MARINE MAMMAL MONITORING:

Methods, Technologies, and Opportunities for Innovation

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

Marine Mammal Monitoring: Methods, Technologies, and Opportunities for Innovation

This report was prepared by members of the Marine Mammal Special Interest Group (MMSIG), a technical group within the Institute of Marine Engineering, Science & Technology (IMarEST). The MMSIG is composed of subject matter experts from diverse sectors, including academia, industry, and government, who collaborate to advance marine mammal science.

Authors – Institute of Marine Engineering Science and Technology:

- Niru Dorrian
- Elizabeth Ferguson
- Lorenzo Scala
- Andrew J. Wright
- Ashley Noseworthy
- Ashleigh Kitchiner

Supporting MMSIG Analysts:

- Mattie Toll
- Julia Pelio
- Kyla Graham
- Denis Kovshov

Acknowledgements

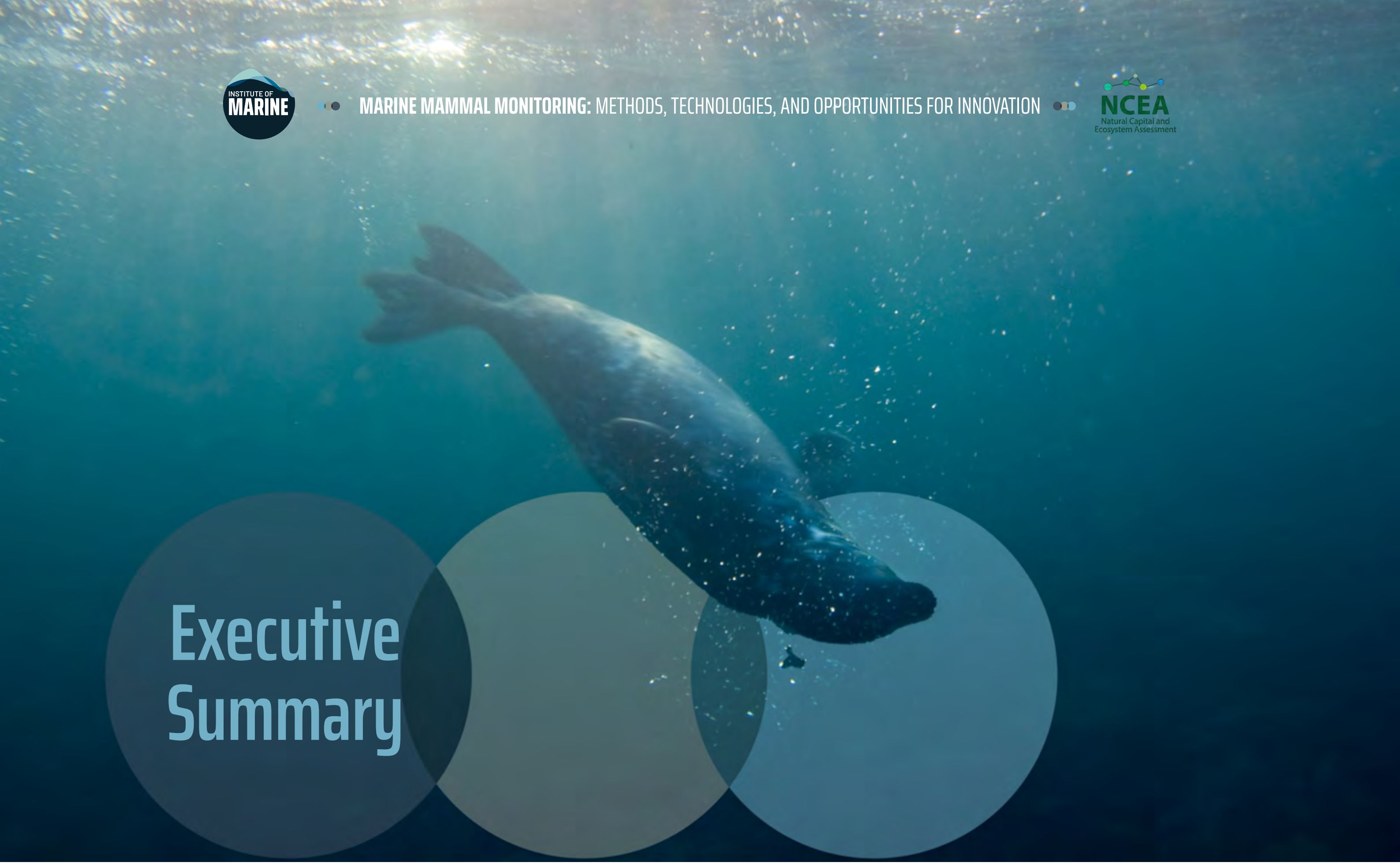
This report has been prepared on behalf of the Department for Environment, Food and Rural Affairs (Defra) as part of the Marine Natural Capital and Ecosystem Assessment (mNCEA) programme, in partnership with the Marine Mammal Special Interest Group (MMSIG) of the Institute of Marine Engineering, Science & Technology (IMarEST).

The authors would like to acknowledge the valuable contributions of industry stakeholder subject matter experts who participated in the survey and workshop, sharing their expertise and insights. Their input was instrumental in shaping the outcomes of this work. The authors also express their gratitude to the UN Ocean Decade Coordination Team for endorsing the Marine Mammal Monitoring Innovation Workshop.

Additionally, they extend their appreciation to the project steering group representatives from Defra mNCEA, including Sancha Holroyd and Deepak Marok, for their support throughout the project, as well as to Peter Sheppard and the IMarEST Technical Team.

Recommended Citation:

Dorrian, N., Ferguson, E. L., Scala, L., Wright, A. J., Noseworthy, A. S., & Kitchiner, A. (2025). *Marine mammal monitoring: Methods, technologies, and opportunities for innovation.* Institute of Marine Engineering, Science & Technology & Department for Environment, Food & Rural Affairs – Marine Natural Capital and Ecosystem Assessment Programme.



Executive Summary

The Marine Mammal Monitoring: Methods, Technologies, and Opportunities for Innovation project, led by the Institute of Marine Engineering, Science & Technology's (IMarEST) Marine Mammal Special Interest Group (MMSIG) in collaboration with the Department for Environment, Food and Rural Affairs (Defra) under the Marine Natural Capital and Ecosystem Assessment (mNCEA) programme, evaluated current methodologies and emerging technologies in marine mammal monitoring.

The project methodology included a comprehensive literature review, stakeholder survey with 133 respondents, a horizon scan, and a dedicated online workshop attended by 188 subject matter experts from academia, industry, government, and conservation organisations. Evaluated technologies included artificial intelligence (AI), passive acoustic monitoring (PAM), environmental DNA (eDNA), satellite-based detection, and automated data integration.

Key findings from the study identified gaps in current monitoring approaches and highlighted opportunities for greater interdisciplinary collaboration and automation to enhance monitoring efficiency and scalability. The horizon scan specifically pinpointed near-term advancements focusing on automation and extended geographic coverage, with long-term priorities aimed at developing multi-sensor integrated monitoring systems. Principal challenges include data standardisation, adaptation of regulatory frameworks, and securing sustained funding.

The stakeholder workshop identified the importance of AI-driven analytics, integration of PAM, eDNA, and satellite detection methodologies, alongside the establishment of open-access data frameworks and standardised protocols. Discussions also emphasised the necessity of robust, long-term funding mechanisms, public-private partnerships, and alignment with regulatory frameworks to accelerate innovation and optimise monitoring effectiveness.

This report highlights the transformative potential of automation, AI analytics, and multi-modal monitoring techniques in marine mammal conservation. It provides strategic recommendations aimed at adopting innovative technologies, real-time data processing, and robust data-sharing frameworks. Implementation of these recommendations will significantly strengthen the UK's marine mammal conservation efforts, improve decision-making capabilities, and support comprehensive marine environmental management aligned with national and international conservation priorities.

Definitions

Abbreviation	Definition
μPa	Micro pascal
25YEP	25-Year Environment Plan
AI	Artificial Intelligence
AIS	Automatic Identification System
ARU	Autonomous Recording Unit
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
BESS	British Energy Security Strategy
BOEM	Bureau of Ocean Energy Management
CNN	Convolutional Neural Network
CSIP	Cetacean Strandings Investigation Programme
CSR	Corporate Social Responsibility
DAS	Digital Aerial Survey
dB	Decibel
DCF	Data Collection Framework
ddPCR	Droplet Digital Polymerase Chain Reaction
Defra	Department for Environment, Food & Rural Affairs (UK)
DFO	Fisheries and Oceans Canada
eDNA/DNA	Environmental Deoxyribonucleic Acid
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
ESRGAN	Enhanced Super-Resolution Generative Adversarial Networks
GES	Good Environmental Status
GIS	Geographic Information System
GSD	Ground Sampling Distances
HPMA	Highly Protected Marine Areas
IAAC	Impact Assessment Agency of Canada
IMarEST	Institute of Marine Engineering, Science & Technology
IR	Infrared and Thermal
JNCC	Joint Nature Conservation Committee (UK)
LED	Light-Emitting Diode

Abbreviation	Definition
LiDAR	Light Detection and Ranging
MMO	Marine Mammal Observer
MMSIG	Marine Mammal Special Interest Group
mNCEA	Marine Natural Capital and Ecosystem Assessment (UK)
MPA	Marine Protected Area
MSFD	Marine Strategy Framework Directive
MSP	Marine Spatial Prioritisation
MWR	Marine Works Regulations
NEPA	National Environmental Policy Act
NGO	Non-Governmental Organisation
NOAA	National Oceanic and Atmospheric Administration (USA)
Omics	Detection of genes, mRNA, peptides & proteins, and metabolic products
ORE	Offshore Renewable Energy
OSPAR	Oslo and Paris Conventions
OWF	Offshore Wind Farm
PAM	Passive Acoustic Monitoring
Photo-ID	Photo-Identification
Q&A	Question and Answer
qPCR/PCR	Quantitative Polymerase Chain Reaction
RGB	Red, Green and Blue
RPAS	Remotely Piloted Aerial System
SCANS	Small Cetaceans in European Atlantic waters and the North Sea
SME	Subject-Matter Expert
SNR	Signal-to-Noise Ratio
SRW	Southern Right Whale
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
UKMS	United Kingdom Marine Strategy
UN	United Nations
USA	United States of America
VHR	Very High-Resolution

1. Introduction

The Institute of Marine Engineering, Science, and Technology (IMarEST) conducted a study on behalf of the Department for Environment, Food and Rural Affairs (Defra) as part of the Marine Natural Capital and Ecosystem Assessment (mNCEA) programme. The project evaluated the current state of marine mammal monitoring and identified opportunities for innovation, investment and advancement in technologies, methodologies and data utilisation. By addressing existing gaps and leveraging emerging advancements, the project aimed to further support Defra in establishing a sustainable, integrated, and ecosystem-based monitoring framework that aligns with domestic and international policy requirements.

The project involved a comprehensive evaluation of marine mammal monitoring systems with a structured approach which included:

1. A literature review of existing marine mammal monitoring technologies and methodologies, supplemented by a technology inventory and gap analysis.
2. Subject matter expert (SME) stakeholder engagement consisting of an online survey and targeted interviews and detailed horizon scan survey to identify emerging trends and technology to explore opportunities for innovation.
3. A dedicated 4-hour SME stakeholder engagement workshop, bringing together international technology providers, offshore industry experts, conservation organisations, and academic institutions playing a crucial role in shaping the findings.

These efforts aimed to provide actionable recommendations for targeted funding and strategic development, enhancing data-driven policy evaluation and decision-making. The project aims to strengthen the UK's leadership in marine environmental protection and sustainable use.

1.1 Background & Context

The United Kingdom (UK) is steward to ~880,000 km2 of marine environment, 3.5-fold greater than the country's land area and is a world leader in the protection and sustainable use of the marine environment. This is exemplified domestically through the UK Marine Strategy (UKMS), the 25-Year Environment Plan (25YEP) and internationally through the signing of the Oslo-Paris (OSPAR) convention and the United Nations (UN) Convention of Biological Diversity.

Marine and fisheries monitoring in the UK has evolved over time to meet both domestic and international requirements. However, since the UK's departure from the European Union, demands for marine and fisheries monitoring data have increased significantly, driven by legislation and policy, including the Environment Act 2021, Fisheries Act 2020, Highly Protected Marine Areas (HPMAs), Marine Spatial Prioritisation (MSP), and the British Energy Security Strategy (BESS). This has necessitated the adoption of a natural capital and ecosystem assessment-based approach to monitoring, ensuring a holistic consideration of environmental, social, and economic factors in decision-making.

As a result of increasing demands, it is essential and timely to comprehensively review and evolve current marine and fisheries monitoring data to identify gaps in existing monitoring approaches and develop a more integrated system which ensures current and future evidence needs are met efficiently. This marine mammal monitoring innovation project incorporates several workstreams that coalesce to further support building the necessary foundations that underpin the meaningful evolution of the marine and fisheries monitoring landscape. This project complements the marine mNCEA and other relevant programmes, including fisheries Data Collection Framework (DCF) reform to inform spending review bids to create a sustainable, integrated, ecosystem-based marine and fisheries monitoring system for the future.

1.1.1 Marine Mammals

Marine mammals are integral to the UK's marine ecosystem, serving as key indicators of ocean health and providing insights into the impacts of anthropogenic pressures, climate change, and ecosystem shifts. UK waters support a diverse array of marine mammal species, including cetaceans (whales, dolphins, and porpoises) and pinnipeds (seals), many of which are of conservation concern under national and international frameworks. As highly mobile, long-lived species that occupy various trophic levels, marine mammals can provide valuable ecological data through long-term monitoring programmes, enhancing our understanding of ecosystem dynamics and informing conservation and management strategies.

Current marine mammal monitoring in the UK is conducted through a range of initiatives, including the UK Cetacean Strandings Investigation Programme (CSIP), the SCANS (Small Cetaceans in European Atlantic waters and the North Sea) surveys, and regional and local monitoring initiatives. These programmes generate important data on population trends, distribution, abundance, health status, and anthropogenic threats such as bycatch, marine noise pollution, and habitat degradation; however, marine mammal monitoring remains largely fragmented, with limited integration across datasets, methodologies, and spatial and temporal scales. This lack of coherence impairs the ability to generate holistic insights into population trajectories and ecological shifts, thereby constraining evidence-based policymaking and conservation interventions.

The UK's departure from the European Union has further heightened the need for a more integrated and robust marine mammal monitoring framework, particularly considering evolving legislative and policy demands. The Marine & Coastal Access Act (2009), 25YEP and UK Marine Strategy (among others) require enhanced data collection to support biodiversity conservation, ecosystem-based management, and marine spatial planning. Recent assessments indicate that while certain populations, such as grey seals (*Halichoerus grypus*) and some cetaceans, are stable or increasing, others, including harbour seals (*Phoca vitulina*) in specific regions, are experiencing declines. These mixed trends highlight the need for ongoing monitoring and targeted conservation efforts to ensure the health and sustainability of the UK's marine mammal populations (Defra 2022; 2025). Additionally, the designation of HPMAs and commitments under the Convention on Biological Diversity necessitate an advanced evidence base to evaluate the effectiveness of conservation measures and assess the cumulative impacts of human activities on marine mammal populations.

To address these challenges, the development of a coordinated, interdisciplinary, and technologically advanced monitoring framework for marine mammals is essential. This includes the integration of traditional survey methodologies with emerging technologies such as passive acoustic monitoring (PAM), satellite telemetry, environmental DNA (eDNA) sampling, and artificial intelligence-driven image analysis. These innovations offer the potential to enhance spatial and temporal coverage, improve species detection rates, and provide real-time data for adaptive management.

1.2 Marine Mammal Monitoring and Innovation Definitions

1.2.1 Marine Mammal Monitoring

As defined in this study marine mammal monitoring is the systematic observation, recording, and analysis of data to assess the presence, behaviour, distribution, abundance, health, and population dynamics of marine mammals. This process generates essential data that serves two primary purposes: documenting these characteristics for regulatory compliance during mitigation activities and informing conservation efforts, policy development, and the sustainable management of marine ecosystems.

By employing advanced methodologies and technologies, marine mammal monitoring ensures compliance with environmental regulations while promoting evidence-based approaches to the protection of these species and their habitats. Effective monitoring is crucial for supporting conservation efforts and ensuring adherence to legal frameworks that safeguard marine biodiversity at both national and international levels.

1.2.2 Marine Mammal Monitoring Technology and Innovation

Also as defined in this study marine mammal monitoring technology includes tools, software, and systems designed to detect, identify, and track marine mammals. Examples range from acoustic devices like hydrophones and PAM systems to advancing technologies such as autonomous underwater vehicles (AUVs), eDNA sampling, and artificial intelligence (AI) for data processing and analysis. These innovations enhance the precision, efficiency, and scalability of monitoring efforts, supporting evidence-based decision-making for conservation and management.

Innovation in this field focuses on addressing challenges and improving current practices through the development and adaptation of novel technologies and methodologies. Advancements in automation, interdisciplinary approaches, and real-time data analysis are increasingly aligning monitoring efforts with emerging policy needs, conservation goals, and industry requirements. By integrating cutting-edge tools with innovative strategies, marine mammal monitoring is becoming more effective and impactful, contributing to the protection of marine ecosystems and species.

1.3 Policy Relevance

The UK government has introduced several key policies in recent years aimed at improving environmental sustainability, particularly within marine ecosystems, with significant relevance to marine mammal and fisheries monitoring. Central to these efforts are the Environment Act 2021, the Fisheries Act 2020, HPMAs, MSP, and the BESS. While marine mammals are also protected under other legislation, these are not discussed in detail here.

For example, the Marine Strategy Regulations 2010 require the UK to achieve and maintain Good Environmental Status (GES), which includes marine mammals under Descriptor 1 (Biodiversity) and Descriptor 4 (Food Webs). These policies emphasise an ecosystem-based approach to marine management, underpinned by natural capital and ecosystem assessments.

The Environment Act (2021) focuses on protecting and enhancing the natural environment across land, air, water, and marine ecosystems. It establishes long-term environmental targets and mandates the monitoring of biodiversity, including marine ecosystems. The Act supports an integrated approach to ecosystem health, encouraging data-driven management that is essential for sustainable fisheries and marine mammal conservation. The use of natural capital accounting quantifying nature's resources and services has been highlighted as important for decision-making in marine policies, especially in terms of monitoring the impacts of human activities on marine species and habitats.

The Fisheries Act (2020) prioritises sustainable fisheries management and ecological protection. It requires the collection of robust data to guide policy, particularly regarding fish stocks, fishing quotas, and conservation efforts. The Act aligns with a natural capital approach by recognising the long-term value of healthy marine ecosystems, including marine mammals, for sustaining fisheries. By mandating better data sharing and scientific monitoring, it strengthens the role of ecosystem assessments in fisheries management, ensuring that policies are based on accurate, up-to-date data on marine life.

The introduction of HPMAs complements these efforts by designating areas of the marine environment where human activities are highly restricted to allow ecosystems to recover. HPMAs play an important role in protecting marine biodiversity, particularly species like marine mammals. Monitoring is essential to assess ecosystem regeneration success of these areas. The data collected is crucial for adapting management strategies and ensuring that these areas provide long-term benefits to marine species and fisheries.

Marine special prioritisation is another key tool that uses data to inform the allocation of marine space for different uses, such as fishing, energy development, and conservation. By integrating marine mammal and fisheries data, MSP ensures that marine activities are planned to minimise negative impacts on ecosystems and species, allowing for more informed, ecosystem-based decisions.

Finally, BESS promotes offshore wind and marine energy development, with policy relevance to marine conservation. The strategy emphasises the need for careful siting and planning of energy infrastructure, considering the potential impacts on marine mammals and fisheries. Ongoing monitoring of marine environments ensures that these renewable projects do not undermine the health of marine ecosystems.

Collectively, these policies represent a shift towards an ecosystem-based management approach, where natural capital and environmental assessments are integral to marine mammal and fisheries monitoring, ensuring the protection and sustainable use of marine resources.

1.3.1 UK Monitoring Framework

As noted above, there are various legal mandates for monitoring marine mammals in the UK. However, a significant proportion of monitoring is also conducted through independent research, which may or may not receive government funding and is often regionally focused to address local needs arising from protected areas or the physical location of research institutions. This includes stranding response efforts, academic research, conservation initiatives, industry-led project-based assessments, and citizen science programmes.

As a result, there is no overarching national monitoring framework, nor is one likely to emerge. Similar situations exist in most other countries, and in some, such as the USA and Canada, additional complexities arise from differences between state, provincial, or regional management authorities.

2. Methodology

2.1 Project Approach

The project adopted a structured approach, organised into several workstreams, comprising three key work packages, each designed with targeted tasks and deliverables to ensure a comprehensive, evidence-based assessment of marine mammal monitoring practices. By integrating a structured methodology across these work packages, the project evaluated existing marine mammal monitoring methodologies, identified emerging opportunities, and facilitated extensive stakeholder engagement.

The three core work packages are listed below:

1. Evaluation of existing marine mammal monitoring methodologies and technologies
2. Horizon scanning for emerging trends and technologies
3. Delivering a stakeholder engagement workshop

2.1.1 Evaluating marine mammal monitoring methodologies and technologies

A comprehensive literature review was conducted to synthesise existing research on marine mammal monitoring methodologies and technologies. This review identified best practices, technological advancements, and knowledge gaps in current monitoring efforts, focusing on:

- **Visual Monitoring Technologies**
  Includes technologies used in visual monitoring from shipboard, shore-based and manned aerial surveys, infrared and thermal image sensing. Visual monitoring technologies included vessel-mounted or handheld infrared/thermal imaging camera systems, light detection and ranging (LiDAR) sensors, 'big eye' binoculars, underwater cameras, satellite imagery, and drone or fixed-wing mounted camera systems for aerial monitoring of marine mammals.

- **Acoustic Monitoring Technologies**
  Includes technologies relating to PAM methods including towed array systems, fixed recorders, multi-recorder arrays, mobile platforms and analytical methods. Technologies included passive acoustic real-time systems or archival broadband autonomous recording units (ARUs), automated click detectors, and associated accessories including hydrophone arrays, mooring systems, buoy systems, and multi-sensor integrated systems used in industry or research applications for mitigation and monitoring of marine mammals. Acoustic monitoring technologies also considered active acoustic methods, including sonar and echo-sounder technologies used in real-time detection, tracking and behavioural analysis of marine mammals.

- **Modern Imaging Technologies**
  This includes technologies related to imaging methods for acquiring high-resolution, non-invasive data across large spatial and temporal scales. The technologies are categorised into three main groups: Unmanned Aerial Vehicles (UAVs) or drones equipped with LiDAR or imaging sensors for photogrammetry and abundance estimates, satellite imaging, and underwater camera systems.

- **Environmental DNA (eDNA) Technologies**
  Detects genetic material shed by marine mammals into the water column. Detectability is influenced by environmental factors such as temperature and acidity.

