ship time and diver-based operations). Their value is maximized when each platform is used for the tasks it does best, in combination with frugal strategies and simple, robust payloads tailored to NEMO-Tools monitoring objectives.

### 3.2.2 Unmanned Aerial Vehicles (UAVs)

Primary roles

- Mapping of shallow-water habitats (e.g. seagrass beds, macroalgal canopies, intertidal zones) under favourable water clarity conditions.
- Fine-scale proxies for surface EOVs (e.g. sand temperature, sea surface temperature patterns with thermal sensors where applicable, surface expressions of fronts and slicks via ocean colour).
- Rapid assessment of localized events such as harmful algal blooms, beaching and stranding events, or coastal disturbance from storms and small-scale developments.

Strengths

- Very high spatial resolution and flexible, rapid deployment.
- Ideal for nearshore, lagoon and archipelagic systems, where line-of-sight operations are feasible.
- Cost-effective relative to crewed aerial surveys, allowing repeated flights within a monitoring season.

### Limitations

- Strongly constrained by weather, flight regulations and battery endurance.
- Glare, turbidity and breaking waves reduce subsurface visibility, particularly in exposed coastal settings.
- Not a substitute for in situ sampling; best used as a spatial “lens” around ground-truth stations and diver/ROV surveys.

In the NEMO-Tools context, UAVs are used to provide high-resolution spatial context for in situ measurements of macrophyte habitats and coastal features, and to support rapid visual screening of priority sites identified by other components of the observatory system.

### 3.2.3 Autonomous Surface Vehicles (ASVs)

#### Primary roles

- Repeated transects for surface and near-surface variables (temperature, salinity, turbidity, fluorescence proxies for chlorophyll).
- Acoustic surveys using compact echo sounders or sonars, where payload and power budgets allow.
- Platforms for water sampling modules, passive samplers (e.g. eDNA, passive chemical samplers) and low-cost hydrophones.

#### Strengths

- Longer endurance than UAVs; can operate as “mobile moorings” around fixed stations.
- Efficient bridge between point-based fixed observatories and subsurface autonomous platforms.
- Can be operated from small vessels or shore, supporting frugal deployments in coastal and shelf environments.

#### Limitations

- Sea state and currents constrain safe operation and energy consumption.
- Payload and power trade-offs require careful selection of sensors and sampling schemes.
- Mission planning and collision avoidance require basic technical capacity and clear operational procedures.

Within NEMO-Tools, ASVs are particularly suited for sandy shores with limited beach furniture and structured transects linking static observation points, providing spatial gradients and repeated coverage that underpin model validation and interpretation of satellite signals.

### **3.2.4 Autonomous / Unmanned Underwater Vehicles (AUVs/UUVs)**

Primary roles

- Subsurface profiling and transects of temperature, salinity, oxygen and other biogeochemical parameters across stratified water columns.
- Acoustic and optical habitat mapping for reefs, seagrass meadows and other benthic features in depth ranges beyond routine SCUBA operations.
- Targeted surveys of water masses, fronts, upwelling structures and other physical features relevant to biodiversity patterns.

Strengths

- Access to subsurface and near-bottom domains that are invisible to remote sensing.
- Repeatable trajectories enable robust detection of change over time (e.g. seasonal evolution, heatwave impacts).
- Capable of carrying multiple sensors on a single platform, increasing efficiency of each mission.

Limitations

- Higher capital and operational costs relative to UAVs and simple ASVs.
- Navigation and georeferencing become challenging in complex topography or strong currents.
- Require specialized expertise for mission planning, risk management and data processing.

In NEMO-Tools, AUVs/UUVs are considered high-value, targeted assets: they are deployed where their unique access to subsurface structures and deep benthic habitats fills critical gaps in understanding, rather than as first-line tools everywhere.

### **3.2.5 Remotely Operated Vehicles (ROVs) in the Observatory Context**

Although ROVs are not autonomous in the strict sense, they are a key component of next generation observatories as high-confidence visual ground-truthing tools. Their role is complementary to the autonomous platforms described above.

Primary roles

- Detailed visual assessments of mesophotic and deeper habitats where diving is unsafe or impractical.
- High-resolution habitat characterization, including condition assessments of coralligenous structures, gorgonian forests and other biogenic reefs.
- Surveys of marine litter distributions and interactions with benthic communities.

### Strengths

- Direct, controllable visual observation in highly complex habitats.
- Ideal for calibration and validation of habitat classifications derived from side-scan sonar, AUV datasets and satellite/drone imagery.
- Compatible with quantitative protocols such as the NEMO-Tools acoustic-optical workflow (Section 3.1), enabling statistically robust indicators rather than purely qualitative descriptions.