- **Health Monitoring**
  Includes biopsy samples, blow collections, and other biological sampling. Omics technologies and photogrammetry body conditioning assessments for the study of sub-lethal impacts and baseline health of animals in a population.

- **Combining Technologies for Multimodal Monitoring Approaches**
  Includes the integration of multiple monitoring technologies to provide a holistic approach to monitoring marine mammals. Multi-sensor monitoring methods utilising technologies such as drones, PAM, satellite

imagery, eDNA sampling for provision of robust and high-resolution data collection for multi-observational monitoring of marine mammals.

- **Current Gaps**
  Includes discussion on limitations in hardware and software technologies to achieve comprehensive monitoring of marine mammals for conservation and mitigation. Also includes issues relating to the accessibility and standardisation of datasets, the challenge of integrating AI technologies effectively into monitoring programmes and addressing biases in monitoring methodologies.

- **Future Directions**
  Considers the future direction for innovation in monitoring technologies, drawing upon the current technology landscape, technology gaps and roadmap suggestions for achieving advancement in marine mammal monitoring in UK waters.

2.1.2 Technology Inventory and Gap Analysis

A supplementary technology inventory has been compiled and provided separately to this report, categorising monitoring technologies by function, application, and technical specifications (Supplementary Material 1). Additionally, a supplementary technology matrix mapping existing methodologies, strengths, limitations and areas for improvement accompanies this report (Supplementary Material 2). A gap analysis has also been conducted to identify underrepresented methodologies and recommend areas for improvement, **detailed in Section 3.8.**

2.1.3 Stakeholder Survey and Interviews

A structured survey was distributed to SMEs and stakeholders across offshore energy, research, and regulatory sectors to gather insights on current methodologies and technologies. Upon reviewing the survey results, targeted interviews with SMEs were conducted to provide deeper qualitative data. The results of this survey are **detailed in Section 4** and the stakeholder survey questions can be found in Supplementary Materials 3, accompanying this report.

2.1.4 Horizon scanning for emerging trends and technologies

A horizon scan was conducted to identify near- and long-term technological advancements in marine mammal monitoring. This process involved questions within an online survey to SMEs, questions within the breakout rooms of the marine mammal monitoring workshop, and a targeted search for technologies in adjacent industries which was complemented by consultations with select participants. A report detailing key innovations and technology gaps, a database of consulted experts and organisations, and a comprehensive list of technology providers and academic collaborators have also been provided. The results of the horizon scan are **detailed in Section 5.**

2.1.5 Stakeholder engagement workshop

A four-hour virtual workshop was conducted in collaboration with Defra mNCEA and officially endorsed by the United Nations (UN) Ocean Decade. The endorsement highlighted the workshop's contribution to advancing ocean observations, enhancing data-sharing frameworks, and promoting cross-sector collaboration to accelerate innovation in marine mammal monitoring technologies and methodologies. The workshop brought together SMEs, researchers, industry professionals, regulators, and conservation organisations to explore emerging monitoring technologies, funding mechanisms, and strategic priorities for investment. Discussions centred on further exploring and validating the findings from the survey and horizon scan, with a focus on identifying key technological advancements, addressing existing gaps, and prioritising areas for future investment in marine mammal monitoring. The results of this workshop are **detailed in Section 6.**

3. Literature review

3.1 Overview

The purpose of this literature review is to explore the current state of common methodologies, advancements, and innovations in technologies used for monitoring marine mammals, a field that plays a crucial role in understanding and protecting these ecologically significant species. By examining key trends, emerging tools, and established methods, this review aims to identify areas where technological progress has enhanced monitoring capabilities, including improvements in detection, data accuracy, and long-term monitoring strategies. It will also address limitations and gaps in current methodologies, such as challenges in detecting species in remote or deep-sea environments, high-cost barriers, and data integration issues. This review seeks to inform future research and development, support innovation, and provide insights to assist regulatory bodies and conservation practitioners in their efforts to develop and improve evidence-based approaches to marine mammal protection.

Monitoring marine mammals is essential for supporting conservation efforts and ensuring compliance with legal frameworks that protect marine biodiversity on both national and international levels. Agreements, such as the UN Convention on the Law of the Sea, the Convention on Biological Diversity, and regional conventions like the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish, and North Seas provide legal guidelines for nations to monitor and mitigate impacts on marine mammals. Much of this is then implemented through domestic legislation of the various member states.

In English waters, Defra plays a key role in implementing marine conservation policies. The UK Marine Strategy is within Defra's mandate, which includes monitoring programs designed to achieve Good Environmental Status (GES) and safeguard marine mammal populations through noise reduction, habitat protection, and sustainable fisheries practices (Defra, 2022; House of Commons, Environment, Food and Rural Affairs Committee, 2023). However, monitoring efforts encompass a wide scope, ranging from tracking population abundance and distribution to assessing the health and behaviour of individuals or populations. Understanding habitat usage and behavioural patterns is particularly important in areas undergoing rapid change, such as regions affected by offshore energy development. Baseline surveys, which gather data prior to development activities, provide crucial benchmarks to evaluate environmental impacts and implement mitigation measures.

A broad range of techniques are employed to monitor marine mammals, reflecting the complexity of their habitats and behaviours. Traditional methods, such as visual observations conducted from ships or shore, remain important but are increasingly complemented by technologies like PAM, which detects vocalisations underwater, and thermal or infrared sensing, which is particularly useful in low-visibility conditions. Emerging technologies, including drones, satellite imagery, and eDNA sampling, offer new ways to track species over large spatial areas or detect elusive individuals.

Predictive modelling further enhances monitoring by integrating real-time and historical data to estimate species presence, behaviour, and habitat usage. Monitoring of animal behaviour and, more recently, also physiological parameters is also becoming increasingly common, helping us to better understand not only influences on detection rates, but also the health of marine species. The selection of monitoring techniques is often guided by regulatory requirements and project-specific priorities, ensuring that data collection aligns with conservation and mitigation goals. However, each method comes with challenges, including harsh weather conditions, limitations in detecting cryptic species, and technological costs.

Effective monitoring integrates scientific methods, technological innovation, and legal compliance, helping to secure long-term biodiversity protection. For example, with the global shift toward renewable energy and increasing offshore projects, robust monitoring programs ensure that development occurs responsibly, minimising risks to marine mammal populations and their ecosystems (Evans & Hammond, 2004; Macrander et al., 2021). However, the need for efforts to address technology gaps in marine mammal monitoring, particularly concerning offshore wind development, has been highlighted through international targeted workshops and stakeholder engagement, emphasising the importance of integrating complementary monitoring technologies and data standardisation (Advisian Worley Group, 2023).

This report summarises the monitoring technologies currently in use and explores several that are emerging as potential options for future monitoring efforts. It highlights their strengths and considers their limitations. It also explores potential avenues for improving marine mammal monitoring in English waters and beyond.

3.2 Visual Monitoring

Traditional visual monitoring of marine mammals involves observing animals directly through shipboard surveys, shore-based observations, and aerial surveys. These methods continue to play a substantial role in modern-day monitoring and mitigation efforts due to their versatility and effectiveness in detecting species and assessing human impacts.

3.2.1 Shipboard Surveys

Shipboard surveys are a core method for monitoring marine mammals and can be employed systematically, dictated by mitigation and monitoring efforts, or opportunistically, depending on the context and objectives. These surveys are typically conducted using line-transect methods to sample marine areas and estimate species abundance and density (Burt et al., 2014; Kinzey et al., 2000). Marine mammal observers (MMOs) stationed onboard vessels scan the ocean surface for visual cues such as blows, dorsal fins, or body parts using binoculars or the naked eye (Smith et al., 2020). Systematic surveys are structured along predefined transect lines to ensure broad spatial coverage and provide reliable density estimates (Burt et al., 2014; Hammond et al., 2021). Surveys driven by mitigation efforts, particularly during geophysical campaigns or construction activities, aim to prevent harm to marine mammals by implementing real-time monitoring to support pauses in activity if animals are detected within specified critical distances (Nowacek et al., 2013). Shipboard surveys are adaptable across various geographic regions and species, allowing for real-time behavioural observations and tracking of interactions with anthropogenic activities such as vessel traffic, fisheries, and underwater noise, thereby informing disturbance impact assessments and management decisions.

However, shipboard surveys face limitations that can affect their reliability and effectiveness. While systematic surveys offer large spatial coverage, they often suffer from low temporal coverage due to constraints related to ship availability and operational schedules (Kaschner et al., 2012). Inclement weather, particularly high sea states, can significantly reduce visibility, with studies showing that species like harbour porpoises are harder to detect under such conditions, potentially leading to underestimations of abundance (Palka, 2000). MMO effectiveness is further impacted by factors such as daylight, fog, waves, and observer fatigue, as well as variables including shift duration, the use of single versus multiple MMOs, the height of the vantage point, and the level of training provided to observers (Harwood & Joynt, 2009; Smith et al., 2020). In the survey conducted by Harwood and Joynt (2009) in the Canadian Beaufort Sea the authors highlight how these factors can reduce detection rates and overall monitoring. Shipboard surveys also face challenges associated with high operational costs, including fuel, crew salaries, and vessel maintenance, which can limit the frequency and duration of survey efforts. These challenges often preclude resource management from investing extensively in this survey modality, leading to the incorporation of additional methods and technologies.

3.2.2 Shore-based Surveys

Shore-based surveys are highly effective for monitoring site-specific locations, such as breeding grounds or migration corridors, where marine mammals reliably occur (Piwetz et al., 2018; Würsig et al., 1999). These surveys often utilise theodolites—surveying instruments that measure angles with high precision—allowing researchers to track marine mammal movements in nearshore environments (Lerczak & Hobbs, 1998). Shore-based studies have played a key role in assessing marine mammal responses to anthropogenic activity. For instance, Mills et al. (2024) used theodolite tracking to examine how vessel traffic influences the movement and social dynamics of bottlenose dolphins (Tursiops truncatus). Similarly, Aerts et al. (2022) monitored marine mammals during mitigation operations, providing real-time data to inform protective measures during industrial activities.

However, shore-based monitoring approaches are limited in spatial extent, specifically to near-shore observations. The effectiveness of theodolite tracking depends on animals consistently occupying nearshore areas, such as seasonal foraging sites (Piwetz et al., 2018). Many species have extensive ranges beyond the visible shore, making long-term monitoring from a fixed location challenging. Additionally, if animals move too far offshore, tracking becomes ineffective, often necessitating complementary methods, such as aerial or acoustic surveys. Despite these constraints, shore-based surveys remain a valuable tool for collecting high-resolution behavioural data and gaining insights into localised marine mammal populations.

3.2.3 Manned Aerial Surveys

Crewed aerial surveys have played a valuable role in marine mammal monitoring, providing large-scale coverage and essential data on population density and abundance (Ferguson et al., 2018; Tucker, 2023). By covering vast and often inaccessible marine areas, aerial surveys help scientists generate robust population estimates, making them an indispensable tool in conservation efforts (Angliss et al., 2018; Hammond et al., 2021). However, several limitations affect their efficiency. The high costs of aircraft operations and the availability of trained observers can restrict survey frequency and geographic scope (Ferguson et al., 2018). Weather conditions such as daylight, fog, high winds, and turbulence can delay or shorten survey windows, limiting the effective use of chartered time (Verfuss et al., 2018). Additionally, Davis et al. (2022) identified gaps in the literature, noting that while most studies focus on correcting non-detection errors, issues such as counting errors and species misidentification often receive less attention. These errors, as demonstrated in case studies, can lead to significant inaccuracies in abundance estimates.

A relatively recent data collection method for obtaining site-specific baseline information that is quickly becoming widely adopted are digital aerial surveys (DAS) (Wang et al., 2019). Using a bespoke camera system mounted on aircraft, DAS typically employs a transect-based collection approach to capture images of the sea surface, with a pre-determined percentage of survey areas analysed. Still images or video footage are collected along survey transect lines, with spacing between tracks designed to achieve specific ground sampling distances (GSD). DAS has become the offshore industry standard, primarily for offshore ornithological studies as part of EIA processes. However, the method is not taxon-specific and data on marine megafauna, including marine mammals, can also be collected (Harris et al., 2024). DAS offers greater spatial coverage than vessel-based or acoustic monitoring methods, making it a useful tool for large-scale marine monitoring and assessment. As technological advancements continue, there is a growing shift toward UAS, offering the potential to mitigate many of these challenges and enhance future marine mammal monitoring efforts, a topic further explored in section 3.4.1.

3.2.4 Infrared and Thermal Sensing

Infrared and Thermal (IR) technologies are often used interchangeably, but they have distinct functions and applications when monitoring marine mammals. Both systems operate by detecting radiated energy within the infrared portion of the electromagnetic spectrum. However, thermal imaging specifically focuses on detecting heat or thermal variations, typically using far-infrared wavelengths to produce thermograms—images where different intensities represent varying temperatures (Lathlean & Seuront, 2014). In contrast, broader infrared systems include other applications, such as detecting reflected or scattered infrared light in addition to emitted heat. For marine mammal monitoring both systems are primarily used to detect animals when they surface, given that water is opaque to infrared radiation (Smith et al., 2020). The primary detection cues include the animals' bodies, blowholes, or exhalations, which create thermal contrasts with the surrounding water.

Thermal imaging systems have become integral to marine mammal monitoring due to their ability to detect these animals' day or night and under varying visibility conditions (Mccafferty, 2007). These systems can detect whale blows and emergent body parts by sensing thermal variations on the ocean surface (Baldacci et al., 2005; Grabner et al., 2011; Zitterbart et al., 2020). They have been employed in population surveys using unmanned aerial vehicles (UAVs) equipped with thermal cameras, which allow researchers to access difficult-to-sample habitats while reducing disturbance to wildlife (Gooday et al., 2018). Additionally, thermal imaging has been used to identify species by analysing unique thermal features, such as the shape and velocity of whale blows or the distinct thermal signatures of body parts like flippers and eyes (Gooday et al., 2018). Beyond population monitoring, thermal imaging systems have been employed in behavioural studies, such as in real-time mitigation efforts to prevent vessel strikes by issuing mariner alerts (Horton et al., 2017). Emerging applications include drone-based thermal imaging, which have enabled non-invasive health assessments such as estimating intranasal temperatures of baleen whales, providing insight into their thermal physiology and respiratory health (Lonati et al., 2025; Yaney-Keller et al., 2025). Despite their many applications, thermal imaging systems face several limitations. Their effectiveness is heavily influenced by environmental conditions, such as sea state, wind, humidity, and fog, which can distort or block thermal signals (Zitterbart et al., 2020). For instance, water on the surface of a marine mammal's body can act as an insulator, masking the thermal signature and making detection more difficult (Smith et al., 2020). The potential for false positive detections, such as mistaking hot rocks, birds, or breaking waves for marine mammals, is another challenge (Gooday et al., 2018). Human observers often classify detections into broad categories rather than specific species, reducing the system's utility as a standalone classification tool (Smith et al., 2020; Zitterbart et al., 2013). Additionally, near-horizontal imaging angles and sea surface emissivity can create issues with accurate thermographic measurements, necessitating careful consideration of imaging geometry and environmental factors (Horton et al., 2017). Automated alerting systems, though useful, can overwhelm observers with excessive alerts, leading to system shutdowns in some cases (Smith et al., 2020).

Ongoing advancements in thermal and infrared technology are addressing many of these challenges. Automatic whale detection systems have been developed to improve efficiency and reduce observer workload (Blackwell et al, 2006; Boebel & Zitterbart, 2015). Optimisation of detection algorithms and calibration for different environments also influence the performance of these systems (Stupariu et al., 2022). UAVs equipped with thermal imaging have improved access to remote habitats and reduced operational costs, making them an attractive alternative to traditional monitoring methods (Gooday et al., 2018). Studies, such as those conducted in the Salish Sea to monitor endangered Southern Resident Killer Whales, demonstrate the effectiveness of long-term automated thermal detection systems for both collision risk assessments and real-time mitigation alerts (Richter et al., 2023). As these technologies continue to evolve, they are expected to play a crucial role in reducing ship strikes, enhancing conservation measures, and improving our understanding of marine mammal behaviour and physiology. The integration of UAVs, high-resolution cameras, and advanced data-processing algorithms will further expand the utility of thermal and infrared systems in comprehensive marine mammal monitoring efforts.

3.3 Acoustic Monitoring

3.3.1 Passive Acoustic Monitoring

PAM is a versatile method for gathering extensive information on the occurrence, behaviour, and habitat use of marine mammals across ocean basins. Unlike traditional visual surveys, PAM operates continuously and is not limited by poor visibility or adverse weather, making it a reliable tool for long-term monitoring (Fleishman et al., 2023; Michel et al., 2024; Sanguineti et al., 2021; Van Parijs et al., 2009). PAM systems are cost-effective compared to many visual methods due to their relatively low hardware and data storage costs, allowing widespread spatial coverage through platforms like fixed static recorders, towed arrays, and mobile systems such as gliders equipped with hydrophones (Cauchy et al., 2023; Gibb et al., 2019; Helal et al, 2024). These platforms can be deployed in diverse environments, from deep-sea habitats using fixed recorders to large-scale surveys using towed arrays during vessel-based operations. Mobile platforms, including autonomous underwater vehicles, further enhance PAM's ability to track animals across dynamic and remote areas.

PAM has become a standard tool in both research and mitigation settings, with established protocols guiding its use in monitoring noise disturbance, evaluating anthropogenic impacts, and contributing to species conservation within regulatory frameworks through EIA (APEM, 2024; Malinka et al., 2018; Van Parijs, 2021). Processed PAM data provide insights into species composition, temporal and spatial distributions, and behavioural responses to human activities, while also supporting density and abundance modelling (Gervaise et al., 2021; Kowarski & Moors-Murphy, 2020; Marques et al., 2013). As the technology evolves, advances in analytical methods including machine learning and automated detection models are enhancing its accuracy, efficiency, and role in ecological assessments. PAM's ability to complement visual methods and provide information across vast marine environments establishes it as an indispensable component of global marine mammal monitoring programs (Fleishman et al., 2023; Gillespie et al., 2009).

3.3.1.1 Towed Array Systems

Towed hydrophone arrays serve as a key acoustic tool, providing real-time data that support both immediate mitigation decisions and long-term monitoring efforts. These systems consist of multiple hydrophones arranged in a linear configuration and towed behind a vessel, allowing for continuous recording of marine mammal vocalisations (Norris et al., 1995). Time-synchronised hydrophones within these arrays enable the determination of the range, bearing, location, and depth of vocalising individuals, making them particularly valuable for tracking marine mammals in dynamic environments (Van Parijs et al., 2021). However, flow noise generated by water movement over the hydrophones can interfere with low-frequency sounds, necessitating reduced vessel speeds to improve detection capabilities while maintaining optimal array orientation (Van Parijs et al., 2021). Studies utilising towed arrays during seismic surveys have demonstrated their effectiveness in localising baleen whales and informing mitigation procedures (Norris et al., 2017). Nonetheless, localisation accuracy depends on precise modelling of array positions, with uncertainties influencing positional estimates (Thode et al., 2021). Despite these challenges, towed arrays provide real-time monitoring capability, making them particularly useful for regulatory compliance and decision-making in high-traffic areas.

3.3.1.2 Fixed Recorders

Fixed, bottom-mounted archival recorders capture long-term acoustic data by continuously monitoring underwater environments for weeks to years. These recorders are deployed on or near the seafloor, allowing for the detection of marine mammal vocalisations across different spatial and temporal scales (Mattmüller et al., 2022; Todd et al., 2020; van Geel et al., 2022; Van Parijs et al., 2021). Spacing of recording devices is a crucial consideration to ensure comprehensive coverage, as detection radii depend on factors such as water depth, substrate type, and background noise levels. While these recorders provide extensive temporal data, their stationary nature limits their ability to track individual animals or capture transient species that move beyond their detection range. Fixed platform observatories equipped with PAM systems offer a cost-effective solution for long-term ocean noise measurement and marine mammal monitoring by leveraging existing or planned infrastructure, such as cabled platforms, powered buoys, and battery-operated housings, while also supporting compliance with EU directives on anthropogenic noise (Luczkovich, et al., 2012; van de Schaar et al., 2017). ARUs can integrate additional sensors to collect oceanographic data, such as water temperature and orientation, enhancing their value for multi-disciplinary studies (Sousa-Lima et al., 2013). Existing ocean infrastructure, such as offshore oil platforms and cabled observatories, offers deployment opportunities for cost-effective monitoring (Satterlee et al., 2018; Scala et al., 2017).

3.3.1.3 Multi-Recorder Arrays

Multi-recorder arrays enhance the capabilities of fixed PAM systems by positioning multiple hydrophones across a study area to improve localisation and tracking of marine mammals. By analysing time delays between an animal's vocalisation reaching different hydrophones, these arrays provide insights into movement patterns, habitat use, and behavioural ecology (Gillespie et al., 2022, 2023; Howe et al., 2019; Macaulay, 2017). Large-aperture hydrophone arrays extend detection ranges, improving the ability to track vocalising individuals over broad spatial scales (Guazzo et al., 2017; Helble et al., 2015; Nosal 2013). Vertical hydrophone arrays are widely used in tidal environments and have been successfully applied to localising echolocating species and tracking sperm whales (Macaulay, 2017, 2022). Distributed acoustic sensing utilises fibre optic cables to detect and record acoustic signals over large spatial scales by converting existing telecommunications infrastructure into dense arrays of hydrophones (Abadi et al., 2015, 2017). These technologies enable real-time monitoring of marine mammal vocalisations, environmental sounds, and human activities, offering a cost-effective and scalable approach for passive acoustic monitoring in marine environments (Lindsey et al., 2023). The effective range of these arrays is often shorter than their maximum detection distance, requiring careful sensor placement and calibration for accurate localisation. When multiple collaborating systems record overlapping detections, precise localisation of individuals is possible even at long distances, making multi-recorder arrays a valuable approach for studying marine mammals in complex acoustic environments (Premus et al., 2022).

3.3.1.4 Mobile Platforms

Mobile PAM platforms, including ocean gliders, AUVs, and drifters, offer flexibility in monitoring marine mammals by covering large areas and adapting to changing ocean conditions. Ocean gliders are particularly advantageous due to their quiet, buoyancy-driven propulsion, which minimises self-noise and allows for extended deployments (Cauchy et al., 2023; Klinck et al., 2012; Kowarski et al., 2020). Unlike fixed recorders, which provide detailed temporal data in one location, mobile platforms collect spatially broad but time-limited information (Pierpoint et al. 2016). Autonomous Surface Vessels (ASVs) enable continuous, autonomous passive acoustic data collection and provide an opportunity for detection of deep-diving species, and species that tend to avoid large vessels (Pierpoint et al., 2016; Poupard et al., 2019). Drifters rely on ocean currents, tides, and wind for movement, enabling opportunistic data collection across large marine areas (Fregosi, 2020; Van Parijs et al., 2021). Mobile PAM systems are already operational in conservation efforts, with gliders transmitting real-time detection data to trigger slowdowns of marine traffic when North Atlantic right whales are present, reducing collision risks (Cauchy et al., 2023). These platforms provide a valuable complement to fixed and towed systems, enhancing spatial coverage and enabling dynamic monitoring strategies.