### Limitations

- Require a vessel, skilled pilot and support crew; operations are weather and sea-state dependent.
- Not suitable for continuous, long-duration monitoring like moorings or passive acoustic stations.

In NEMO-Tools, ROVs are deliberately integrated into multi-platform observatory designs rather than deployed as standalone tools, ensuring that the high cost per survey hour is offset by their strong contribution to reference datasets and indicator calibration.

### 3.2.6 Passive Acoustic Stations (Hydrophones)

Although Passive Acoustic Stations are not autonomous in the strict sense, they are a key component of next generation observatories as could offer a wealth of information, providing continuous time series that are directly relevant to MSFD Descriptor 11 and to biodiversity inference via soundscape metrics (Van Parijs et al., 2009; Merchant et al., 2015; Erbe et al., 2019).

### Primary roles

- Monitoring of “ocean sound” as a cross-disciplinary EOY, capturing both biological and anthropogenic acoustic signals.
- Detection of vocal marine fauna (cetaceans, some fish species) and characterization of soundscape complexity as a biodiversity proxy.
- Assessment of anthropogenic noise levels relevant to MSFD Descriptor 11 and broader disturbance analyses.

### Strengths

- Non-invasive and capable of long-term, continuous recording at fixed locations.
- Scalable, including low-cost and DIY concepts compatible with frugal monitoring strategies.
- Highly effective for trend detection and timing of events (e.g. seasonal presence of vocal species, changes in vessel traffic patterns).

### Limitations

- Generate large data volumes; require robust processing pipelines and storage solutions.
- Calibration and standardization are essential if outputs are to be used in compliance monitoring.
- Interpretation of complex soundscapes demands specialized expertise and validated analytical methods.

Within NEMO-Tools, low-cost hydrophone systems are treated as core building blocks for coastal observatories, particularly where budgets limit the deployment of more complex platforms but continuous context for biological and human activities is required.

### **3.2.7 Drifters, Low-Cost Sensors and “Observations of Opportunity”**

Beyond the main vehicle classes, drifters, mini-sensors and opportunistic sampling play a crucial role in NEMO-Tools by providing high information value at low cost.

- Drifters provide measurements of surface currents and sea state, adding physical context to biologically focused surveys.
- MiniCTDs and simple probes enable repeated measurements of temperature, salinity, turbidity or oxygen from small boats, coastal structures or even citizen-operated platforms.
- Passive eDNA samplers and other low-maintenance devices can be deployed from moorings, small vessels or sailing networks to collect biodiversity information with minimal support.

These elements are central to the frugal monitoring philosophy underpinning NEMO-Tools: they allow expansion of observational coverage beyond the limited footprints of high-end platforms, provided that minimum quality-assurance and data-handling standards are maintained. As such, they are integral to the design of affordable observatory networks in coastal and shelf environments.

## **3.3 Synthesis: Autonomous Platforms within the NEMO-Tools Observatory Concept**

Taken together, the ROV-based acoustic–optical workflow, UAV/ASV/AUV systems, passive acoustic stations and low-cost drifters and sensors form a coherent family of

platforms that can be combined into modular, next generation observatories. In the NEMO-Tools framework, each platform is assigned “best-fit” monitoring tasks; ROVs for mesophotic habitat ground-truthing, UAVs for high-resolution coastal habitat mapping, ASVs and AUVs for repeated transects in sandy shores and subsurface profiling, hydrophones for continuous soundscape monitoring, and frugal sensors for gap-filling and citizen-enabled sampling.

By design, these components are interoperable and oriented toward delivering decision-ready indicators linked to MSFD and WFD requirements (e.g. biodiversity, seafloor integrity, underwater noise, eutrophication, non-indigenous species). When embedded in standardized sampling designs and common data pipelines, NEMO-Tools autonomous platforms allow coastal and shelf observatories to move from sparse, ship-dependent campaigns to distributed, hybrid monitoring systems that combine fixed time series, spatial intelligence and scalable, low-cost sampling.

## **4. Image Analysis and Remote Sensing**

### **4.1 Automated Image Analysis of Macroalgal Communities**

Automated image analysis platforms represent a transformative advancement in benthic habitat monitoring, employing deep neural networks to perform rapid, standardized annotation of underwater imagery (Beijbom et al., 2015; Rubbens et al., 2023). These cloud-based systems utilize convolutional neural networks trained on confirmed annotations to classify benthic substrates and biotic categories, dramatically reducing costs and processing time compared to manual annotation (Goodwin et al., 2021).

The technology enables semi-automated workflows where high-confidence predictions are accepted automatically while uncertain classifications are flagged for human validation, maintaining quality control while maximizing efficiency. Within operational frameworks, custom bridging scripts enable integration with existing annotation software and workflows, allowing reuse of historical datasets for classifier training. Performance is constrained by image quality factors including illumination, turbidity, and habitat complexity, while class imbalance presents challenges for rare but ecologically important taxa such as canopy-forming macroalgae. Despite requiring significant upfront investment in expert-annotated training datasets, these platforms fundamentally expand what is feasible in large-scale marine monitoring by enabling comprehensive spatial and temporal coverage, reducing observer bias through algorithmic consistency, and supporting compliance with marine environmental reporting frameworks through accelerated, standardized biodiversity assessments (Beyan & Browman, 2020; Riebesell et al., 2021).

## 4.2 Machine Learning for Data Integration

Artificial intelligence and machine learning constitute essential infrastructure components for modern marine observatories, extending far beyond image classification to enable comprehensive data fusion, quality control automation, and pattern extraction from complex, high-dimensional environmental datasets (Malde et al., 2020; Rubbens et al., 2023). These approaches harmonize heterogeneous data streams including remote sensing products, in situ observations, and diverse biological data sources such as imagery, environmental DNA and acoustic recordings, creating integrated analytical frameworks that link environmental drivers to biological responses across multiple scales (Goodwin et al., 2021; Urien et al., 2024).

Machine learning algorithms function as integration engines by standardizing analytical pipelines across partners and regions, providing reproducible workflows for ecological indicator calculation, and transparently quantifying uncertainty in ways that support management decision-making. When applied to coupled acoustic and optical datasets, these methods reduce manual classification burdens for habitat and marine litter mapping while improving consistency across large-scale assessments (Bicknell et al., 2021; Testor et al., 2019). The transition from experimental prototypes to operational monitoring tools demonstrates how AI/ML capabilities can be systematically embedded within practical frameworks supporting marine strategy implementation, enabling predictive modeling, early-warning systems, and scenario analyses that were previously constrained by data processing bottlenecks and the complexity of integrating diverse observational streams into coherent ecological assessments.

## 4.3 Remote Sensing Technologies for Habitat Monitoring

Remote sensing provides scalable, synoptic monitoring capabilities for coastal habitat distribution, condition and temporal dynamics through multispectral satellite imagery, hyperspectral sensors and high-resolution drone platforms that capture repeated observations suitable for mapping shallow-water ecosystems (Mumby et al., 2004; Lyons et al., 2020; Phinn et al., 2018). Multispectral platforms such as Sentinel-2 enable detection of habitat extent changes, fragmentation patterns and stress indicators in seagrass meadows and macroalgal forests, while hyperspectral sensors resolve finer spectral signatures that support detailed community classification and habitat quality assessment (Hedley et al., 2018).

For ecologically critical brown algae forests dominated by *Cystoseira sensu lato*, remote sensing can map canopy distribution and detect large-scale changes such as forest loss or depth-limit shifts, particularly when combined with ground-truth data from underwater surveys and AI-assisted image analysis to ensure ecological relevance (Vergara et al., 2019; Gouvêa et al., 2020). However, operational effectiveness is constrained by water turbidity, depth penetration limits, temporal resolution gaps due to cloud cover, and the inability of spectral data alone to capture

fine-scale ecological processes such as species turnover or recruitment dynamics. Effective integration within multi-method observatories requires careful spatial and temporal scale matching between remote and in situ data, systematic ground-truthing campaigns for algorithm calibration, explicit uncertainty quantification, and data-fusion approaches that combine satellite products with underwater surveys, model outputs and historical datasets (Müller-Karger et al., 2018; Gittings et al., 2022).

### 4.4 UAV Imagery and Deep Learning

This automated detection system combines low-cost unmanned aerial vehicle imagery with deep-learning object detection to enable efficient monitoring of marine megafauna in nearshore coastal environments, specifically employing a YOLOv8-nano model that can be trained on limited datasets to reliably identify threatened species such as the loggerhead sea turtle (*Caretta caretta*) in heterogeneous coastal waters (Mawdsley et al., 2022; Gray et al., 2019).. The system's methodology utilizes window-sliding tiling to subdivide high-resolution RGB images into 640×640 pixel segments with 20% overlap, addressing the challenge of detecting small objects within large imagery while preventing target truncation at tile boundaries. To overcome the inherent class imbalance where positive detections typically represent only 5-6% of tiles, the tool incorporates targeted data augmentation techniques including horizontal flipping, rotation, scaling, and contrast adjustments that maintain YOLO format compliance while implementing parent-image-level dataset splitting to prevent spatial data leakage during model training. The lightweight YOLOv8-nano architecture, trainable on consumer-grade GPU hardware achieves robust operational performance with F1-scores exceeding 0.93, precision of 0.97, recall of 0.93, and mAP@0.5 of 0.973, demonstrating reliable detection capability even when trained on modest datasets of 60-100 annotated images, though precision boundary delineation remains challenging for partially submerged animals as reflected in lower mAP@50-95 values.