3.3.1.5 Analytical Methods

Advancements in analytical methods have greatly expanded the ability to extract meaningful insights from passive acoustic data. PAM sensors, including hydrophones and sound recorders, generate extensive datasets that require automated detection and classification techniques for efficient processing (Browning et al., 2017). Machine learning and signal processing methods are increasingly used to identify marine mammal vocalisations amid environmental and anthropogenic noise (Bittle & Duncan, 2013; Caruso et al., 2020; Frasier 2021; Licciardi & Carbone, 2024; Lu et al., 2024; Shiu et al., 2020). Long-term datasets contribute to global ecological repositories, supporting large-scale analyses of species distribution and habitat use (Napier et al., 2024). However, standardisation in detection and classification software remains a challenge, as performance metrics vary across studies, making direct comparisons of occurrence results difficult (Kowarski & Moors-Murphy, 2020; Szesciorka et al., 2025). Calibration is another key factor, particularly as PAM sensors age or when integrating newer, low-cost hydrophones into monitoring programs (Ross et al., 2023). Best practices recommend incorporating ambient noise metrics into PAM plans to track changes in sound levels, particularly in environments affected by offshore wind development and vessel traffic (Marotte et al., 2022; Van Parijs et al., 2021). Standardised methodologies in data analysis and calibration will be essential for improving reliability and comparability across studies, ensuring PAM continues to provide high-quality data for marine mammal research and conservation.

3.3.2 Active Acoustics

Active acoustic monitoring is a less frequently utilised tool that has the potential to enable real-time detection, tracking, and behavioural analysis (Benoit-Bird et al., 2004; Fregosi et al., 2016). Unlike passive acoustic methods that rely on listening for marine mammal vocalisations, active acoustics transmits controlled sound pulses (e.g., sonar, echo sounders) to detect animals in their environment. Active acoustic systems also contribute to habitat mapping and prey distribution studies to understand how food availability influences marine mammal movement (Benoit-Bird et al., 2009). While active acoustics offers significant benefits in other areas, its use in marine mammal monitoring presents challenges, particularly concerns over potential disturbance from sound transmissions. Regulatory frameworks, particularly the Marine Strategy Framework Directive (MSFD) and UK Marine Strategy, stress the importance of minimising acoustic impact to marine mammals; therefore, active acoustic monitoring systems must be carefully designed and implemented to reduce potential disturbances.

3.4 Modern Imaging Technologies

Modern imaging technologies have revolutionised the monitoring of marine mammals, offering innovative ways to collect high-resolution, non-invasive data across large spatial and temporal scales. Techniques such as drones, satellite imagery, and underwater video provide diverse capabilities for detecting, identifying, and studying marine species in various habitats. This section explores these technologies, highlighting their applications, advantages, and limitations. By comparing crewed and uncrewed aerial surveys, showcasing advancements in satellite imagery, and examining underwater video systems, this section demonstrates how emerging imaging technologies complement traditional methods and enhance marine mammal monitoring and conservation efforts.

3.4.1 Unmanned Aerial Vehicles (UAV)

Unmanned aerial vehicles commonly referred to as drones, have become a valuable tool for marine mammal research, offering a non-invasive and efficient method for studying species across vast and often inaccessible areas (Verfuss et al., 2019). Traditional monitoring methods, such as vessel-based surveys and manned aerial flights, face challenges due to weather conditions, observer fatigue, and the logistical difficulties of reaching remote locations. UAV technology helps overcome these challenges by providing high-resolution aerial imagery, extended spatial coverage, and greater flexibility in data collection. A review of 169 studies published between 2009 and 2022 highlights the increasing use of UAVs in marine mammal research, particularly for abundance and distribution assessments, photo-identification (photo-ID), morphometric analyses through photogrammetry, blow sample collection, and behavioural studies (Álvarez-González et al., 2023).

Drones have been integrated into a range of monitoring methodologies, with applications spanning from population assessments to fine-scale behavioural analyses and body condition assessments (see below). UAV-based surveys have been particularly effective for abundance and distribution studies, accounting for 37.28% of the research reviewed by Álvarez-González et al. (2023). These studies utilise both still imagery and video recordings to document species presence, group size, and habitat use. According to Hodgson et al. (2023), the flexibility of UAV platforms allows for more accurate survey efforts compared to boat-based methods, with studies showing improved population estimates for species such as bottlenose dolphins. Additionally, UAVs allow for extended observation times, with grey whale *(Eschrichtius robustus)* surface behaviour recorded at three times the capacity of traditional vessel-based surveys (Torres et al., 2018). UAV imagery has also been instrumental in refining behavioural assessments by identifying previously undocumented behaviours and providing insights into foraging ecology, habitat use, and social interactions.

Advancements in UAV-based image analysis have further enhanced their research applications. Convolutional neural networks (CNNs) are now used to automate individual identification of right whales from aerial photos, improving efficiency and reducing human error (Degollada et al., 2023; Gray et al., 2019). Automated detection algorithms and AI-assisted processing techniques enable rapid classification of animals, behaviour states, and population estimates, significantly decreasing the time required for manual image review (Boulent et al., 2023; Torres et al., 2018). However, despite these advancements, deep learning applications in cetacean studies remain constrained by small datasets, and expert validation remains necessary to refine AI-generated predictions (Boulent et al., 2023).

Drones offer significant advantages in marine mammal research, including cost reduction, increased spatial and temporal coverage, and minimal disturbance to animals when operated at recommended altitudes (Álvarez-González et al., 2023). UAV-based surveys provide higher-resolution data at finer spatial scales and greater temporal frequency than traditional methods, enabling more detailed assessments of population health and demographic trends. UAV technology has also proven effective in difficult conditions, with successful detection of humpback *(Megaptera novaeangliae)* and killer whales *(Orcinus orca)* during the polar night (Aniceto et al., 2018). Additionally, rotary-wing UAVs have facilitated the collection of biological samples, such as blow exhalates from cetaceans, allowing researchers to analyse respiratory health and stress hormone levels without direct contact (Álvarez-González et al., 2023).

Despite their many benefits, UAVs present operational challenges. High-quality UAVs, particularly large fixed-wing models, can be expensive, limiting their accessibility for smaller research initiatives. Weather conditions such as strong winds, fog, and precipitation pose risks, including equipment loss, reduced image quality, and lower detection success (Álvarez-González et al., 2023). Regulatory restrictions governing UAV operations in civil airspace may also constrain study designs, as flight altitude and range limitations vary by country (Stöcker et al, 2017). Another limitation is flight autonomy; most UAVs require frequent battery changes, restricting continuous survey efforts. Future improvements in UAV technology will help mitigate these challenges. Developments in waterproofing, enhanced battery efficiency, and more durable designs will expand the applicability of UASs for marine mammal monitoring (Álvarez-González et al., 2023). Additionally, the integration of AI-driven automated detection systems and machine learning algorithms will refine species identification, behavioural classification, and abundance estimation (Boulent et al., 2023). As these technologies continue to advance, UAVs will play an increasingly important role in non-invasive, scalable, and high-resolution marine mammal monitoring, supporting conservation and management efforts worldwide.

3.4.2 Satellite Imaging

Very high-resolution (VHR) satellite imagery is increasingly used for studying great whales, offering a large-scale, non-invasive method for population assessments and habitat monitoring (Cubaynes & Fretwell, 2022; Khan et al., 2023). Advances in spatial resolution have greatly improved detection capabilities, with image resolution increasing from 46 cm to 31 cm in 2014, allowing finer details such as whale flukes to be visible (Hodul et al., 2023). Recent studies suggest that even higher resolution, around 15 cm, may enable individual identification of whales (Hodul et al., 2023). Whale detection in satellite imagery can be performed manually, through software-assisted analysis, or via fully automated approaches. While manual analysis is effective, it is time-intensive, making automated detection models an important advancement (Green et al., 2023). Deep learning models, such as YOLOv5 and Tiny YOLOv3 with dilated convolutions, have been trained to systematically detect gray whales in VHR imagery, demonstrating the potential for AI-driven methods to improve efficiency (Kapoor et al., 2023). CNNs further enhance detection and species classification by learning distinct features from large datasets, enabling improved whale counting and identification (Guirado et al., 2019). Expanding access to annotated datasets through open-source repositories is a key priority, as training algorithms require extensive reference data for accurate classification (Cubaynes & Fretwell, 2022).

Satellite-based whale monitoring offers several advantages, including the ability to assess populations in remote or difficult-to-access regions and track large-scale movements without disturbing the animals. Satellite imagery from platforms such as GeoEye-1, Quickbird-2, WorldView-2, and WorldView-3 has provided valuable data on species distribution, migration patterns, and potential risks such as ship strikes (Cubaynes et al., 2019). The integration of deep learning techniques has further improved detection capabilities, reducing the need for manual scanning and expanding the scope of global whale surveys (LeCun, Bengio, & Hinton, 2015). However, several challenges remain, including the difficulty of distinguishing whale species in VHR satellite images, as differentiation has not been systematically tested and is often inferred based on expected species presence in an area (Cubaynes et al., 2019). Whale detectability is influenced by environmental factors such as body position, water depth, and sea state, which can reduce visibility in certain conditions (Green et al., 2023). Access to high-quality imagery is another limitation, as free sources like Google Earth offer only Red Green and Blue (RGB) images rather than the more detailed multispectral data used in scientific studies. Image enhancement techniques, such as Enhanced Super-Resolution Generative Adversarial Networks (ESRGAN), have been proposed to improve satellite image clarity and preserve important features (Kapoor et al., 2023). As remote sensing technology continues to develop, integrating satellite imagery with aerial and acoustic data may provide more comprehensive and reliable whale population assessments.

3.4.3 Underwater Camera Systems

Underwater camera systems offer real-time visual insights into the behaviour, habitat use, and interactions of marine mammals with the underwater environment. Systems like the PelagiCam, an unbaited midwater video monitoring tool, have been successfully used for cost-effective remote data collection at offshore structures (Sheehan et al., 2020). When integrated with computer vision techniques, these systems improve efficiency and accuracy by automating motion detection and reducing the time-consuming nature of manual video analysis (Katona et al, 2024; Sheehan et al., 2020). Additionally, video-based monitoring has been extended to deep-sea environments through installations such as the Barkley Canyon node, where multi-modal observation platforms cross-reference spatial and temporal data to provide valuable behavioural insights (Frouin-Mouy et al., 2024). For example, video cameras have recorded sub-adult northern elephant seals resting and foraging in deep-sea habitats, with observations indicating sablefish as a key prey species (Frouin-Mouy et al., 2024). The method also allows for individual identification of animals based on unique body markings, enhancing studies on repeated visits and focal foraging areas.

Despite its capabilities, underwater video monitoring has limitations. The performance of video systems can be influenced by water clarity, light availability, and the potential for behavioural reactions from marine mammals to artificial lighting, as demonstrated by the strong reactions of elephant seals *(Mirounga angustirostris)* to light-emitting diode (LED) lights during deep-sea observations (Frouin-Mouy et al., 2024). Additionally, manual video review remains labour-intensive without the support of advanced computer vision software, and species misidentification can occur in turbid conditions or when multiple species are present (Sheehan et al., 2020). While baited remote underwater video systems have been effective for monitoring, they are biased toward predatory species, and unbaited cameras are often preferred for studying species attracted to artificial habitats without external influence (Sheehan et al., 2020). Although challenges remain, ongoing technological advancements in video analytics and automated processing are enhancing the effectiveness of underwater video monitoring, making it an increasingly valuable method for marine mammal research and conservation.

3.5 Environmental DNA (eDNA)

eDNA has emerged as a transformative tool for marine mammal monitoring, offering a non-invasive and highly sensitive method for detecting species presence, distribution, and population structure. Unlike traditional survey techniques, which often rely on direct visual or acoustic detections, eDNA sampling captures genetic material shed by marine mammals into the surrounding water through skin cells, mucus, faeces, and urine. This approach enables species identification even in vast and remote oceanic regions where direct observations are challenging. As advancements in molecular techniques continue to refine detection capabilities, eDNA has the potential to enhance marine mammal monitoring by providing complementary data to aerial, satellite, and acoustic surveys.

The application of eDNA for cetacean and pinniped research has gained traction in recent years, with studies demonstrating its efficacy in detecting a broad range of species, including cryptic and elusive taxa. For instance, the successful detection of North Atlantic right whales *(Eubalaena glacialis)*, sperm whales *(Physeter macrocephalus)*, and harbour porpoises using eDNA highlights its viability for monitoring both highly migratory and coastal species (Boyse et al., 2024). Similarly, eDNA analyses have been instrumental in identifying previously undocumented species occurrences in specific habitats, contributing to more accurate biodiversity assessments (Juhel et al., 2021; Valsecchi et al., 2023). The integration of metabarcoding techniques further enhances detection sensitivity, allowing researchers to simultaneously identify multiple species from a single water sample (Boyse et al., 2024).

Beyond species detection, eDNA holds promise for assessing population genetics and health parameters. Advances in quantitative polymerase chain reaction (PCR; qPCR) and droplet digital PCR (ddPCR) enable the estimation of relative species abundance and the detection of intraspecific genetic variation (Tsokana et al., 2023). Emerging research suggests that eDNA sampling may facilitate the identification of sex, kinship, and individual genetic profiles in marine mammals, although this application remains in its early stages (Boyse et al., 2024). Additionally, the extraction of hormonal biomarkers from eDNA samples presents a novel avenue for monitoring physiological states such as stress, pregnancy, and reproductive cycles, complementing existing hormone analyses from skin and blow samples (Burgess et al., 2016).

Despite its advantages, eDNA-based monitoring presents several challenges. DNA degradation rates in marine environments can vary due to factors such as temperature, salinity, UV exposure, and microbial activity, potentially affecting detection efficiency and temporal resolution (Suarez-Bregua et al., 2022). Distinguishing between recent presence and historical DNA traces requires careful interpretation, particularly in dynamic oceanographic conditions where water movement influences eDNA dispersal (Boyse et al., 2024). The risk of contamination and false positives also necessitates stringent laboratory protocols and the use of negative controls to ensure data reliability. Current limitations in reference databases for marine mammal eDNA further underscore the need for expanding genetic libraries to improve taxonomic resolution and reduce misidentifications (Boyse et al., 2024). As the field progresses, integrating eDNA data with traditional monitoring approaches, such as aerial surveys and acoustic monitoring, can provide a more comprehensive understanding of marine mammal ecology. This holistic approach will support conservation and management efforts by offering detailed insights into species presence, distribution, and interactions within marine ecosystems

3.6 Marine Mammal Health Monitoring

Marine mammal health monitoring is a crucial aspect of conservation and management, offering insights into population viability, disease prevalence, and the impacts of environmental stressors (National Academies of Sciences, Engineering, and Medicine, 2017; Nelms et al., 2021; Sehnal et al., 2021). UAV-based photogrammetry has been employed to assess body condition and reproductive costs in humpback whales, providing a non-invasive method of health monitoring without the stress of capture or tagging (Christiansen et al., 2016). Both live and deceased animals contribute valuable data through non-invasive sampling techniques, such as blow and skin hormone analysis, as well as post-mortem examinations via necropsies and virtopsy methods (Gassen et al., 2024). Advances in physiological tagging, eDNA, and automated image analysis further enhance health assessments by enabling real-time monitoring of stress responses, reproductive status, and disease outbreaks (Bohara et al., 2024).

The development of further advanced biological techniques for studying genes, proteins, and metabolites has significantly improved our understanding of the structure, function, and interactions of biological components. In marine mammal research, omics approaches encompassing genomics, transcriptomics, proteomics, and metabolomics have become powerful tools for monitoring health, stress responses, and population dynamics (Collí-Dulá., et al 2022; Senevirathna and Asakawa., 2021; Van Cise et al., 2024). These technologies have revolutionised the study of marine mammal health by enabling large-scale molecular analyses, providing critical insights into how these animals respond to environmental stressors, pollutants, and disease. Traditionally, marine mammal biology was studied through morphological, behavioural, and ecological observations; however, advancements in molecular biology have facilitated deeper exploration of the genetic and biochemical processes underlying health and disease (Mancia, 2018; Sanganyado et al., 2021).

By integrating molecular, physiological, and behavioural indicators, marine mammal health monitoring supports ecosystem-based management and informs mitigation strategies for key threats, including climate change, pollution, and anthropogenic disturbances.

3.7 Combining Technologies for Multimodal Monitoring Approaches

The integration of multiple monitoring technologies has revolutionised marine mammal research by enhancing data accuracy, spatial coverage, and ecological insights. Multimodal approaches leverage the strengths of various tools, such as satellite imaging, UAVs, acoustic monitoring, eDNA analysis, and underwater camera systems, to provide a comprehensive understanding of marine mammal ecology, behaviour, health, and population dynamics (Ollier, 2024; Potter et al., 2007; Stewart, 2024; Vieira, 2024; Yang, 2024). By combining these technologies, researchers can mitigate the limitations of individual methods while gaining a more complete understanding of species distribution, behaviour, and conservation needs.

For example, UAVs provide high-resolution aerial imagery for population assessments and behavioural studies, while hydrophones deployed from small vessels enable real-time monitoring of vocalisations and stress responses to anthropogenic disturbances. In cases where direct observations are challenging, eDNA analysis from seawater samples can confirm species presence, complementing passive acoustic surveys to improve biodiversity assessments. The integration of these methods facilitates a more holistic approach to marine mammal monitoring, ensuring that conservation strategies are informed by robust, high-resolution data across multiple observational scales.

Multimodal approaches have also proven effective in assessing the impact of human activities on marine mammals. The integration of satellite tracking with acoustic data has significantly enhanced the study of large whale movements, providing insights into migration patterns and habitat use while informing marine spatial planning efforts to mitigate ship strikes (Mate et al., 2021). As technology continues to advance, the incorporation of artificial intelligence (AI) and machine learning is further transforming multimodal marine mammal research (Cazau et al., 2021; Reynolds et al., 2025). AI-driven algorithms can now automate species identification from UAV and satellite imagery, reducing the need for labour-intensive manual analysis (Bakker, 2022; Delplanque et al., 2024; Mandal, 2024).

The combination of in situ sampling, remote sensing, and AI-assisted data processing enables more efficient and large-scale monitoring, addressing key conservation challenges such as cryptic species detection and dynamic habitat mapping. By embracing these interdisciplinary approaches, marine mammal monitoring is becoming increasingly effective, allowing for data-driven conservation strategies that are adaptive to environmental and anthropogenic changes.

3.8 Current Gaps

Despite advancements in marine mammal monitoring technologies, significant gaps remain in both hardware and software capabilities, limiting the effectiveness of conservation and mitigation efforts.

- **Species-Level Identification**
  One major challenge is achieving species-level identification, as many current technologies struggle to classify marine mammals beyond broad taxonomic groups (Advisian Worley Group & Biodiversity Research Institute, 2023; Szesciorka et al., 2025).

- **Data Collection Limitations**
  Data collection is constrained by limitations in sampling duration, spatial coverage, and resolution, as well as the lack of real-time monitoring capabilities. Improvements in battery life, power access, and remote data transmission are necessary to enhance efficiency and longevity (Szesciorka et al., 2025).

- **Integration with Offshore Wind Farms**
  Monitoring technologies are rarely integrated into Offshore Wind Farm (OWF) infrastructure, making deployments costly and reducing data collection efficiency. Effective integration would require placing monitoring equipment on OWF structures, transmitting power and data through these platforms, and utilising existing operations systems to streamline collection and processing (Courbis et al., 2024).

- **Lack of Standardisation**
  A major barrier to effective monitoring is the lack of standardisation across data collection methods and reporting metrics. Inconsistent protocols hinder habitat modelling and limit cross-study comparisons, emphasising the need for standardised pathways for technology verification, data collection, and open-access datasets (Advisian Worley Group & Biodiversity Research Institute, 2023; Courbis et al., 2024).

- **Interdisciplinary Collaboration Gaps**
  Limited collaboration between oceanographers and biologists restricts the integration of remotely sensed oceanographic data with marine mammal observations. This reduces the ability to comprehensively understand species distributions and behaviours (Courbis et al., 2024).

- **Marine Mammal Behaviour Data Gaps**
  Data gaps in marine mammal behaviour, particularly in tidal habitats, complicate efforts to predict how species will respond to marine energy developments, including underwater and surface tidal devices. Key biological parameters such as density, depth distribution, and avoidance behaviours remain poorly understood, impacting the accuracy of collision risk models (Booth et al., 2020; Copping and Grear, 2018; Horne et al., 2021; Onoufriou et al., 2021).

- **Technology Validation and Calibration**
  Many monitoring systems lack concurrent environmental data collection, making it difficult to distinguish the effects of OWF development from natural variability. Metrics such as detection distance, latency, system reliability, and data variability are inconsistently reported across baleen whale monitoring studies, complicating performance assessments (Szesciorka et al., 2025).

- **Challenges in AI Implementation**
  AI has the potential to enhance marine conservation by automating data collection and improving decision-making. However, challenges such as limited training datasets, integration barriers, and accessibility issues hinder its full implementation in monitoring frameworks. Additionally, limited public access to monitoring system data and OWF operational parameters further restricts opportunities for broader deployment and refinement of existing technologies (Ditria et al., 2022; Courbis et al., 2024).

- **Biases in Monitoring Technologies**
  Several inherent biases affect the accuracy of monitoring technologies. Availability bias occurs when an animal fails to display a detectable cue within a sensor's range, such as Passive Acoustic Monitoring (PAM) relying on baleen whales vocalising, despite calling rates varying with behaviour. Perception bias further affects data accuracy, as detection systems must distinguish signals from background noise, with infrared imaging being particularly susceptible to atmospheric and sea surface conditions (Szesciorka et al., 2025). Multi-modal monitoring systems, which integrate multiple sensor types, have not been thoroughly evaluated for their effectiveness in tracking baleen whales.

- **Vessel-Based Survey Constraints**
  Vessel-based environmental surveys face significant challenges, including limitations in charter availability, scheduling, costs, and suitability for operating within offshore construction sites. These constraints can hinder effective survey program execution, leading to project delays, data gaps, and increased project expenses.

To address these issues, future approaches could include:

- Greater automation through developing autonomous monitoring systems to reduce reliance on vessel-based surveys and improve efficiency.
- Enhanced telemetry through advancing tracking and data transmission methods to support long-term monitoring and reduce data gaps.
- Real-time data outputs through integrating systems that provide immediate insights into marine mammal presence and underwater noise levels.
- Improved offshore monitoring infrastructure through the installation of monitoring equipment on offshore wind structures to enhance data collection and transmission.
- Standardisation of data collection and reporting by establishing consistent protocols for technology validation, detection metrics, and data accessibility to improve cross-study comparisons.
- Multi-modal monitoring systems by expanding the use of acoustic, infrared, and optical sensors to address detection challenges and improve reliability.
- Interdisciplinary collaboration through cooperation between oceanographers, biologists, technologists and engineers to refine marine mammal distribution models and habitat assessments.
- Technology validation and calibration by ensuring monitoring systems collect environmental data alongside species observations to differentiate development impacts from natural variability.

These developments would further support more efficient, cost effective, and enhanced offshore monitoring, improving data quality and the assessment of potential environmental impacts.

3.9 Future Directions

The future of marine mammal monitoring in offshore environments is being shaped by advancements in technology, data management solutions, and evolving monitoring standards. As offshore activities, such as wind energy development and shipping, continue to increase, more sophisticated tools and methods will be required to track marine mammal populations and assess their well-being.

Innovative monitoring technologies are at the forefront of these advancements. Autonomous underwater vehicles (AUVs), drones, and satellite tagging are already being used to track marine mammals in real-time, providing more detailed and precise data than traditional methods. Digital aerial and satellite surveys are also revolutionising monitoring by enabling large-scale, cost-effective mapping of marine mammal distribution over vast offshore areas, even in challenging weather conditions. These methods help to obtain more comprehensive data, enhancing our understanding of species' behaviours and movements. Passive acoustic monitoring (PAM) remains central to monitoring marine mammals by their vocalisations, but recent advancements in autonomous, long-duration, real-time systems are streamlining monitoring. These systems reduce the need for intrusive equipment, lessen risks to personnel, and lower operational costs. They also help to reduce uncertainty in the consenting process for offshore industries, providing regulators with more reliable data for decision-making.

In terms of data management, the integration of big data and machine learning is revolutionising how marine mammal monitoring data is processed and analysed. Data collected from various sources can now be stored in centralised, cloud-based platforms that allow for real-time analysis and seamless sharing among researchers, regulators, and stakeholders. This enables faster decision-making and more adaptive management strategies to mitigate the impact of offshore developments on marine mammal populations.

Monitoring standards are also evolving to ensure consistency and reliability across different offshore monitoring projects. Standardised protocols for data collection, reporting, and analysis are being developed to ensure that monitoring efforts are comparable across regions and projects. International collaboration and the development of global frameworks will help align these standards and improve the overall effectiveness of marine mammal conservation efforts.

4. Stakeholder survey

4.1 Survey Methods

A structured survey was distributed to industry stakeholders to gather insights into commonly used technologies, methodologies, and their limitations. It was shared directly with stakeholders via targeted emails, posted to various distribution lists, and made available on LinkedIn, as well as through a press release and numerous industry media outlets. A dedicated web landing page was also created, providing additional information and context for potential respondents. The survey remained open for responses from 9th to 24th January 2025, spanning a period of 16 days. It contained 39 questions, primarily rating scale questions with some open-ended questions. Open-ended responses were systematically categorised into one or more groupings that best reflected the intent of the comments provided, with selected responses included as illustrative examples. In addition to the survey, targeted interviews with SME's were conducted to gain deeper qualitative insights and further contextualise the data collected.

4.2 Survey Results

A total of 133 individuals responded to the survey, although not all participants completed every question. The survey respondent demographics highlighted a diverse representation of organisations involved in marine mammal monitoring **(Figure 1).** Most respondents were headquartered in the USA (41%) and the UK (37%), with additional representation from Canada (14%), Ireland (4%), Australia (4%), and several European countries, including Denmark, Portugal, Germany, and Slovenia. This distribution reflects the strong presence of marine mammal monitoring efforts in North America and Europe. The areas of operation indicated a global reach, with many organisations conducting monitoring activities in multiple areas. Of the 131 respondents who answered this question, 34% operated on the UK & Irish continental shelf, 25% in the North Sea, and 20% in the Northwest Atlantic. A significant portion of respondents also reported working globally (34%), highlighting the widespread scope of marine mammal research. Beyond the UK and adjacent waters, other key regions of operation included North American Atlantic coastal waters (29%), the Northeast Atlantic (28%), the Gulf of Mexico (20%), and the Arctic (16%), with additional monitoring efforts extending to the Antarctic, Baltic Sea, Northwest Pacific, South Pacific, Mediterranean Sea, and Indian Ocean. This geographic distribution suggests that marine mammal monitoring is prioritised across a broad range of ecosystems, including coastal, polar, and deep-sea environments.

In terms of the species being monitored, cetaceans featured prominently, with 88% of respondents identifying small odontocetes as targets, 78% for mysticetes and 72% for large odontocetes (beaked whales and/or sperm whales). Pinnipeds (47%), sirenians (24%) and other protected species (e.g., basking sharks and sea turtles; 7%) were less often monitored. "Other" responses included broad mentions of all detectable species (5%) or identified a focus on monitoring habitat or anthropogenic noise (2%), acknowledging that both might have been more common if offered as selectable options.

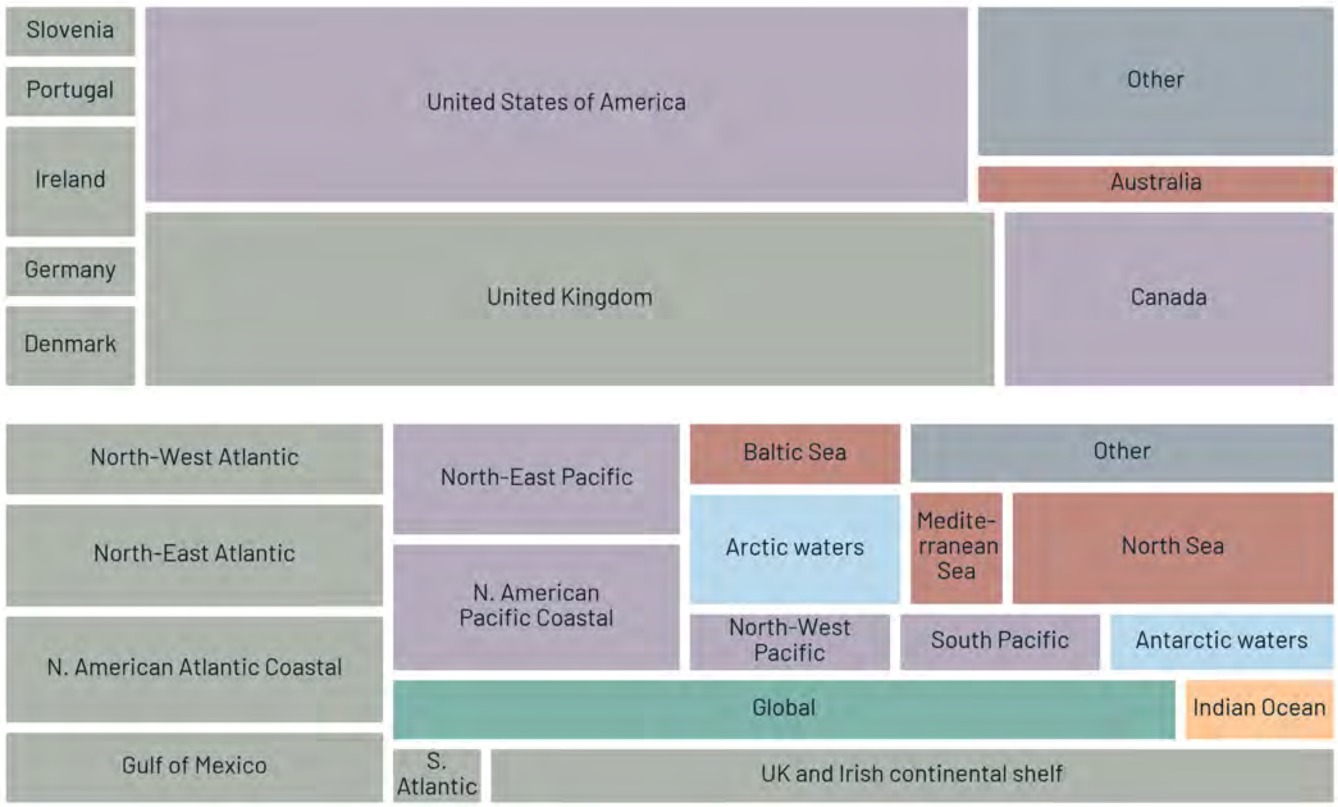


Figure 1. Survey respondent demographics, showing the headquarters location of companies and organisations (top; n = 124) and their areas of operation for marine mammal monitoring (bottom; n = 131, multiple choices possible).

The survey responses are reported in a variety of figures below that relate to a combination of scalar and open response questions. Response distribution regarding considerations were reported largely on a scale of 1 (high priority) to 5 (low priority) when addressing specific survey questions. Within the figures below, average importance ratings were often shown. These were calculated by treating a response of 1 as 1, 2 as 0.75, and 3 as 0.5, 4 as 0.25, and 5 as 0 (or 1 as 1, 2 as 0.67, 3 as 0.33, and n/a as 0 for a 3-point scale), then taking the average of all responses, is plotted on top of the bars to demonstrate overall sentiment. Additional figures were used to represent the magnitude of importance of reported categories by survey respondents.

Of the 131 respondents who provided information on monitoring data types, acoustic and visual data were the most utilised, with similar levels of frequency across the top three priority levels. These data types were either directly collected by respondents, or the target data for collection by products that they are developing **(Figure 2).** Biologging data emerged as the third most preferred option. Drone-derived imagery and biological samples leading the main grouping where data types were used at relatively similar levels, with non-visible wavelength data being the least commonly utilised.

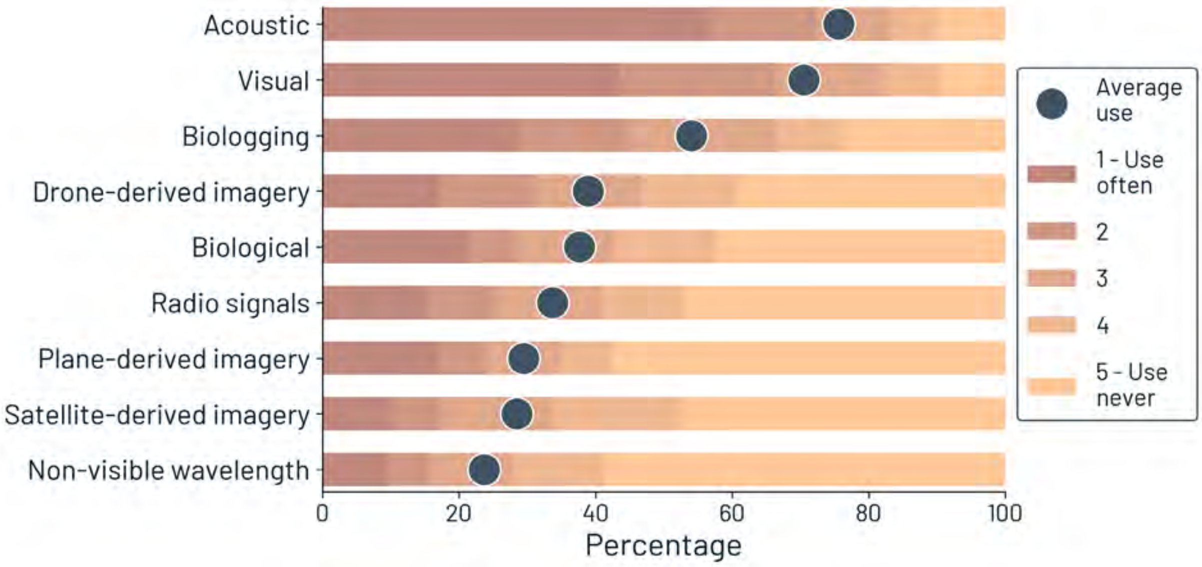


Figure 2. Survey responses (n = 131) on the use of different data types in marine mammal monitoring. Respondents rated their use of each data type on a scale from 1 (use often) to 5 (never use). The colour gradient represents response distribution, with darker shades indicating more frequent use. The average use rating is plotted as a dark circle on each bar to indicate overall sentiment.

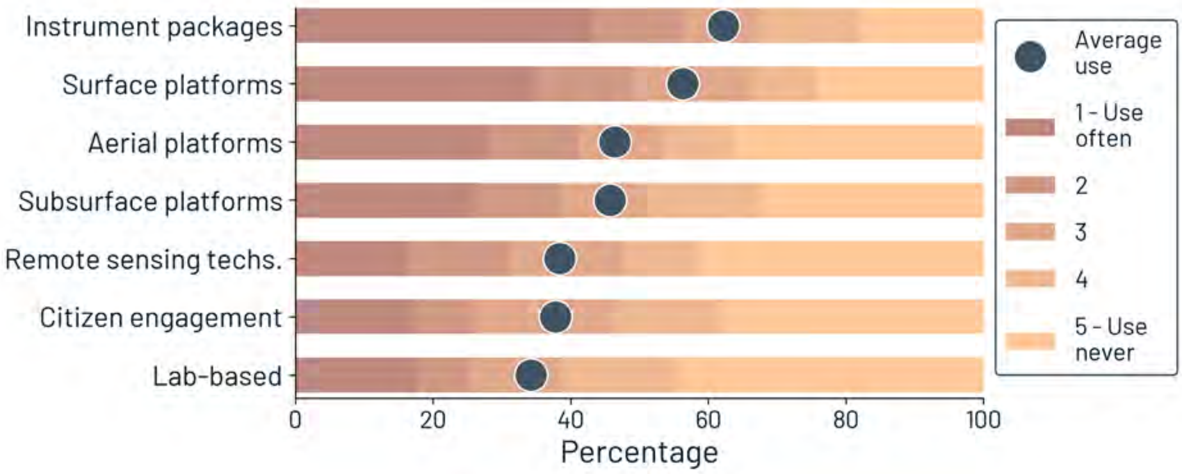


Figure 3. Survey responses (n = 132) on the use of different platforms for marine mammal monitoring. Respondents rated their use of each platform on a scale from 1 (use often) to 5 (never use). The colour gradient represents response distribution, with darker shades indicating more frequent use. The average use rating is plotted as a dark circle on each bar to indicate overall sentiment.

Of the 132 respondents who provided information on the platforms they use **(Figure 3),** instrument packages—such as oceanographic unit deployments (e.g., seafloor moored systems, floating acoustic arrays, and autonomous integrated multi-sensor systems) and surface platforms were the most commonly utilised (priority levels 1 to 3). Subsurface and aerial platforms were the next most frequently used. However, seafloor moorings could be classified as either subsurface platforms or instrument packages, suggesting some overlap between these categories.

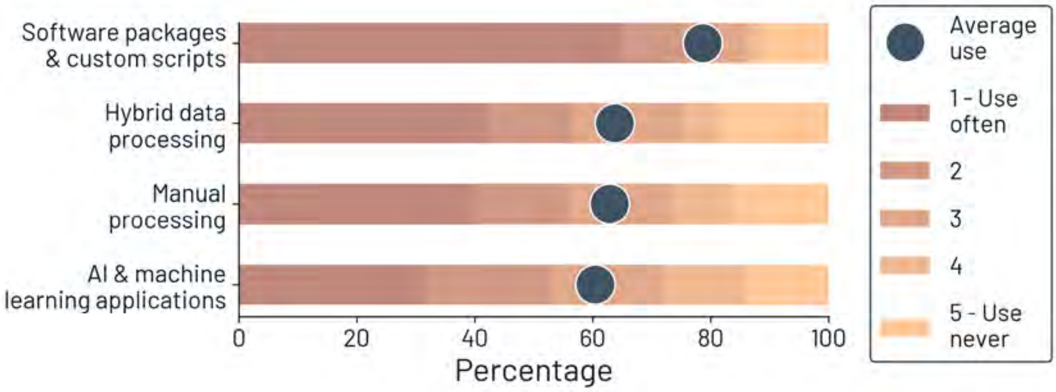


Figure 4. Survey responses (n = 131) on the use of different data processing techniques in marine mammal monitoring. Respondents rated their use of each technique on a scale from 1 (use often) to 5 (never use). The colour gradient represents response distribution, with darker shades indicating more frequent use. The average use rating is plotted as a dark circle on each bar to indicate overall sentiment. (Note – an additional 11 mentions of other processing methods are not displayed on this image.)

Among the 131 respondents who provided information on data processing methods, the use of commercial software packages and custom scripts was the preferred approach. This was followed by hybrid methods (e.g., human-in-the-loop processing), manual processing, and, finally, AI-driven analysis **(Figure 4).** Other processing methods were reported by 11 respondents, including proprietary software packages (e.g., F-POD app by Chelonia and the eOceans software) and general data handling tools (e.g., GIS, AIS, qPCR, and radio collar technology), which could be analysed using any of the aforementioned methods. Additionally, some respondents referenced laboratory-based techniques, such as molecular and diagnostic methods.

Respondents were asked to list the products they used to conduct these analyses **(Figure 5).** The category "Other" contains all software reported only once by any respondent, including several common to monitoring, such as, but not limited to, DBsea, LFDCS, Mobius, Google Earth, Photoshop, VLC, Igor Pro, Morphometrix, Mysticetus, NRKW ID app, SOCPROG, and eOceans.

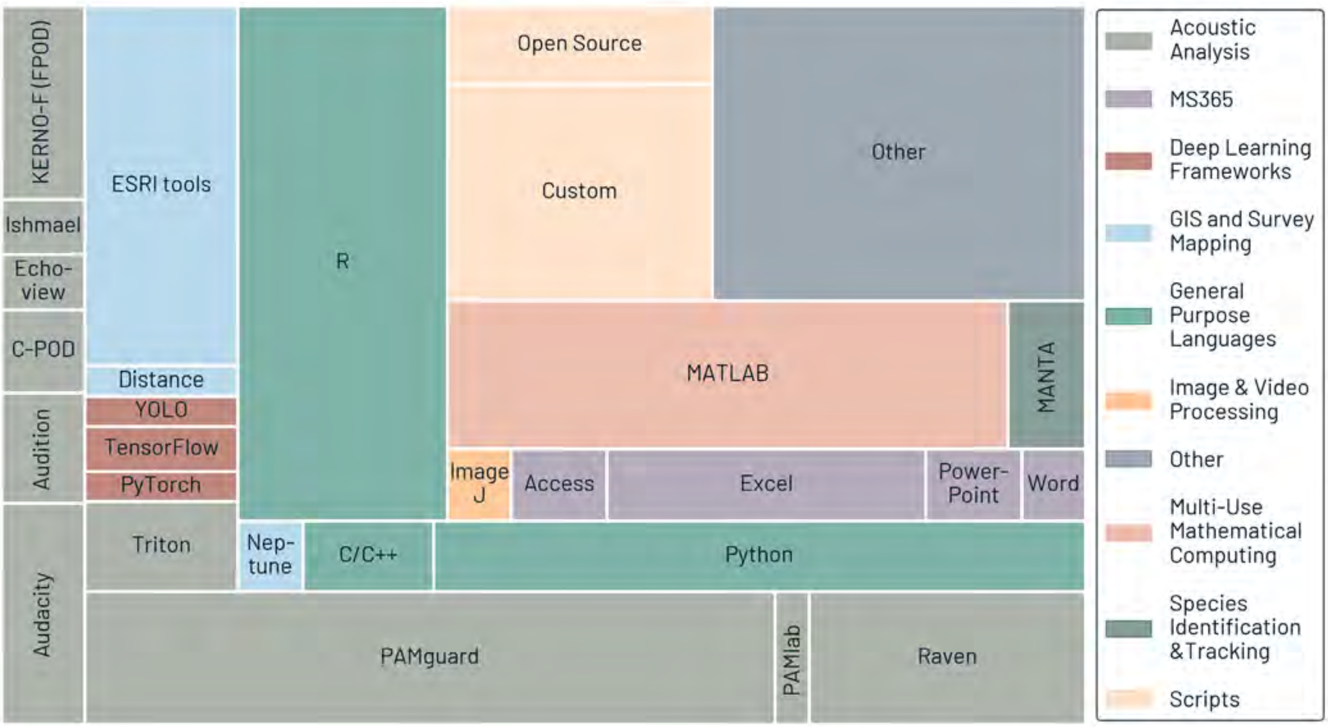


Figure 5. Survey responses (n = 101) on the specific software used for data processing in marine mammal monitoring. All software reported more than once are shown, while those reported only once are included in "Other." (Note – respondents were asked to list all software.)

A total of 127 respondents provided information on their objectives for data collection **(Figure 6).** The most frequently cited objective was assessments, including the mitigation of harmful interactions. Other common applications included, baseline surveys, effect monitoring, population estimates, regulatory compliance monitoring, behavioural studies, and habitat use assessments. Health assessments were the least frequently reported objective. Additional objectives provided by respondents included:

- All of the above
- Research
- Mitigation during testing of sonar technologies.
- Marine mammal mitigation during 2DHR geophysical surveys
- Fisheries interactions
- Community involvement
- Behavioural response analyses

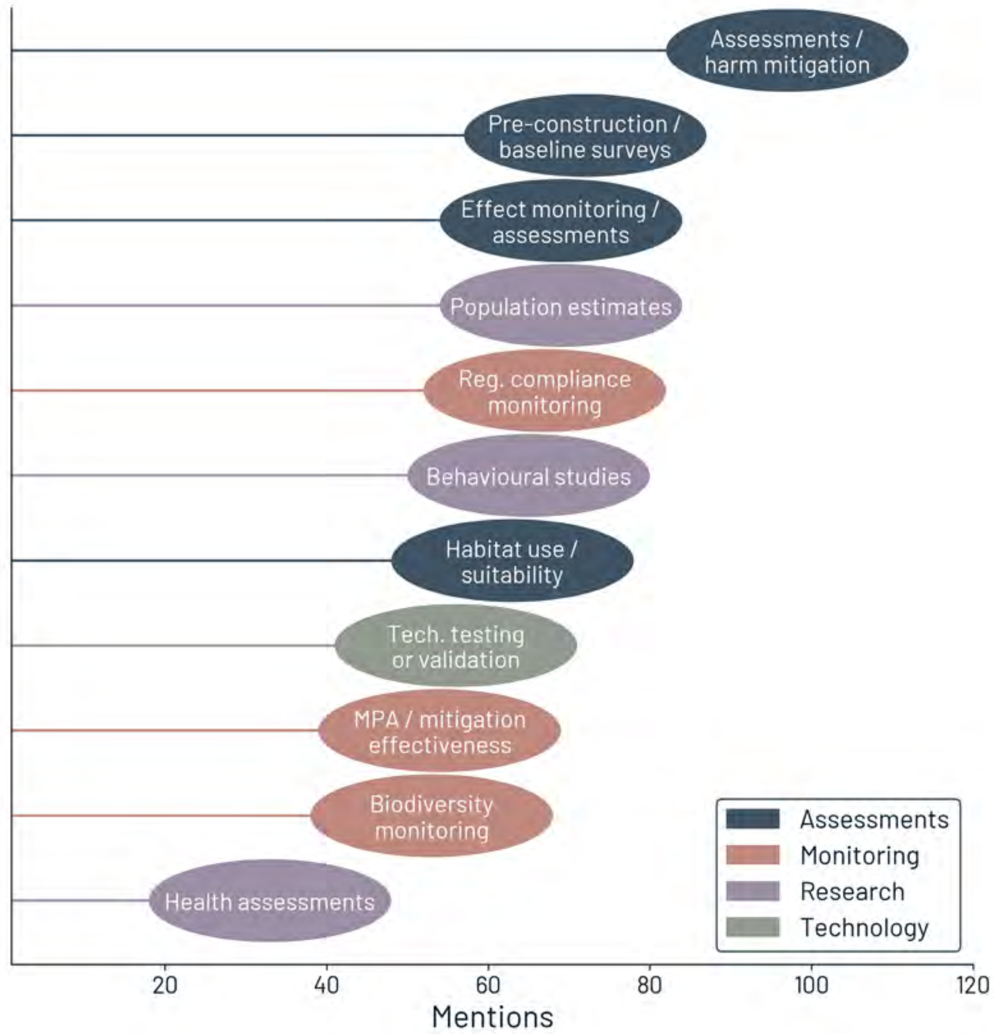


Figure 6. Survey responses (n = 127) on study objectives in marine mammal monitoring. The number of mentions for each objective is shown, categorised into Assessments, Monitoring, Research, and Technology. Respondents could provide multiple responses. (Note – an additional 8 mentions of other processing methods are not displayed on this image.)