The system's scalability, cost-effectiveness, and computational efficiency fundamentally expand monitoring capacity for conservation practitioners and protected area managers operating under resource constraints, providing spatially explicit, non-invasive detection capabilities that support identification of critical foraging areas, coastal development impact assessments, marine protected area design optimization, and detection of fine-scale habitat use shifts indicative of climate-driven ecological change (Hodgson et al., 2018; Seymour et al., 2017). This integrated UAV-based detection tool represents an accessible, operationally proven technology for implementing data-driven marine megafauna monitoring programs that enhance conservation planning and enable adaptive management responses to environmental change.

## 5. Implementation Considerations and Future Perspectives

### 5.1 Operational Readiness and Scalability

#### 5.1.1 Technology Readiness Levels

The technologies described in this report span a range of operational readiness levels. Some, such as passive acoustic monitoring, have been extensively validated and are being integrated into national monitoring programs. Others, such as AI-assisted image analysis and low-cost autonomous platforms, are in earlier stages of operational deployment and require additional validation, standardization, and capacity building before widespread adoption.

Successful scaling from pilot projects to operational monitoring networks requires sustained investment in infrastructure, training, quality assurance, and data management systems. It also requires institutional commitment to harmonization of protocols, intercalibration exercises, and collaborative frameworks that enable data sharing and joint analysis across institutions and jurisdictions.

#### 5.1.2 Cost-Effectiveness Assessment

While the technologies described emphasize affordability and accessibility, true cost-effectiveness must be evaluated holistically, considering not only capital equipment and consumables but also personnel time, training requirements, data processing and storage costs, and long-term maintenance. In many cases, the most significant cost driver is skilled personnel rather than hardware.

Frugal approaches that reduce reliance on expensive research vessels, enable participation of citizen scientists, or leverage automated analysis can substantially reduce per-sample costs and enable broader spatial and temporal coverage. However, initial investments in capacity building, protocol development, and quality assurance systems remain essential to ensure data reliability and policy relevance.

### 5.2 Citizen Science and Public Engagement

#### 5.2.1 Roles and Opportunities

Citizen science represents a powerful mechanism for expanding spatial and temporal coverage of marine biodiversity monitoring while simultaneously enhancing public awareness and stewardship of marine environments (McKinley et al., 2017; Kelly et al., 2020). Several technologies described in this report are well suited for citizen

participation, including passive eDNA sampling, low-cost hydrophone deployment, visual surveys of marine life, and photographic documentation of habitats.

State-of-the-art technological advancements, such as smart mobile apps, do-it-yourself technologies, drones, and artificial intelligence services, are increasingly used by citizen end-users navigating through unlimited potential of novel tools. The Sailing for Science initiative exemplifies how recreational sailing can be transformed into a platform for systematic data collection, connecting citizens with scientific research while leveraging sustainable transport.

### **5.2.2 Quality Assurance and Data Governance**

Effective citizen science programs require careful attention to training, standardized protocols, quality control mechanisms, and clear communication of data uses and limitations. All personal data collected from citizen participants must be handled in full compliance with General Data Protection Regulation requirements, including informed consent, anonymization, and secure data storage.

Validation strategies may include expert review of submitted data, cross-validation against professional monitoring, replicate sampling designs, and statistical methods for detecting and accounting for observer bias. When properly designed and implemented, citizen science can generate large volumes of valuable data that complement professional monitoring and enhance both scientific understanding and public engagement with marine conservation.

## **5.3 Policy Integration and Governance**

### **5.3.1 Marine Strategy Framework Directive**

The technologies and approaches described in this report directly support implementation of the Marine Strategy Framework Directive and the Water Framework Directive by enabling systematic, cost-effective monitoring of multiple descriptors including marine biodiversity, non-indigenous species, commercial fish and shellfish, food webs, eutrophication, seabed integrity, underwater noise, contamination of seafood, marine litter and hydrographical conditions (European Commission, 2000, 2008; Borja et al., 2010; Boyes & Elliott, 2014).