In terms of which considerations influence the choice of monitoring technologies and data streams (n = 126), project objectives and regulatory requirements, data quality and resolution, and safety concerns were reported as the most important factors (at levels 1 or 2). However, the potential impact on animals and the environment was just below these top tier considerations **(Figure 7).**

The next tier of influencing factors included practical considerations, such as monitoring duration and scale, budgetary constraints, logistical challenges, site remoteness, and equipment durability, as well as the detectability of species of interest. Another practical consideration, the availability of trained field personnel, was not far behind. Regulatory and permitting and environmental conditions were also recognised as significant determinants. In contrast, factors such as multiple-use considerations within the study area, the choice between real-time and archival data capabilities, and the development or testing of new technologies were reported as the least influential in decision-making.

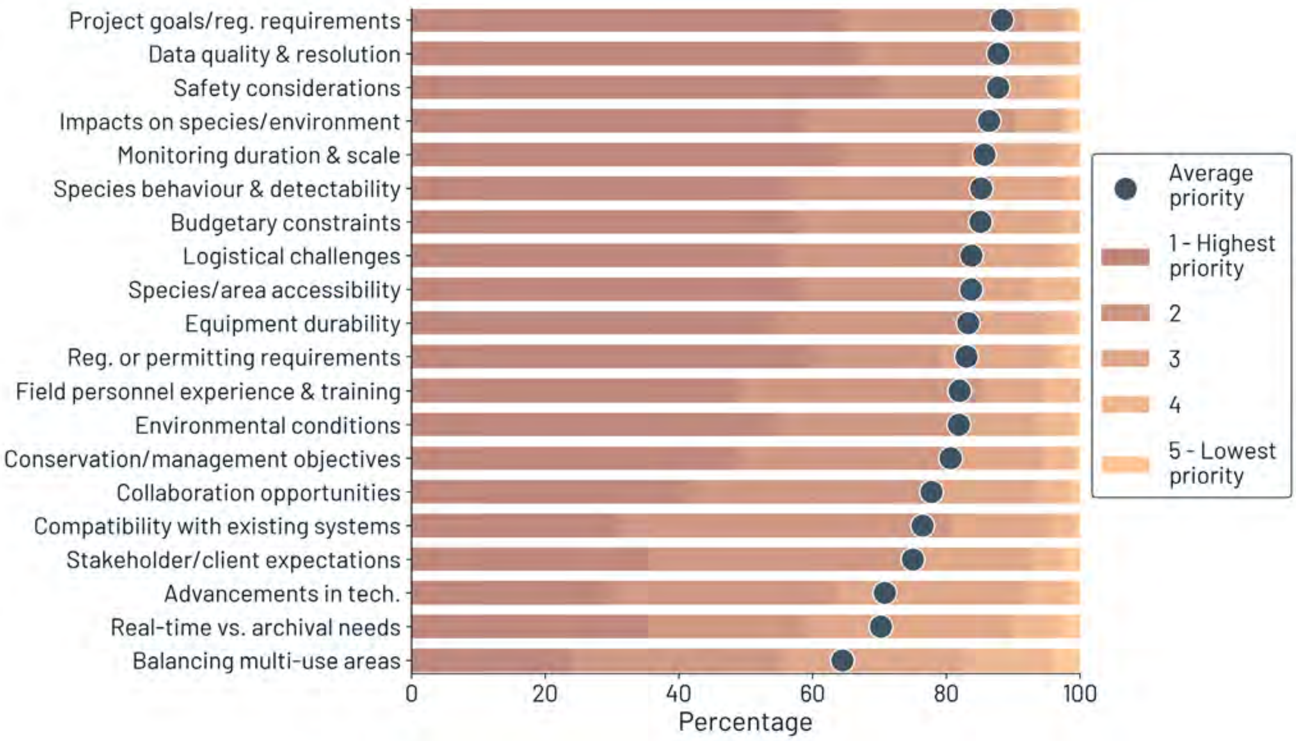


Figure 7. Survey responses (n = 126) on key considerations for marine mammal monitoring. Respondents rated each factor on a scale from 1 (highest priority) to 5 (lowest priority). The colour gradient represents response distribution, with darker shades indicating higher priority. The average priority rating is plotted as a dark circle on each bar to indicate overall sentiment.

When asked about hardware concerns (n = 124), data quality assurance and validation processes and the availability of reliable species detection or classification tools were identified as the two most influential factors in decision-making **(Figure 8).** A range of additional factors formed a secondary tier of importance, including data accessibility and sharing, sensor sensitivity and calibration, power availability, and vessel availability and costs. Equipment durability was the leading concern leading among the remaining options, while data transmission costs were reported as the least important consideration.

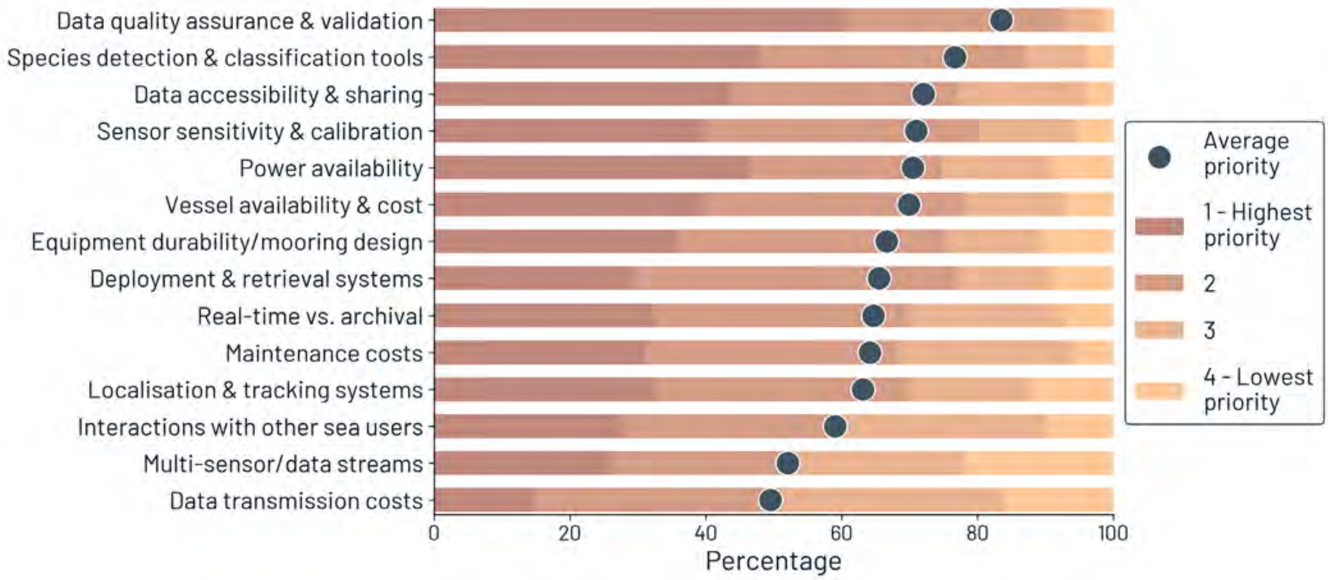


Figure 8. Survey responses (n = 126) on considerations for hardware selection in marine mammal monitoring. Respondents rated each factor on a scale from 1 (highest priority) through 3 (lowest priority) and to 4 (not a consideration). The colour gradient represents response distribution, with darker shades indicating higher priority. The average priority rating is plotted as a dark circle on each bar to indicate overall sentiment.

The clear top three under-utilised technologies that would benefit from increased scalability in order to meet current or future monitoring requirements that were identified by respondents (n = 123) were artificial intelligence (AI) and other machine learning applications, multi-sensor platforms, and passive acoustic monitoring (PAM) **(Figure 9).**

Uncrewed surface vehicles and aerial vehicle technologies formed a very narrow secondary tier, with surface visual equipment and subsurface autonomous vehicles (e.g., gliders) a third tier just behind that. Radar systems were the least favoured technology, while underwater camera systems were reported as only slightly more utilised.

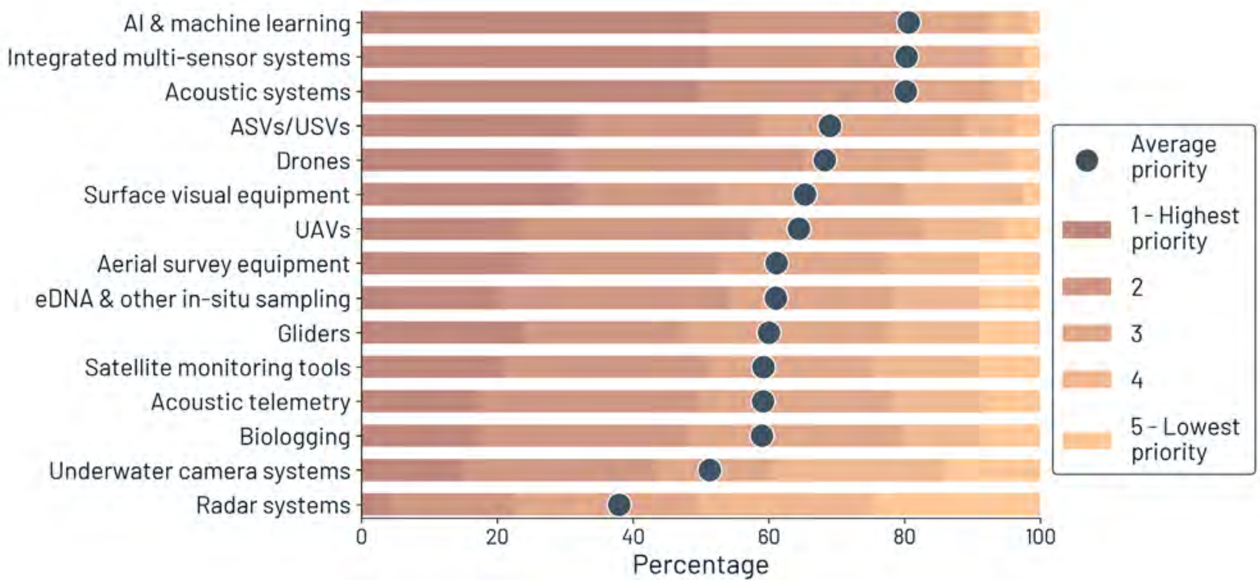


Figure 9. Survey responses (n = 123) on underutilised technologies in marine mammal monitoring. Respondents rated each technology on a scale from 1 (highest priority for increased use) to 5 (lowest priority). The colour gradient represents response distribution, with darker shades indicating higher priority. The average priority rating is plotted as a dark circle on each bar to indicate overall sentiment.

In terms of current technologies requiring improvement to better support marine mammal monitoring (n = 127), software development was identified as the most critical area for enhancement. Respondents also particularly highlighted the need for improved species identification capabilities as a key area for further advancement, alongside the need to enhance detection rates across different levels of presence and behaviour **(Figure 10).**

Data quality assurance and validation, power capabilities and localisation and tracking capabilities were recognised as the next tier of priority, while most of the remaining factors were ranked similarly. However, it is noteworthy that real-time monitoring received the lowest ranking overall, although compatibility with existing datasets was ranked least often at the highest priority level.

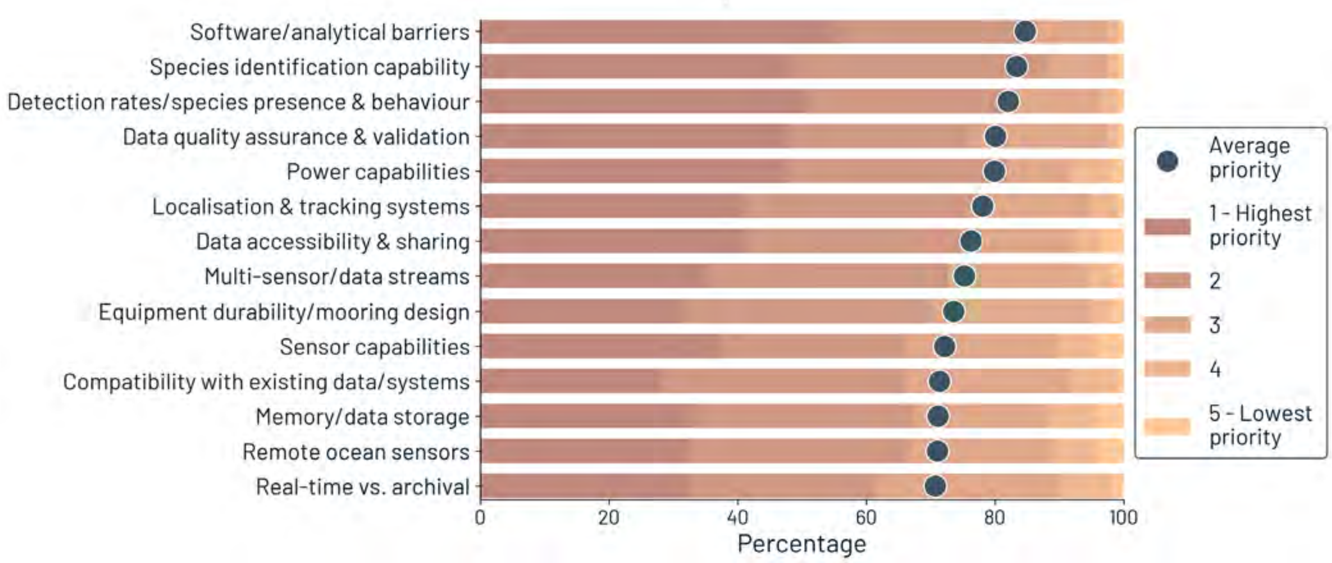


Figure 10. Survey responses (n = 127) on development priorities for marine mammal monitoring technologies. Respondents rated each priority on a scale from 1 (highest priority) to 5 (lowest priority). The colour gradient represents response distribution, with darker shades indicating higher priority. The average priority rating is plotted as a dark circle on each bar to indicate overall sentiment.

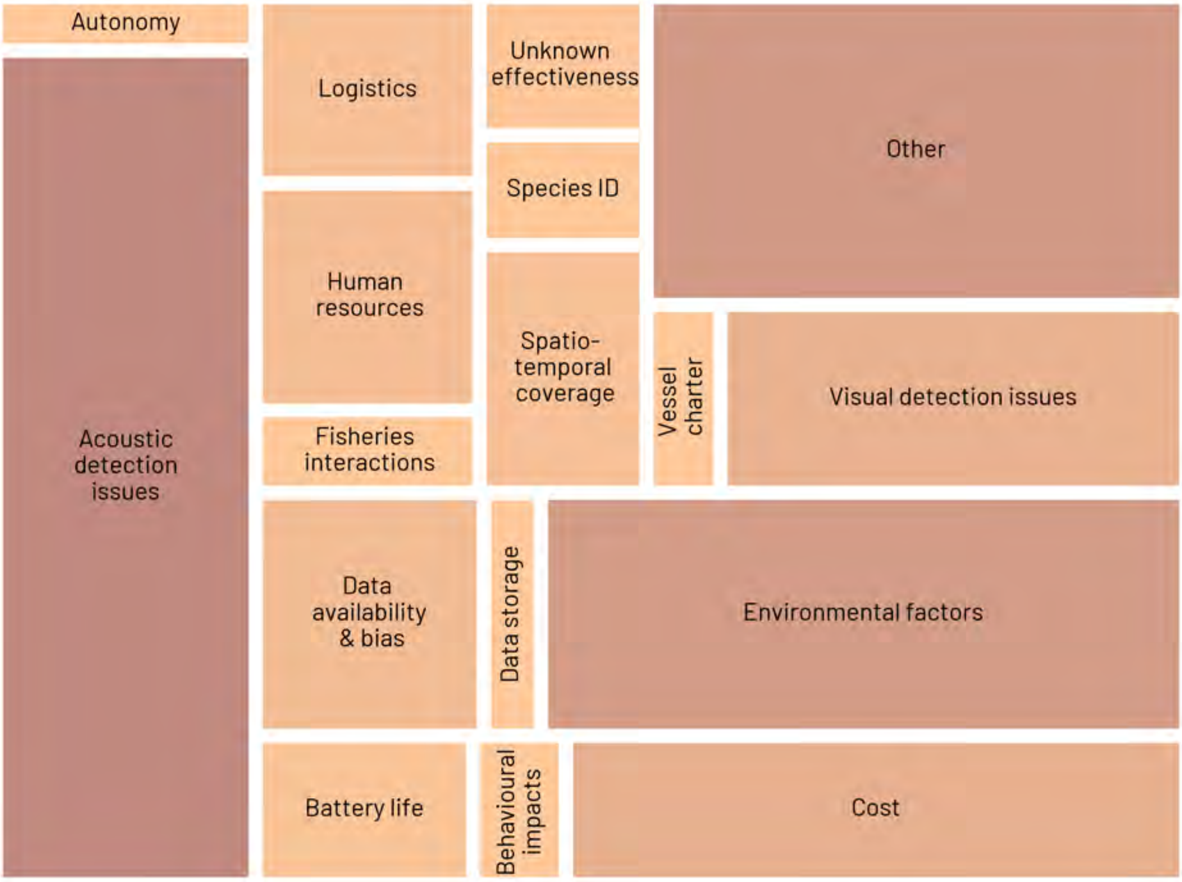


Figure 11: Top reported constraints in marine mammal monitoring identified by respondents (n = 107, multiple responses possible). The size of each box represents the relative frequency of each reported constraint, with larger boxes indicating more frequently mentioned challenges.

Finally, when asked to identify the constraints and boundaries to current monitoring techniques, respondents (n = 107) noted that marine mammal monitoring is frequently constrained by costs, equipment availability, access to trained observers and operators, and vessel availability **(Figure 11).** Autonomy and vessel charter access were minor constrains in comparison. "Other" options include a range of concerns like biofouling, and access to 1st world training programs.

4.3 Survey Conclusions

4.3.1 Interpreting the Survey Results

These results must be considered in the context of the survey respondents. For example, acoustic instrument use was identified as highly under-utilised; however, since most respondents reported either using or developing acoustic technologies, this finding may reflect their professional background rather than an actual gap particularly given the widespread global use of PAM. Nonetheless, several limitations of PAM were noted, and upscaling AI and automated processing techniques was highlighted as a key opportunity to enhance its effectiveness.

Similarly, most respondents reported using monitoring data to assess human impacts from development projects rather than for broader biological research. This focus may explain why comparability with existing datasets and tagging technologies was rated as a lower priority for improvement or wider adoption.

4.3.2 Key Constraints in Marine Mammal Monitoring

Despite potential biases in the survey responses, several important conclusions emerge. For example, a lot of other issues raised, such as costs, vessel charter access, equipment availability, and human resource limitations, are mostly external factors that will likely continue to limit monitoring regardless of technological advancement, necessitating careful consideration and mitigation strategies. Regulatory requirements for specific monitoring technologies and safety considerations also present substantial challenges that cannot always be addressed through research and development unless transformative innovations, such as replacing aerial surveys with alternative techniques, are introduced. In that case, any regulatory requirements specifically mentioning certain techniques would then act as a barrier to use of the new approaches.

However, many respondents noted the need to overcome the various existing inherent or environmental limitations affecting detection technologies, especially for two of the most common approaches at this time: visual monitoring and PAM, which could conceivably be overcome through technological advancement. The importance of these limits and the need to overcome them is reflected throughout this survey. In contract, the unknown effectiveness of monitoring methods is only identified in the question specifically addressing constraints. Crucially, the effectiveness of new detection technologies is commonly called into question, while the effectiveness of long-standing tools, such as visual scanning and PAM, is challenged less. While we may ultimately need to accept assessments of relative effectiveness under given conditions, the more accurately effectiveness can be established the better for all monitoring techniques.

4.3.3 Priority Areas for Improvement

Machine learning and AI were identified as key areas for development, although autonomy of monitoring was not highly identified as an issue. As a result, this probably indicated that the need for AI is related to the other needs identified for better species detection, identification and localisation and tracking. Data quality and assurance were also consistently highlighted as requiring further refinement. From a hardware perspective, improvements in battery life, memory capacity, and equipment durability were deemed critical. Similarly, advancements in detection rates and sensor capabilities were identified as high priorities.

4.3.4 Contradictions Emerging from the Data

Some inconsistencies were observed in the findings. For instance, multi-sensor platforms and data streams were simultaneously identified as under-utilised technologies in need of improvement while being ranked as low priority for current monitoring applications. This suggests that while commercial products exist, they may not yet be fully developed or widely adopted. Similarly, understanding detection rates and the influence of animal behaviour was highlighted as a key priority, yet tagging technologies—which could help address this issue—were not classified as under-utilised, raising questions about their perceived role in improving monitoring efforts. It is for these reasons that the answers to individual questions should not be used individually to inform policy or funding decisions, but rather the aggregate of all the survey data, within the context of the literature review and other information contained within this report.

5. Horizon scan of marine mammal technologies

The horizon scan, in combination with the survey and workshop, was conducted to identify emerging trends, challenges, and opportunities relevant to marine mammal monitoring. This process aimed to provide a forward-looking perspective on technology that could assist in shaping future monitoring practices. By reviewing existing research through the literature review, collecting industry insights via the survey and workshop, and collecting expert opinions, the scan sought to highlight key areas where advancements or improvements may be needed.

5.1 Horizon Scan: Survey Results

Survey respondents were asked about the technologies they believed would benefit from further development in order to enhance marine mammal monitoring capabilities and what critical advancements are needed to best support future monitoring objectives. Respondents were also asked about the timeframe over which they believed those developments could be realised.

When interpreting these results, the make-up of the respondents should be considered. For example, only two veterinarian / pathologists provided data, which may mean that health-related monitoring technologies and techniques are under-represented.

Over the near-term, the top three technologies where respondents (n = 89) expected critical developments included, AI methods, acoustic detection methods, and aerial detection methods (including from drone / Remotely Piloted Aerial System: RPAS) **(Figure 12).** AUVs distributed acoustic sensing (e.g., use of fibre optic cables), thermal methods, and satellite methods formed a secondary grouping. A fewer number of respondents expect somewhat critical improvements in drone tagging and sampling, wave gliders, integrated detection methods, and eDNA. The majority of these developments are expected over the timeframe of 1 to 5 years, with some respondents indicating an expected breakthrough in acoustic detection methods over the next year or so **(Figure 13)**.

Over the longer-term, respondents (n = 68) provided a wider range of potential technologies where critical developments might occur, although many overlapped with those reported for the near-term **(Figure 12).** AI methods and satellite detection methods dominated in this timeframe, with acoustic detection methods, aerial detection methods and autonomous underwater vehicles also being leading choices **(Figure 12).** This corresponded with average importance reported for technologies in development with the same four technologies all ranking highest amongst respondents (Figure 13). Most of the developments were expected over the 3-10-year timeframe, although there was less agreement in long-term developments than the near-term ones, with some respondents spreading their expectations across a wider range, between one to ten years **(Figure 13).**

Over both timeframes other interesting inclusions were provided, such as the Internet of Things, Lithium battery alternatives, integrated detection technologies and platforms, and the rise of an as-yet unknown detection method categorised as "other" **(Figure 12)**.

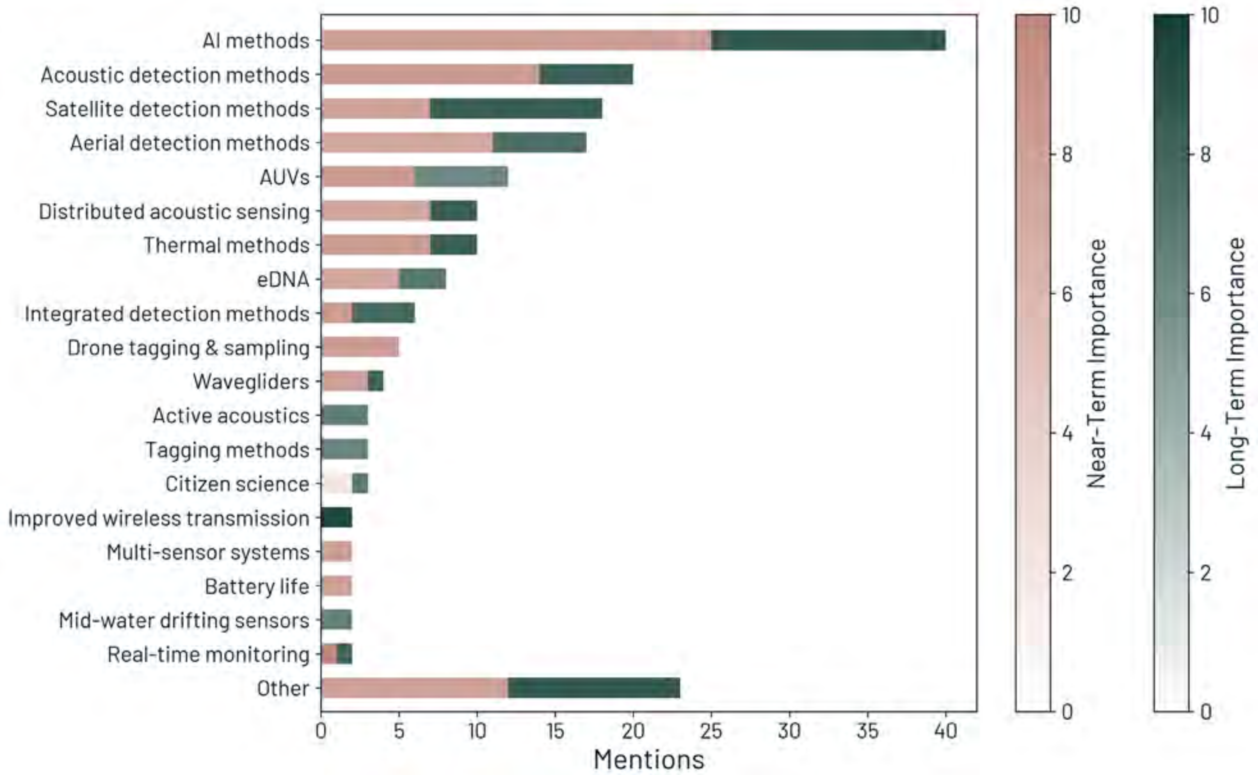


Figure 12. Technologies that respondents expected to show critical developments over the near- and long-term (n = 89 and 68 respectively). The bar lengths indicate the number of mentions for each technology, with colours representing their perceived near-term (light brown) and long-term (dark green) importance.

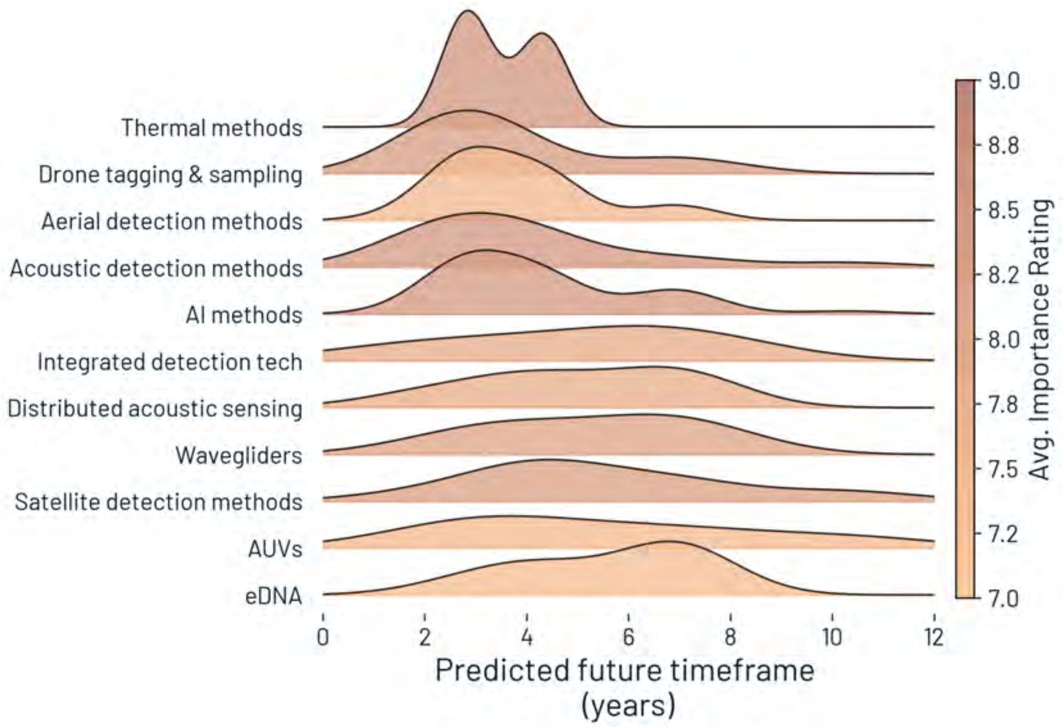


Figure 13. Timeline for expected critical developments, with responses to questions of time-to-emergence of critical developments over the near-term and long-term were combined. The data is represented as a probability distribution that illustrates the relative likelihood of each response at each time point. Additionally, importance ratings (for which there was a scale of 1-10 for responders, although all responses ranged from 7 to 9) for each technology from both near- and long-term questions were averaged and are reflected by colour in accordance with the scale on the right.

When queried on what benefits developing technologies may provide in the near term (n-89), increased spatiotemporal coverage was seen as the most likely **(Figure 14).** Improved detection, quick, accurate detection and classification and an ability to build a better understanding of the species under study also ranked relatively highly **(Figure 14).** Over the long-term (n = 68), increased spatiotemporal coverage was also the key benefit, with reduced costs of monitoring and better information on species coming in second and third **(Figure 14).** Improved real-time monitoring capabilities and an improved detection capability overall also ranked quite highly here.

Interestingly, although not a major benefit over either timeframe, it seems expected that we should be more able to reduce our impacts on the study species through the use of these technological developments over the longer-term than the near-term **(Figure 14).** Over both timeframes, many of the logistical and cost-based benefits raised by respondents revolved around an increasing reliance upon unmanned detectors and remote operation, although ease of deployment and generally cheaper equipment also factored into the comments received. Similarly, various independent comments explored the expansion of uses for a given technology, such as the use of thermal methods in tracking lesions and other health aspects of marine mammals. Finally, one respondent emphasised that technological advancements alone are not the main challenge, stating, *"Nothing currently being developed has any potential if policymakers don't get on board, so it's not a tech problem."* Instead, they highlighted increased funding as a key solution to overcoming many of the existing barriers to effective monitoring and mitigation.

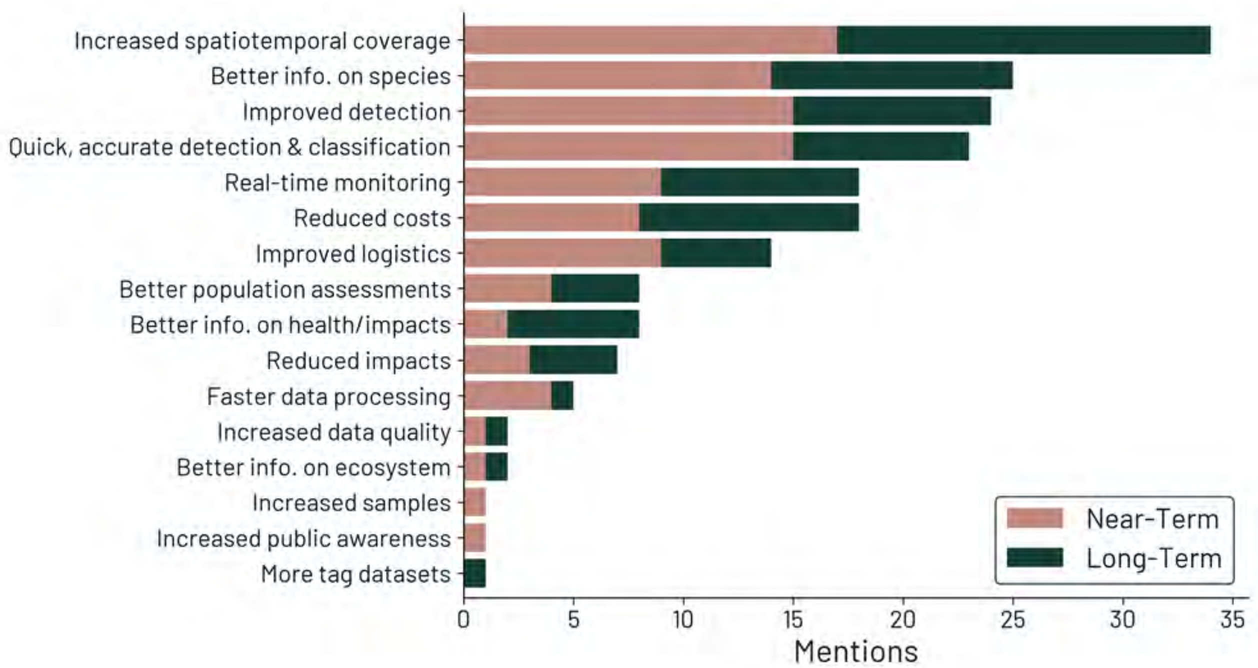


Figure 14. The expected benefits of critical developments respondents foresee for the near- and long-term (n = 89 and 68 respectively). They are categorised by near-term (light brown) and long-term (dark green) importance.

When considering the near-term benefits of developing technologies, AI methods were primarily recognised for their ability to enable quick and accurate detection and classification, accounting for 9 out of 37 mentions **(Figure 15).** Additionally, AI was noted for its potential to enhance species understanding (5/37), address logistical challenges (4/37), expand spatiotemporal coverage, and reduce costs (4/37). Aerial detection methods (including drones) are believed to help obtain a better understanding of the species (3/16). Improvements in AUVs are expected to increase spatiotemporal coverage (4/9), as aerial and acoustic detection **(Figure 15).** Finally, thermal methods (4/10) are thought to improve detection overall (3/6).

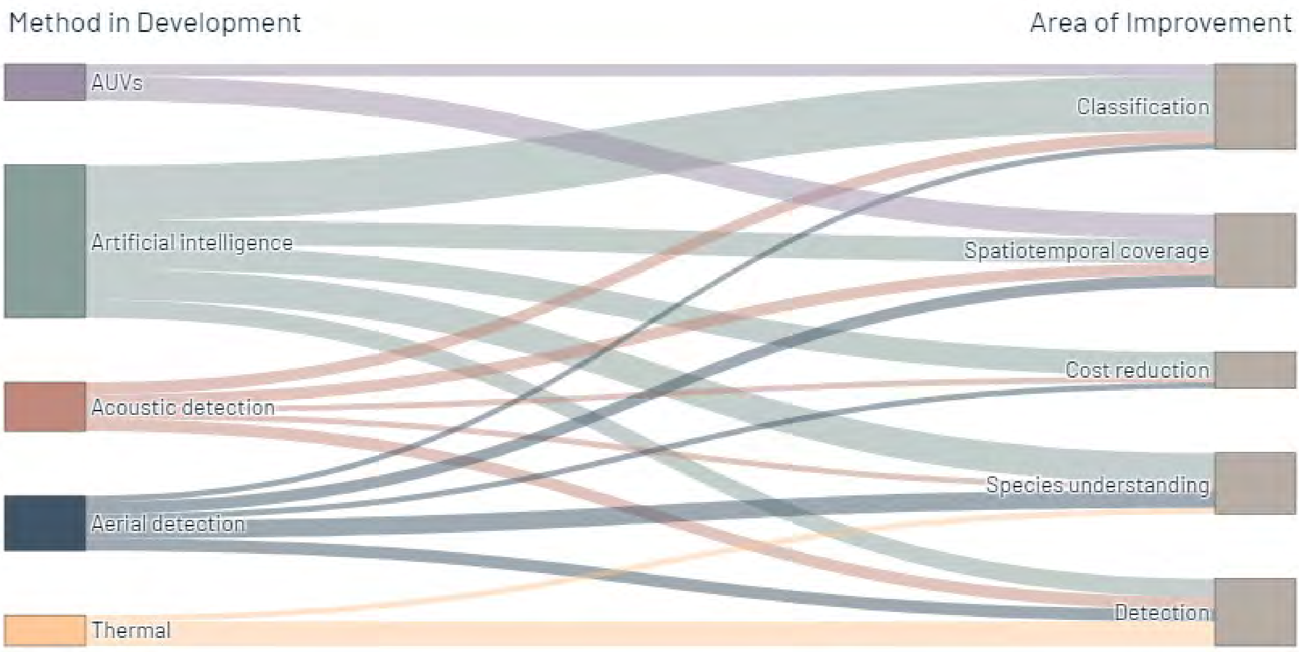


Figure 15. Near-term needs filled by emerging technology for marine mammal monitoring. The left side represents different methods in development, while the right side shows corresponding areas of improvement these technologies aim to address. Lines connecting methods to improvements indicate the contributions of each technology to key monitoring challenges.

Over the long-term there was less consistency in expectations **(Figure 16)**. AI methods still seem to be expected to primarily address the need for quick, accurate detection & classification (6/22), while also reducing costs (4/22). Satellite technology development is expected to increase spatiotemporal coverage (5/15). Notably, respondents did not identify long-term advancements in acoustic detection as a key factor in improving detection **(Figure 16).**

Overall, respondents indicated a need to invest in the advancement of detection techniques for a number of reasons **(Figure 17).** The leading expected benefits of technology breakthroughs were reported to be cost efficiency, expanded coverage, real time monitoring and increased data collection **(Figure 17)**. Additional benefits will arise through a more efficient way to integrate the varied data streams and a higher level of accuracy. Although less commonly mentioned, there are also some substantial, although perhaps more indirect, benefits expected. For example, investment in marine mammal monitoring techniques is expected to increase collaborations across institutions and industries, provide some level of reduction in the risk to health and safety of the people involved in marine mammal monitoring efforts, and generally support more sustainable ocean use **(Figure 17).**

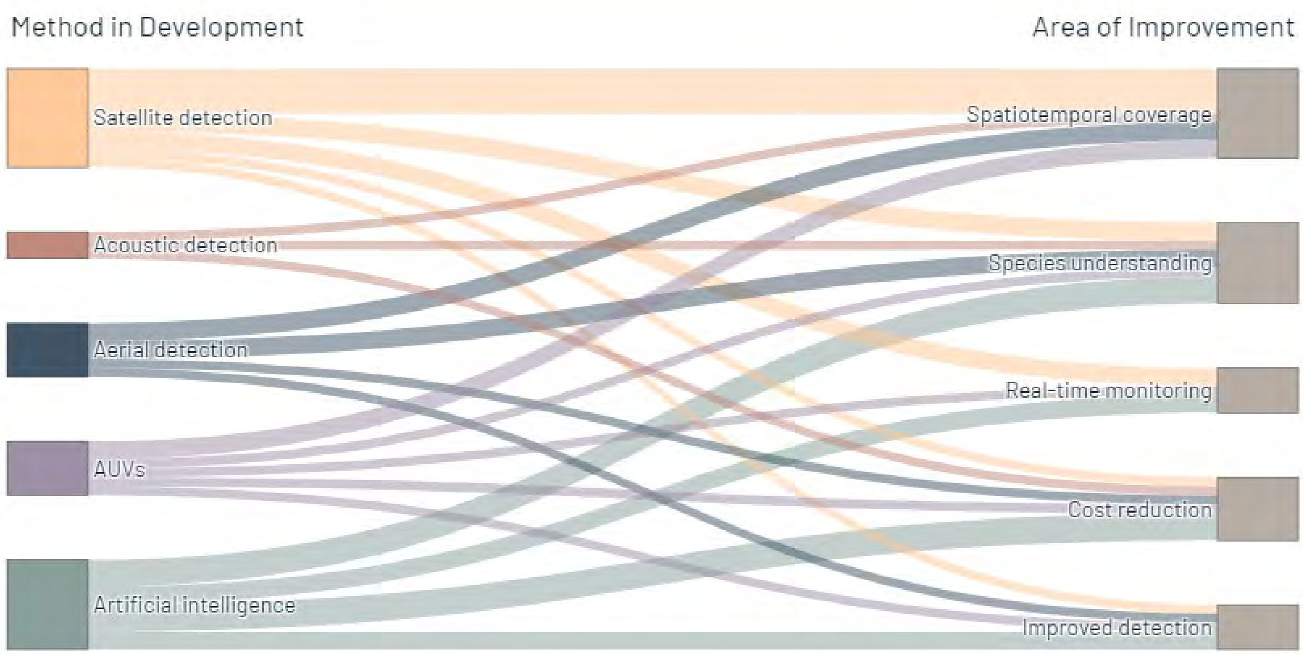


Figure 16. Long-term needs filled by emerging technology for marine mammal monitoring. The left side represents different methods in development, while the right side shows the areas of improvement these technologies aim to address in the long term. Lines connecting methods to improvements indicate how each technology contributes to advancing monitoring capabilities.

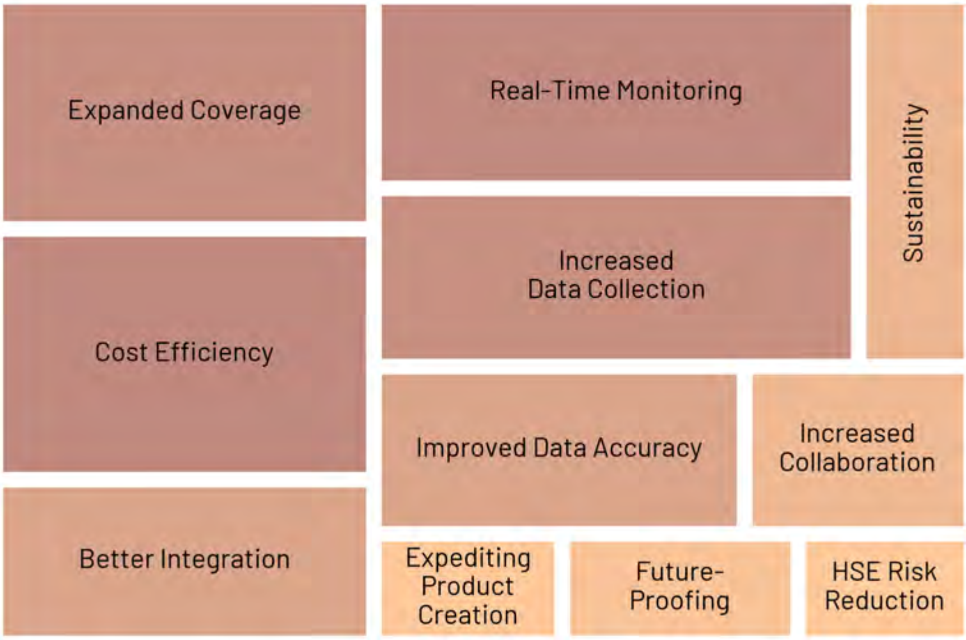


Figure 17. Expected benefits of breakthroughs in monitoring techniques over the next decade, with responses combined across near-term and long-term survey responses. Larger boxes indicate more frequently mentioned reasons.

Respondents clearly believe that improvements in AI and other processing advances to aid detection, classification, localisation and processing times could and should be pursued to improve marine mammal monitoring over the next decade. Likewise, a general interest was expressed in reducing costs and logistical barriers for use of monitoring technologies going forward.

Similarly to the predominance in the discussion of current technologies, the focal placement of acoustic detection techniques may reflect more the current usage of respondents, rather than a fully objective expert opinion. However, the inclusion of detection technologies that are only used in a limited way currently, such as distributed acoustic sensing, thermal methods, and satellite detection methods, highlight these technologies as key areas for potential improvement in marine mammal monitoring.

There is also a need to improve information of the health of marine mammals and the impacts of human activities upon them, which rated moderately for support for future development even though few respondents currently work in this area. This demonstrates an understanding among respondents with expertise in other areas of the value of this information.

Some inconsistencies do appear. For example, there was support for developing both real-time monitoring and eDNA techniques over the next decade, even though they were not considered to be under-utilised at the current time. Similarly, the desire to achieve a better understanding of species behaviour and improving detection rates and accuracy is not accompanied by an equal level of support for developing tagging technology, which is likely to be one avenue for achieving this. However, when interpreted in combination the value of these techniques does seem to be reflected in the survey responses, and improvements seem to be supported.