Integration of new technologies into existing monitoring frameworks requires coordination with national and regional competent authorities, alignment with established reporting formats and indicators, and demonstration that new methods meet or exceed technical standards for data quality and precision. Pilot projects and comparative studies that validate new approaches against established reference methods play a crucial role in building confidence and facilitating regulatory acceptance (Borja et al., 2016; Queirós et al., 2022).

### **5.3.2 International Coordination**

Marine ecosystems do not respect political boundaries, and effective monitoring and management require international coordination and data sharing. The Global Ocean Observing System provides an overarching framework for coordinating ocean observations and ensuring interoperability of data systems (Lindstrom et al., 2012; GOOS, 2019). Regional initiatives such as Regional Seas Conventions and Regional Fisheries Management Organizations enable harmonization of monitoring approaches and joint assessment of shared marine resources (Muller-Karger et al., 2018; Ruggiero et al., 2023). Adoption of standardized Essential Ocean Variables and Essential Biodiversity Variables frameworks, implementation of FAIR data principles and investment in shared data infrastructure and analytical tools are essential for enabling cross-border collaboration and detection of large-scale patterns and trends (Miloslavich et al., 2018; Wilkinson et al., 2016).

## **5.4 Future Directions and Emerging Technologies**

### **5.4.1 Technological Advancements**

Continued innovation in sensor technologies, autonomous platforms, molecular methods, and data analytics will further expand capabilities for marine biodiversity monitoring. Anticipated developments include miniaturization of sensors enabling deployment on smaller, more affordable platforms; advances in battery technology and energy harvesting extending deployment durations; development of multi-modal sensors integrating optical, acoustic, and chemical detection; and improvements in real-time data transmission enabling adaptive sampling strategies.

### **5.4.2 Integration and System-Level Innovation**

Perhaps more important than individual technological advances is system-level innovation in how different technologies, data streams and analytical approaches are integrated. Development of digital-twin frameworks that combine observations with process-based models to create virtual representations of marine ecosystems could enable scenario testing, impact assessment and optimization of monitoring strategies (Kok et al., 2021; Díaz et al., 2023). Integration of observational data with genetic databases, biogeochemical models and socioeconomic information could enable holistic assessments linking ecosystem condition to human activities and supporting development of integrated management strategies (Muller-Karger et al., 2018; Queirós et al., 2022).

### 5.4.3 Vision for Next Generation Observatories

The long-term vision is a globally coordinated network of marine observatories that seamlessly integrate multiple technologies and data streams to provide comprehensive, near-real-time assessments of marine ecosystem status and trends. Such observatories would combine satellite remote sensing for synoptic coverage, autonomous platforms for sustained in situ observations, molecular methods for biodiversity detection, and citizen science for broad spatial coverage and public engagement.

These observatories would be underpinned by robust data infrastructures implementing FAIR principles, AI-powered analytical tools enabling rapid data processing and synthesis, and collaborative governance frameworks ensuring data sharing and joint interpretation. They would directly support policy implementation, enable early detection of ecosystem changes and emerging threats, and provide basis for adaptive management strategies that enhance resilience of marine ecosystems in face of global change.

## 6. Conclusions

Next generation observatories and autonomous systems represent a transformative opportunity for marine biodiversity monitoring. The technologies and approaches described in this report demonstrate that it is possible to achieve unprecedented spatial and temporal coverage of marine ecosystem observations while maintaining scientific rigor and remaining economically viable for resource-constrained institutions and national monitoring networks.

Success in implementing these systems requires more than technological innovation. It demands sustained investment in capacity building, standardization of protocols, development of integrated data infrastructures, and cultivation of collaborative frameworks that span disciplines, institutions, and jurisdictions. It requires engagement with diverse stakeholders including researchers, managers, policymakers, industry, and citizens to ensure that monitoring efforts are aligned with societal needs and management priorities.

The rapid pace of environmental change in marine systems, driven by climate warming, pollution, overexploitation, and habitat destruction, demands equally rapid evolution in our monitoring capabilities. The technologies described here, provide tools for meeting this challenge. However, tools alone are insufficient. They must be embedded within coherent monitoring frameworks that translate observations into actionable knowledge supporting conservation and sustainable management.

As marine ecosystems face unprecedented pressures, the imperative for cost-effective, scalable, and technologically advanced monitoring has never been clearer. Next generation observatories and autonomous systems offer a path forward, enabling us to observe, understand, and ultimately protect the marine biodiversity upon which human societies fundamentally depend. The challenge now is to

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transform this potential into operational reality through sustained commitment, collaborative action, and continued innovation in service of marine conservation and sustainable ocean management.

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