5.2 Workshop Horizon Scan Responses

A Marine Mammal Monitoring Innovation Workshop was held on 25 February 2025, bringing together stakeholders from academia, industry, conservation organisations, and government. A full breakdown of the event and its results is summarised in Section 6. The event featured interactive breakout sessions to discuss two key areas where the report sought further input for the horizon scan: the role of AI in marine mammal monitoring and priority areas for targeted investment.

5.2.1 The Role of AI in Marine Mammal Monitoring

AI has emerged as a dominant technology in both the near-term and long-term future of marine mammal monitoring, as highlighted in the horizon scan survey (**Figures 12** and **13**). However, AI encompasses a broad range of applications, from machine learning for automated detection to predictive modelling and advanced data analysis. To refine the focus of AI-driven innovation, workshop participants were asked to identify the most promising aspects, use cases, and developments that could significantly impact marine mammal monitoring. A full breakdown of topics and questions is **detailed in Section 6.5.2.**

AI was unanimously recognised as a transformative tool with high-potential applications in several key areas. Machine learning for automated species detection, predictive modelling, and bioacoustic analysis were identified as particularly impactful. Participants highlighted automated image recognition systems for UAV and satellite surveys as a potential innovation that could improve efficiency in species identification, behavioural analysis, and habitat mapping. Similarly, AI-based PAM classifiers were extensively discussed for their potential to enhance detection accuracy, reduce manual workload, and enable long-term data analysis.

Despite its potential, workshop attendees indicated that challenges remain in the standardisation of AI-generated data, algorithm transparency, and mitigating biases in AI training datasets. Participants emphasised the need for collaborative AI models trained on diverse global datasets to improve accuracy and reduce regional biases in species identification. Ensuring equitable access to AI-driven tools and fostering partnerships between research institutions, industry, and policymakers were also noted as important steps in advancing AI applications for marine mammal monitoring.

5.2.2 Priority Areas for Targeted Investment

Building on insights from the survey and horizon scan, participants discussed priority areas for investment to maximise impact in the short and long term. The consensus was that AI development and integration should be a top funding priority, particularly in automated image analysis, bioacoustics, and predictive modelling. AI-driven technologies were seen as critical for improving monitoring efficiency, reducing manual processing time, and enabling real-time decision-making in conservation efforts.

Another key investment area identified was the development of open-access data-sharing frameworks to standardise and integrate data from different monitoring technologies. Participants stressed the importance of cloud-based collaborative platforms, which would enhance real-time data access, improve interoperability, and support global research initiatives. Such platforms would allow multiple stakeholders including researchers, policymakers, and conservation groups to share and analyse data more effectively, further enabling collaborative decision-making.

In addition to AI, participants emphasised the need for funding initiatives that support multi-modal monitoring, advocating for the integration of AI, PAM, eDNA, and satellite tracking. This comprehensive approach would facilitate scalable monitoring programmes capable of detecting marine mammals across diverse habitats and conditions.

Finally, participants highlighted the necessity of long-term funding models, including multi-year grants and industry-supported investment programmes, to ensure that emerging technologies can be tested, validated, and operationalised at scale. They underscored that consistent and sustained investment is essential to drive innovation; however, this must also align with regulatory requirements. Therefore, regulations need to accommodate the integration of emerging technologies, adapt to scientific advancements, and even incentivise innovation to enhance monitoring effectiveness and conservation outcomes.

5.3 Leveraging Cross-Sector Innovations

Advancements in marine mammal monitoring can be significantly enhanced by innovations from other fields, including terrestrial wildlife research, aerospace, and artificial intelligence. Cross-sector collaboration drives innovation by enabling experts to refine existing tools, advance automation, and improve data accuracy. Increased collaboration was also identified as an expected benefit of technological breakthroughs. This section explores adjacent and cross-sector technologies with the potential to enhance or contribute to novel marine mammal monitoring methodologies.

Through an internet search, 39 companies were identified as developing wildlife monitoring technologies, many of which are already used in marine mammal research but could benefit from further innovation and scaling. The majority are headquartered in North America and Europe, with a smaller presence in Asia, Australia, and the Middle East. Many of these companies specialise in wildlife monitoring and technology development, designing solutions with broad applicability across various species, including birds, bats, and large terrestrial mammals.

Technologies include satellite tracking, bioacoustics, drone surveillance, AI-powered data analysis, and telemetry systems, all of which are widely used in marine environments but continue to evolve with advancements in automation, miniaturisation, and integration. These technologies also align with many of the near- and long-term emerging innovations expected to shape marine mammal monitoring over the next decade.

5.3.1 Industry Responses and Perspectives

From the 39 companies identified, eight responded to questions or participated in online interviews, providing direct insights into the potential applications, challenges, and future advancements of their technologies in marine mammal monitoring. These interviews aimed to explore how technologies from outside the field of marine mammal monitoring could be applied, assessing their adaptability and identifying key innovations. The discussions also highlighted challenges and limitations in integrating these technologies into marine mammal monitoring and mitigation.

A diverse range of technological solutions was examined, including satellite tracking and bio-logging (Argos, Max Planck Institute of Animal Behaviour), bioacoustics (Carbon Rewild), UAV-based monitoring (NextTech), VHF telemetry (Telenax, Wildlife Drones), and AI-driven species identification (WildTrack). Interview feedback emphasised that satellite tracking remains essential for large-scale monitoring, with MoveBank (Max Planck Institute) offering a global data-sharing framework that could be enhanced through expanded sensor integration and AI-driven analytics. Bioacoustic monitoring (Carbon Rewild) and AI-powered species identification (WildTrack) were identified as promising non-invasive solutions; however, challenges exist in data standardisation and integration with existing platforms. Similarly, UAV-based monitoring (NextTech) and VHF telemetry (Wildlife Drones, Telenax) offer valuable tracking options for semi-aquatic species; however, signal loss in saltwater for deep-diving marine mammals remains a major barrier to broader applications (Qureshi et al., 2016; Hays et al., 2007).

The interviews and survey results underscore the growing potential for multi-sensor integration, AI-driven analytics, and enhanced data-sharing platforms. This aligns with the findings from the horizon scan survey regarding the expected benefits of near- and long-term technological developments (**Figures 12, 14,** and **17**). Companies such as EarthRanger (US) and Wild Me (US) demonstrate how AI-powered analytics can improve large-scale monitoring efforts, integrating bioacoustic sensors, remote sensing, and machine learning to refine species detection and behavioural analysis.

Despite these advancements, several overarching challenges remain when applying these technologies to the marine environment, including environmental constraints (e.g., saltwater signal interference) and regulatory compliance.

6. Stakeholder workshop

6.1 Workshop Summary

The Marine Mammal Monitoring Innovation Workshop, held on 25th February 2025, brought together 188 SMEs and stakeholders from academia, industry, conservation organisations, and government agencies to explore emerging technologies, funding mechanisms, and collaborative approaches for enhancing marine mammal monitoring. The event featured expert presentations, interactive breakout sessions, and a plenary discussion to identify key technological advancements, challenges, and investment priorities in the field. The workshop was also formally endorsed as an official activity of the UN Ocean Decade recognising its contribution to advancing global efforts in marine science for sustainable development.

The workshop provided critical insights into the advancements and challenges in marine mammal monitoring, focusing on the integration of emerging technologies and funding strategies. The workshop was designed to validate findings from the stakeholder survey and horizon scan, ensuring that industry and academic expertise informed the final recommendations. The workshop focused on multiple technologies and evaluating their applications in marine conservation, species detection, and behavioural studies. Expert speakers highlighted innovations in AI-assisted marine mammal detection, real-time eDNA monitoring, and remote sensing methodologies, while breakout discussions examined lesser-represented technologies, funding challenges, and future prioritisation.

A major theme from the discussions was the increasing role of AI and automation in streamlining data collection and analysis, particularly in PAM, satellite imaging, and drone-based surveys. AI-driven systems were recognised for their potential to improve efficiency, reduce observer bias, and enhance real-time detection capabilities; however, participants highlighted the need for standardisation in AI algorithms and improved training datasets to ensure accuracy across different monitoring applications.

The integration of multi-modal monitoring technologies was another key takeaway, with discussions emphasising the need for greater synergy between acoustic, visual, and molecular (e.g. eDNA) methods. Multi-sensor approaches were seen as critical for enhancing detection reliability, addressing species-specific monitoring challenges, and improving large-scale data interpretation. Participants also stressed the importance of open-access data-sharing platforms, which could facilitate cross-sector collaboration and ensure long-term monitoring efforts remain accessible and scientifically robust.

Funding was a recurrent topic throughout the breakout sessions, with SMEs emphasising the need for sustained investment in technology development and long-term monitoring programs. Several funding mechanisms were discussed, including public-private partnerships, government-backed innovation grants, and industry-led initiatives that could support the scalability of emerging technologies. Regulatory frameworks, particularly under the MSFD and UK Marine Strategy, were highlighted as key drivers for ensuring that funding is allocated effectively to address monitoring gaps.

The workshop also underscored the importance of enhanced collaboration between industry, government agencies, and academia to accelerate technology adoption and implementation. Cross-sector engagement was identified as essential for aligning monitoring methodologies with regulatory needs, ensuring compliance with environmental policies, and addressing knowledge gaps in marine mammal behaviour, habitat use, and responses to anthropogenic stressors.

Overall, the workshop reaffirmed the need for a holistic, data-driven approach to marine mammal monitoring, where cutting-edge technologies, strategic funding, and collaborative frameworks work in tandem to support conservation efforts, mitigate human-induced risks, and improve long-term ecological assessments.

6.2 Introduction & Workshop Objectives

The Marine Mammal Monitoring Innovation Workshop brought together key stakeholders and SMEs to explore opportunities for advancing technologies, funding mechanisms, and interdisciplinary collaboration in marine mammal monitoring. The workshop provided a platform to evaluate current methodologies, identify emerging innovations, and discuss strategic investment priorities.

The workshop aimed to:

- Discuss the latest advancements in monitoring technologies, such as AI, PAM, satellite tracking, eDNA, and cloud-based data sharing.
- Identify key challenges and gaps in existing monitoring frameworks and propose innovative solutions.
- Explore funding strategies and investment priorities to support technological development and implementation.

The workshop was structured into SME presentations, interactive breakout discussions, and a plenary question and answer (Q&A) session to facilitate knowledge sharing and problem-solving.

6.3 Workshop Methods & Agenda

The workshop was divided into the following components:

1. Plenary Session & SME Presentations
   - Experts from academia and industry provided insights into cutting-edge monitoring technologies and their real-world applications. Key topics included:
2. Breakout Session 1: Technology Gaps & Funding
   - Participants discussed barriers to adopting underrepresented monitoring technologies (e.g., eDNA, satellite tracking, drone tagging, and cloud-based data sharing) and explored how to integrate these approaches more widely.
3. Breakout Session 2: AI & Investment Priorities
   - Stakeholders examined funding mechanisms for marine mammal monitoring, exploring how investment can drive innovation, ensure long-term sustainability, and maximise conservation impact.
4. Plenary Q&A

The workshop concluded with an open discussion and Q&A session, where participants reflected on the key insights, provided recommendations, and outlined the next steps for future collaboration.

6.4 Subject Matter Expert (SME) Presentations

The workshop featured a series of presentations showcasing recent developments in marine mammal monitoring technologies.

6.4.1 Session 1 Summary

Session one of the workshop featured presentations on cutting-edge technologies used in marine mammal monitoring. The session began with Nathan Geraldi (NatureMetrics) discussing the role of eDNA as a scalable and non-invasive tool for detecting marine mammals. His presentation showcased how eDNA sampling has been successfully used to identify 29 cetacean species, particularly in offshore wind farm impact assessments. While the method has proven effective, challenges remain in species-specific detection and its integration with acoustic and visual monitoring.

Doug Gillespie and James McCauley (PAMGuard, University of St Andrews) highlighted advancements in passive acoustic monitoring (PAM), particularly in fine-scale movement tracking of porpoises near tidal turbines. Long-term studies have demonstrated behavioural avoidance of active rotors, providing critical data for collision risk assessments. Additionally, McCauley discussed how AI-driven spectrogram analysis is being used to automate the detection of porpoise clicks and identify behavioural responses to static fishing nets, offering valuable insights for bycatch reduction strategies.

The role of AI-assisted remote sensing was presented by Rob Lee (Seiche), who emphasised its increasing application in real-time marine mammal detection for regulatory compliance. His talk outlined three levels of autonomy in monitoring systems augmented, semi-autonomous, and fully autonomous and demonstrated case studies using thermal imaging AI to mitigate vessel strikes. Daniel Toogood (Atlas Elektronik) then provided insights into satellite tracking and underwater acoustic modelling, showcasing how these technologies contribute to marine mammal movement studies and ship strike risk assessments.

Additional speakers covered a variety of high-tech solutions, including real-time AI-based processing for species identification (Prithvi Reddy, Thaum), high-definition aerial surveys (Laura Williamson, BioConsult SH/HiDef), and satellite-based marine mammal detection (Julika Voss, BioConsult SH/SPACEWHALE). New innovations in multi-sensor data collection, bioacoustics, cloud-based monitoring platforms, and low-cost passive acoustic monitoring arrays were also explored.

This session underscored the importance of integrating multiple technologies, such as AI, remote sensing, and eDNA, to enhance monitoring accuracy and scalability. While new methods are improving data collection efficiency, ongoing challenges in standardisation, funding, and technology adoption across sectors were noted as barriers to widespread implementation.

6.4.2 Session 2 Summary

Session two focused on international monitoring programs and policy-driven applications, with discussions on emerging tools and regulatory frameworks for marine mammal conservation. Genevieve Davis (NOAA Fisheries) introduced NOAA's North Atlantic PAM database, which provides an open-access platform for tracking species detections across different monitoring stations. She announced the launch of PAM 2.0, which will include expanded datasets and automated species classification tools to support better regulatory decision-making.

Emily Charry Tissier (Whale Seeker) presented an AI-assisted MMO support tool, which enhances human-based marine mammal observations through automated detection validation. This technology was developed to improve efficiency while maintaining high levels of accuracy in mitigation and impact assessment programs.

Kate Indeck (University of New Brunswick) presented findings on Canada's dynamic shipping lane regulations for North Atlantic right whales (NARW). She discussed how visual, acoustic (glider-based), and automated classification tools are being used to monitor shipping impacts on whale populations and inform speed restriction policies.

Ross Culloch (APEM Group) explored RGB cameras and event-based imaging for monitoring seals in tidal energy zones. He detailed laboratory-based signal-to-noise ratio (SNR) assessments, as well as field trials in rehabilitation settings. Future research will expand trials in Turkey to further validate the technology's effectiveness.

Further discussions focused on satellite-based monitoring (Penny Clarke, BAS), novel PAM techniques (Kerri Seger, Integral Consulting), and autonomous acoustic buoys for high-noise environments (Corentin Troussard, RTSYS). AI and automation were recurring themes, with Els Vermeulen (Mammal Research Institute - Whale Unit) discussing AI-driven photo-ID processing for southern right whales (SRW). She highlighted that existing AI algorithms struggle with SRW identification, requiring manual validation and further AI refinement.

In the final talks, Alexander Sutin (Stevens Institute of Technology) showcased advanced PAM localisation techniques, while Francois Gauthier (Devocean) introduced AI-driven ropeless fishing technologies aimed at reducing entanglement risks for marine mammals. The session concluded with presentations on multi-sensor mobile monitoring systems (Erin Falcone, MarEcoTel) and advancements in marine mammal tracking using AI-enhanced PAM algorithms (Pina Gruden, Pina Gruden s.p.).

6.4.3 Key Takeaways

Both sessions underscored the growing role of AI, automation, and data-sharing platforms in marine mammal monitoring. Participants emphasised the need for multi-modal monitoring frameworks that integrate bioacoustics, eDNA, satellite tracking, and drone-based surveys to provide comprehensive, high-resolution datasets. Funding and regulatory challenges remain a significant barrier to widespread adoption of these technologies. Researchers emphasised the importance of industry partnerships, long-term funding models, and international collaboration to drive innovation and support marine conservation goals.

6.5 Breakout Session Summaries

The two breakout sessions explored key themes related to technological innovation, funding strategies, and investment priorities for marine mammal monitoring. The discussions were structured around specific guiding questions to facilitate focused and actionable insights.

6.5.1 Breakout Session 1: Technology Gaps & Funding

Topic 1: This session aimed to identify opportunities for incorporating underrepresented technologies into marine mammal monitoring. While AI, PAM, and aerial detection methods were frequently mentioned in the horizon scan, eDNA, cloud-based data sharing, drone tagging, and satellite-based detection methods were identified as less widely adopted but potentially valuable technologies. This session asked the below question:

1. What opportunities exist for incorporating less-represented technologies into marine mammal monitoring?

Discussions highlighted several underrepresented technologies that could significantly enhance marine mammal monitoring if integrated more widely. Cloud tools and data sharing were seen as essential for improving data accessibility, collaboration, and interoperability between researchers, regulators, and industry. Participants emphasised the need for standardised platforms to facilitate real-time data sharing while addressing concerns around data privacy and security.

Drone tagging and sampling were recognised as promising but underdeveloped due to challenges in tag attachment, retrieval, and battery life. Advancements in AI-assisted drone detection and automated flight pathing were suggested as potential solutions to increase deployment efficiency and minimise human intervention. Satellite detection methods were seen as valuable for large-scale marine mammal movement tracking, but limitations in image resolution, cloud cover interference, and real-time applicability remain barriers. Participants suggested combining satellite data with acoustic and eDNA methods to improve accuracy.

eDNA monitoring was identified as an emerging tool with strong potential, particularly for detecting rare or cryptic species; however, its integration with other monitoring techniques, validation protocols, and standardisation for species-specific detection thresholds were seen as key challenges. Participants emphasised the need for greater investment in research to refine eDNA methodologies and to explore its use alongside PAM and visual surveys.

Topic 2: Developing and scaling new technologies—whether in AI, bioacoustics, eDNA, drone-based methods, or cloud data sharing—requires strategic funding. This session asked the below questions:

1. In your experience, what funding strategies work best to support the development of emerging technologies for this field?
2. Are there specific funding mechanisms or approaches that you think could drive progress?

Participants discussed various funding strategies to support the development and scaling of new monitoring technologies. Public-private partnerships were seen as crucial for ensuring long-term financial sustainability, particularly for AI and data-driven solutions that require continuous development and refinement. Government grants were highlighted as an essential funding source for foundational research, but participants noted that short-term grant cycles often limit long-term monitoring programs. Industry-backed initiatives, particularly from offshore renewable energy (ORE) and fisheries sectors, were identified as potential co-funding opportunities for monitoring projects tied to regulatory compliance.

Philanthropic funding and corporate social responsibility (CSR) programs were also discussed as alternative investment sources; however, participants stressed the importance of coordinated funding efforts that align research and industry needs, ensuring that technology development remains both scientifically rigorous and practically applicable.

Participants also highlighted the importance of challenge-based innovation funding and incubator programs to support early-stage research and accelerate the transition from concept to operational readiness.

Longer-term investment models were considered essential not only for technology development but also for supporting the broader infrastructure required to scale innovation such as data repositories, AI training libraries, and cloud-based platforms for real-time analytics. Several participants noted that government funding has a critical role to play in de-risking innovation for developers, helping to incentivise uptake of novel technologies in commercial settings.

There was a strong emphasis on interdisciplinary and cross-sector funding mechanisms that could bring together marine science, offshore energy, climate resilience, and policy development, enabling broader investment impact. Strategic collaboration between government, industry, and academia was viewed as vital for ensuring that funding supports real-world applications and is responsive to regulatory and policy priorities.

Funding to support capacity building and workforce development was also highlighted, ensuring that emerging tools such as drone-based monitoring, eDNA sampling, and AI-driven detection systems can be deployed effectively and responsibly. In addition, participants identified the need for investment in technology demonstration and validation projects to support regulatory acceptance and industry adoption.

Several discussions pointed to the importance of funding targeted toward closing critical data gaps, especially for data-deficient species or poorly monitored geographic regions, and for enabling open-source innovation through shared tools, code, and benchmark datasets. Support for shared access models—such as equipment leasing schemes—was also suggested as a practical way to lower barriers to technology use among smaller organisations.

Ultimately, participants agreed that funding must not only support innovation but also its integration into practice, helping to build a robust, collaborative, and policy-relevant monitoring ecosystem.

6.5.2 Breakout Session 2: AI & Investment Priorities

Topic 3: AI has emerged as the most frequently mentioned technology in both the near-term and long-term future of marine mammal monitoring, according to our horizon scan survey; however, AI is a broad field, covering a wide range of applications, from machine learning for automated detection to predictive modelling and advanced data analysis. This session asked the below questions:

1. What specific aspects of AI do you believe hold the most potential for marine mammal monitoring?
2. Are there particular use cases, methods, or innovations within AI that could make a significant impact?

AI was unanimously recognised as a transformative tool for marine mammal monitoring, with multiple high-potential applications. Participants identified machine learning for automated species detection, predictive modelling, and AI-driven bioacoustics analysis as some of the most promising areas.

Automated image recognition systems for UAV and satellite surveys were highlighted as a key innovation, allowing for more efficient species identification, behavioural analysis, and habitat mapping. AI-based PAM classifiers were also discussed, with participants emphasising their ability to improve detection accuracy, reduce manual workload, and analyse long-term datasets.

Participants noted that while AI has already made significant advancements, challenges remain in data standardisation, algorithm transparency, and reducing biases in AI training datasets. The need for collaborative AI models trained on diverse global datasets was emphasised to improve accuracy and reduce regional biases in species identification.

Topic 4: Throughout this project, insights gathered from the survey and horizon scan, have consistently emphasised the critical role of technological innovation in marine mammal monitoring. Building on these findings, the next step is to identify key priority areas for targeted funding, ensuring that investment is strategically directed towards high-impact developments. This session asked the below question:

1. What priority areas should target funding focus on and why?

The discussion focused on identifying priority areas for investment that would yield the greatest impact in the short and long term. Participants agreed that AI development and integration should be a top funding priority, particularly for automated image analysis, bioacoustics, and predictive modelling. Investments in open-access data-sharing frameworks were seen as essential for standardising and integrating data from different monitoring technologies. Cloud-based collaborative platforms were identified as a key area requiring funding, as they would enable real-time data access, improve interoperability, and support global research initiatives.

Participants also emphasised the importance of multi-modal monitoring, advocating for funding initiatives that support the integration of AI, PAM, eDNA, and satellite tracking. This would enable more comprehensive and scalable monitoring programs that can detect marine mammals across diverse habitats and conditions. Discussions highlighted the importance of miniaturising and commercialising monitoring technologies, as well as addressing gaps in AI training datasets to enhance automated detection capabilities. Finally, participants stressed the need for long-term funding models, including multi-year grants and industry-supported investment programs, to ensure that emerging technologies can be tested, validated, and operationalised at scale.

6.6 Workshop Insights

The workshop provided valuable insights into emerging marine mammal monitoring technologies, investment priorities, and collaboration strategies. Discussions highlighted the need for interdisciplinary partnerships, standardised data-sharing frameworks, and sustainable funding models to support long-term conservation and research efforts.

Key takeaways from the workshop emphasised the need to expand AI-driven monitoring capabilities across multiple modalities, leveraging advancements in machine learning, image recognition, and bioacoustics to enhance detection accuracy and efficiency. Participants highlighted the importance of integrating multi-modal monitoring technologies, such as PAM, eDNA, satellite tracking, and UAV-based surveys, to create more comprehensive and reliable marine mammal monitoring frameworks. Additionally, discussions underscored the necessity of developing long-term funding strategies to support ongoing technological advancements and infrastructure development, ensuring that innovations can be effectively scaled and implemented. Lastly, there was a strong consensus on the value of open-access data-sharing initiatives, which would facilitate greater collaboration among researchers, industry stakeholders, and policymakers, ultimately improving the accessibility and interoperability of marine mammal monitoring data.

The workshop concluded with a Q&A session, followed by closing remarks from the project team, encouraging continued collaboration to drive forward marine mammal monitoring innovation. The insights gathered from this workshop will contribute to ongoing discussions on marine mammal monitoring innovation and help shape future conservation and policy initiatives.

7. Report summary & conclusion

7.1 Summary

This report evaluated current marine mammal monitoring methodologies and identified key areas for innovation and improvements by integrating insights from a comprehensive literature review, a stakeholder survey of 133 participants, and a horizon scan of emerging technologies, including AI, PAM, eDNA, and satellite-based detection. Additionally, a workshop involving 188 SMEs from academia, industry, regulatory agencies, and conservation organisations provided critical input to guide future advancements. These efforts highlighted significant gaps in existing monitoring frameworks, particularly in health monitoring, and underscored the need for interdisciplinary collaboration and technological integration.

Key findings emphasise the necessity of incorporating automated, AI-enhanced methodologies alongside traditional approaches to enhance efficiency, reduce costs, and improve species detection accuracy. There is a clear call for targeted investment in emerging multi-modal detection techniques to improve detection rates across diverse conditions. Furthermore, the report stresses the importance of understanding marine animal health, behaviour, and the cues they produce to refine monitoring practices. By integrating advanced analytics with established techniques such as bioacoustics, aerial and satellite monitoring, and cloud-based data-sharing platforms, the UK can strengthen its marine mammal monitoring capabilities.

7.2 Conclusion

The project encourages enhancing marine mammal monitoring in the UK by leveraging innovative technologies and methods. It is clear from the information gathered that specific recommendations would need to be tailored to the geographic region and species of concern, given the unique combination of challenges these produce. However, some general recommendations can be made. Firstly, the findings detailed through the report demonstrate that existing monitoring technologies and methods require further integration of automated and AI-enhanced methodologies to increase efficiency, reduce costs, and improve species detection accuracy. This emphasis on AI-methodologies is not exclusive of the human-in-the-loop component, but rather requires they have a high level of domain-based expertise. Secondly, to address current gaps, targeted investment should prioritise efforts seeking to increase detection rates across any and all conditions, including expanding existing capabilities, but especially in developing emerging and multi-modal detection techniques. Finally, all monitoring efforts will be better supported through an improved understanding of marine animal health, behaviour and detection cue production rates and availability.

By implementing these general recommendations, through the lens of the more detailed information outlined in this report as it may relate to any specific objective, Defra and its partners can strengthen the UK's leadership in marine mammal conservation, environmental monitoring, and evidence-based policymaking, ensuring that marine biodiversity is protected in alignment with national and international environmental commitments.

8. References

Abadi, S. H., Wilcock, W. S. D., Tolstoy, M., Crone, T. J., & Carbotte, S. M. (2015). Sound source localization technique using a seismic streamer and its extension for whale localization during seismic surveys. *The Journal of the Acoustical Society of America, 138*(6). https://doi.org/10.1121/1.4937768

Abadi, S. H. T., Maya; Wilcock, William S.D. (2017). Estimating the location of baleen whale calls using dual streamers to support mitigation procedures in seismic reflection surveys. *PLOS ONE, 12*(2). https://doi.org/10.1371/journal.pone.0171115

Advisian Worley Group & Biodiversity Research Institute. (2023). Technology gaps for marine mammal monitoring in relation to offshore wind development: Final workshop report (Report No. 418160-42106 Agreement #165486-113). National Offshore Wind Research and Development Consortium.

Aerts, L., Jenkerson, M. R., Nechayuk, V. E., Gailey, G., Racca, R., Blanchard, A. L., Schwarz, L. K., Melton, H. R., Aerts, L., Jenkerson, M. R., Nechayuk, V. E., Gailey, G., Racca, R., Blanchard, A. L., Schwarz, L. K., & Melton, H. R. (2022). Seismic surveys near gray whale feeding areas off Sakhalin Island, Russia: assessing impact and mitigation effectiveness. *Environmental Monitoring and Assessment 2022 194:1, 194*(1). https://doi.org/10.1007/s10661-022-10016-9

Álvarez-González, M., Suarez-Bregua, P., Pierce, G. J., Saavedra, C., Álvarez-González, M., Suarez-Bregua, P., Pierce, G. J., & Saavedra, C. (2023). Unmanned Aerial Vehicles (UAVs) in Marine Mammal Research: A Review of Current Applications and Challenges. *Drones 2023, Vol. 7, Page 667, 7*(11). https://doi.org/10.3390/drones7110667

Amerson, A., & Dexheimer, D. (2024). Enhancing Marine Wildlife Observations: The Application of Tethered Balloon Systems and Advanced Imaging Sensors for Sustainable Marine Energy Development.

Angliss, R. P., Ferguson, M. C., Hall, P., Helker, V., Kennedy, A., & Sformo, T. (2018). Comparing manned to unmanned aerial surveys for cetacean monitoring in the Arctic: methods and operational results. *Journal of Unmanned Vehicle Systems, 6*(3). https://doi.org/10.1139/juvs-2018-0001

Aniceto, A. S., Biuw, M., Lindstrøm, U., Solbø, S. A., Broms, F., & Carroll, J. (2018). Monitoring marine mammals using unmanned aerial vehicles: quantifying detection certainty. *Ecosphere, 9*(3). https://doi.org/10.1002/ecs2.2122

APEM. (2024). *Arklow Bank Wind Park 2: Marine Mammal Mitigation Plan.*

Bakker, K. (2022). Smart Oceans: Artificial intelligence and marine protected area governance. *Earth System Governance, 13*. https://doi.org/10.1016/j.esg.2022.100141

Baldacci, A., Carron, M., & Portunato, N. (2005). Infrared detection of marine mammals. *NATO Undersea Research Centre Technical Report SR-443. NATO Undersea Research Centre, New York, New York, USA.*

Barkley, Y. M., Nosal, E.-M., & Oleson, E. M. (2021). Model-based localization of deep-diving cetaceans using towed line array acoustic data. *The Journal of the Acoustical Society of America, 150*(2). https://doi.org/10.1121/10.0005847

Benoit-Bird, K. J., Würsig, B., & Mfadden, C. J. (2004). Dusky dolphin (Lagenorhynchus obscurus) foraging in two different habitats: active acoustic detection of dolphins and their prey. *Marine Mammal Science, 20*(2), 215-231. https://doi.org/10.1111/j.1748-7692.2004.tb01152.x

Benoit-Bird, K. J., Dahood, A. D., & Würsig, B. (2009). Using active acoustics to compare lunar effects on predator–prey behavior in two marine mammal species. *Marine Ecology Progress Series, 395*, 119-135. https://doi.org/10.3354/meps07793

Bittle, M., & Duncan, A. (2013). A review of current marine mammal detection and classification algorithms for use in automated passive acoustic monitoring. In *Proceedings of Acoustics* (Vol. 2013, pp. 1-8). Victor Harbor, SA: Australian Acoustical Society.

Blackwell, B. F., Seamans, T. W., Washburn, B. E., & Cepek, J. D. (2006). Use of Infrared Technology in Wildlife Surveys. *Proceedings of the Vertebrate Pest Conference, 22*. https://doi.org/10.5070/v422110116

Bohara, K., Joshi, P., Acharya, K. P., & Ramena, G. (2024). Emerging technologies revolutionising disease diagnosis and monitoring in aquatic animal health. *Reviews in Aquaculture, 16*(2). https://doi.org/10.1111/raq.12870

Booth, C. G., Sinclair, R. R., & Harwood, J. (2020). Methods for monitoring for the population consequences of disturbance in marine mammals: a review. *Frontiers in Marine Science, 7*, 115. https://doi.org/10.3389/fmars.2020.00115

Boulent, J., Charry, B., Kennedy, M. M., Tissier, E., Fan, R., Marcoux, M., Watt, C. A., & Gagné-Turcotte, A. (2023). Scaling whale monitoring using deep learning: A human-in-the-loop solution for analyzing aerial datasets. *Frontiers in Marine Science, 10*. https://doi.org/10.3389/fmars.2023.1099479

Boyse, E., Robinson, K. P., Beger, M., Carr, I. M., Taylor, M., Valsecchi, E., & Goodman, S. J. (2024). Environmental DNA reveals fine-scale spatial and temporal variation of marine mammals and their prey species in a Scottish marine protected area. *Environmental DNA, 6*(4). https://doi.org/10.1002/edn3.587

Browning, E., Gibb, R., Glover-Kapfer, P., Jones, K. E., Browning, E., Gibb, R., Glover-Kapfer, P., & Jones, K. E. (2017). Passive acoustic monitoring in ecology and conservation. https://doi.org/10.25607/OBP-876

Burgess, E. A., Hunt, K. E., Kraus, S. D., & Rolland, R. M. (2016). Get the most out of blow hormones: validation of sampling materials, field storage and extraction techniques for whale respiratory vapour samples. *Conserv Physiol, 4*(1), cow024. https://doi.org/10.1093/conphys/cow024

Burt, M. L., Borchers, D. L., Jenkins, K. J., & Marques, T. A. (2014). Using mark-recapture distance sampling methods on line transect surveys. *Methods in Ecology and Evolution, 5*(11). https://doi.org/10.1111/2041-210X.12294

Caruso, F., Dong, L., Lin, M., Liu, M., Gong, Z., Xu, W., Alonge, G., & Li, S. (2020). Monitoring of a Nearshore Small Dolphin Species Using Passive Acoustic Platforms and Supervised Machine Learning Techniques. *Frontiers in Marine Science, 7*. https://doi.org/10.3389/fmars.2020.00267

Cauchy, P., Heywood, K. J., Merchant, N. D., Risch, D., Queste, B. Y., & Testor, P. (2023). Gliders for passive acoustic monitoring of the oceanic environment. *Frontiers in Remote Sensing, 4*. https://doi.org/10.3389/frsen.2023.1106533

Cazau, D., Nguyen Hong Duc, P., Druon, J. N., Matwins, S., & Fablet, R. (2021). Multimodal deep learning for cetacean distribution modeling of fin whales (Balaenoptera physalus) in the western Mediterranean Sea. *Machine Learning, 112*(6), 2003-2024. https://doi.org/10.1007/s10994-021-06029-z

Christiansen, F., Dujon, A. M., Sprogis, K. R., Arnould, J. P. Y., & Bejder, L. (2016). Noninvasive unmanned aerial vehicle provides estimates of the energetic cost of reproduction in humpback whales. *Ecosphere, 7*(10). https://doi.org/10.1002/ecs2.1468

Cise, A. M. V., Switzer, A. D., Apprill, A., Champagne, C. D., Chittaro, P. M., Dudek, N. K., Gavery, M. R., Hancock-Hanser, B. L., Harmon, A. C., Jaffe, A. L., Kellar, N. M., Miller, C. A., Morin, P. A., Nelms, S. E., Robertson, K. M., Schultz, I. R., Timmins-Schiffman, E., Unal, E., & Parsons, K. M. (2024). Best practices for collecting and preserving marine mammal biological samples in the 'omics era. *Marine Mammal Science, 40*(4). https://doi.org/10.1111/mms.13148

Collí-Dulá, R. C., & Ruiz-Hernández, I. M. (2022). Applications of Omics Approaches to Decipher the Impact of Contaminants in Dolphins. In *Marine Mammals*. doi: 10.5772/intechopen.102424

Compton, R., Goodwin, L., Handy, R., & Abbott, V. (2008). A critical examination of worldwide guidelines for minimising the disturbance to marine mammals during seismic surveys. *Marine Policy, 32*(3). https://doi.org/10.1016/j.marpol.2007.05.005

Copping, A. E., & Grear, M. E. (2018). Applying a simple model for estimating the likelihood of collision of marine mammals with tidal turbines. *International Marine Energy Journal*, *1*(1 (Aug)). https://doi.org/10.36688/imej.1.27-33

Courbis, S., Williams, K., Stepanuk, J., Etter, H., McManus, M., Campoblanco, F., & Pacini, A. (2024). Technology Gaps for Monitoring Birds and Marine Mammals at Offshore Wind Facilities. *Marine Technology Society Journal*, *58*(3). https://doi.org/10.4031/MTSJ.58.3.1

Cubaynes, H. C., Fretwell, P. T., Bamford, C., Gerrish, L., & Jackson, J. A. (2019). Whales from space: Four mysticete species described using new VHR satellite imagery. *Marine Mammal Science*, *35*(2). https://doi.org/10.1111/mms.12544

Davis, K. L., Silverman, E. D., Sussman, A. L., Wilson, R. R., & Zipkin, E. F. (2022). Errors in aerial survey count data: Identifying pitfalls and solutions. *Ecology and Evolution*, *12*(3). https://doi.org/10.1002/ece3.8733

Davis, R., Baumgartner, M., Comeau, A., Cunningham, D., Davies, K., Furlong, A., Johnson, H., L'Orsa, S., Ross, T., Taggart, C., & Whoriskey, F. (2016). *Tracking whales on the Scotian Shelf using passive acoustic monitoring on ocean gliders* IEEE. https://ieeexplore.ieee.org/abstract/document/7761461

Degollada, E., Amigó, N., O'Callaghan, S. A., Varola, M., Ruggero, K., Tort, B., Degollada, E., Amigó, N., O'Callaghan, S. A., Varola, M., Ruggero, K., & Tort, B. (2023). A Novel Technique for Photo-Identification of the Fin Whale, Balaenoptera physalus, as Determined by Drone Aerial Images. *Drones 2023, Vol. 7, Page 220*, *7*(3). https://doi.org/10.3390/drones7030220

Delplanque, A., Théau, J., Foucher, S., Serati, G., Durand, S., & Lejeune, P. (2024). Wildlife detection, counting and survey using satellite imagery: are we there yet? *GIScience & Remote Sensing*, *61*(1). https://doi.org/10.1080/15481603.2024.2348863

Department for Environment, F. R. A. (2022). *Marine Strategy Part Two: UK updated monitoring programmes* (ISBN 978-1-5286-3716-9, CP 748). UK Government.

Department for Environment, F. R. A. (2025). *Marine Strategy Part Three: 2025 UK Programme of Measures*. UK Government.

Ditria, E. M., Buelow, C. A., Gonzalez-Rivero, M., & Connolly, R. M. (2022). Artificial intelligence and automated monitoring for assisting conservation of marine ecosystems: A perspective. *Frontiers in Marine Science*, *9*, 918104. https://doi.org/10.3389/fmars.2022.918104

Endangered Species Act of 1973, 16 U.S.C. §§ 1531–1544 (1973). U.S. Fish and Wildlife Service. https://www.fws.gov/law/endangered-species-act

Evans, P. G. H., & Hammond, P. S. (2004). Monitoring cetaceans in European waters. *Mammal Review*, *34*(1-2), 131-156. https://doi.org/10.1046/j.0305-1838.2003.00027.x

Ferguson, M. C., Angliss, R. P., Kennedy, A., Lynch, B., Willoughby, A., Helker, V., Brower, A. A., & Clarke, J. T. (2018). Performance of manned and unmanned aerial surveys to collect visual data and imagery for estimating arctic cetacean density and associated uncertainty1. *Journal of Unmanned Vehicle Systems*, *6*(3). https://doi.org/10.1139/juvs-2018-0002

Fiori, L., Doshi, A., Martinez, E., Orams, M. B., & Bollard-Breen, B. (2017). The Use of Unmanned Aerial Systems in Marine Mammal Research. *Remote Sensing*, *9*(6), 543. https://doi.org/10.3390/rs9060543

Fisheries Act (R.S.C., 1985, c. F-14), (1985). https://laws-lois.justice.gc.ca/eng/acts/f-14/

Fleishman, E., Cholewiak, D., Gillespie, D., Helble, T., Klinck, H., Nosal, E. M., & Roch, M. A. (2023). Ecological inferences about marine mammals from passive acoustic data. *Biological Reviews*, *98*(5), 1633-1647. https://doi.org/10.1111/brv.12969

Frasier, K. E. (2021). A machine learning pipeline for classification of cetacean echolocation clicks in large underwater acoustic datasets. *PLOS Computational Biology*, *17*(12). https://doi.org/10.1371/journal.pcbi.1009613

Fregosi, S., Klinck, H., Horning, M., Costa, D. P., Mann, D., Sexton, K., ... & Southall, B. L. (2016). An animal-borne active acoustic tag for minimally invasive behavioral response studies on marine mammals. *Animal Biotelemetry*, 4, 1-15. https://doi.org/10.1186/s40317-016-0101-z

Fregosi, S. (2020). *Applications of Slow-moving Autonomous Platforms for Passive Acoustic Monitoring and Density Estimation of Marine Mammals* Oregon State University].

Fretwell, P. T., Cubaynes, H. C., & Shpak, O. V. (2023). Satellite image survey of beluga whales in the southern Kara Sea. *Marine Mammal Science*, *39*(4). https://doi.org/10.1111/mms.13044

Frouin-Mouy, H., Rountree, R., Juanes, F., Aguzzi, J., & De Leo, F. C. (2024). Deep-sea cabled video-observatory provides insights into the behavior at depth of sub-adult male northern elephant seals, Mirounga angustirostris. *PLOS ONE*, *19*(9), e0308461. https://doi.org/10.1371/journal.pone.0308461

Gassen, D., Yap, Z., Jacob, J. D., Bruck, J., Damiano, S., & Gunnars, T. (2024). Development and Flight Testing of a Passive Collection Uncrewed Aircraft System for Dolphin Health Assessment. In *AIAA AVIATION FORUM AND ASCEND 2024* (p. 3570). https://doi.org/10.2514/6.2024-3570

Gervaise, C., Simard, Y., Aulanier, F., & Roy, N. (2021). Optimizing passive acoustic systems for marine mammal detection and localization: Application to real-time monitoring north Atlantic right whales in Gulf of St. Lawrence. *Applied Acoustics*, *178*. https://doi.org/10.1016/j.apacoust.2021.107949

Gibb, R., Browning, E., Glover-Kapfer, P., & Jones, K. E. (2019). Emerging opportunities and challenges for passive acoustics in ecological assessment and monitoring. *Methods in Ecology and Evolution*, *10*(2). https://doi.org/10.1111/2041-210X.13101

Gillespie, D., Hastie, G., Montabaranom, J., Longden, E., Rapson, K., Holoborodko, A., & Sparling, C. (2023). Automated Detection and Tracking of Marine Mammals in the Vicinity of Tidal Turbines Using Multibeam Sonar. *Journal of Marine Science and Engineering*, *11*(11), 2095. https://doi.org/10.3390/jmse11112095

Gillespie, D., Mellinger, D. K., Gordon, J., McLaren, D., Redmond, P., McHugh, R., Trinder, P., Deng, X. Y., & Thode, A. (2009). PAMGUARD: Semiautomated, open source software for real-time acoustic detection and localization of cetaceans. *The Journal of the Acoustical Society of America*, *125*(4_Supplement). https://doi.org/10.1121/1.4808713

Gillespie, D., Oswald, M., Hastie, G., & Sparling, C. (2022). Marine mammal HiCUP: A high current underwater platform for the long-term monitoring of fine-scale marine mammal behavior around tidal turbines. *Frontiers in Marine Science*, *9*, 850446. https://doi.org/10.3389/fmars.2022.850446

Gooday, O. J., Key, N., Goldstien, S., & Zawar-Reza, P. (2018). An assessment of thermal-image acquisition with an unmanned aerial vehicle (UAV) for direct counts of coastal marine mammals ashore. *Journal of Unmanned Vehicle Systems*, *6*(2), 100-108. https://doi.org/10.1139/juvs-2016-0029

Gray, P. C., Bierlich, K. C., Mantell, S. A., Friedlaender, A. S., Goldbogen, J. A., & Johnston, D. W. (2019). Drones and convolutional neural networks facilitate automated and accurate cetacean species identification and photogrammetry. *Methods in Ecology and Evolution*, *10*(9). https://doi.org/10.1111/2041-210X.13246

Green, K. M., Virdee, M. K., Cubaynes, H. C., Aviles-Rivero, A. I., Fretwell, P. T., Gray, P. C., Johnston, D. W., Schönlieb, C.-B., Torres, L. G., & Jackson, J. A. (2023). Gray whale detection in satellite imagery using deep learning. *Remote Sensing in Ecology and Conservation, 9*(6). https://doi.org/10.1002/rse2.352

Guazzo, R. A., Helble, T. A., D'Spain, G. L., Weller, D. W., Wiggins, S. M., & Hildebrand, J. A. (2017). Migratory behavior of eastern North Pacific gray whales tracked using a hydrophone array. *PLOS ONE, 12*(10). https://doi.org/10.1371/journal.pone.0185585

Guirado, E., Tabik, S., Rivas, M. L., Alcaraz-Segura, D., Herrera, F., Guirado, E., Tabik, S., Rivas, M. L., Alcaraz-Segura, D., & Herrera, F. (2019). Whale counting in satellite and aerial images with deep learning. *Scientific Reports 2019 9:1, 9*(1). https://doi.org/10.1038/s41598-019-50795-9

Harris, D., Chudzińska, M., Jacobson, E., Brown, A., Burt, L., Macleod, K.,, & Marques, T. A., Marshall, L., Oedekoven, C.S., ScoM-Hayward, L.A.S., Thomas, L. (2024). *Methodology for Combining Digital Aerial Survey Data and Passive Acoustic Baseline Data.*

Harwood, L. A., & Joynt, A. (2009). *Factors Influencing the Effectiveness of Marine Mammal Observers on Seismic Vessels, with Examples from the Canadian Beaufort Sea* (DFO Can. Sci. Advis. Sec. Res. Doc. 2009/048). Fisheries and Oceans Canada.

Helal, K. M., Fragasso, J., & Moro, L. (2024). Effectiveness of ocean gliders in monitoring ocean acoustics and anthropogenic noise from ships: A systematic review. *Ocean Engineering, 295.* https://doi.org/10.1016/j.oceaneng.2024.116993

Helble, T. A., Ierley, G. R., D'Spain, G. L., & Martin, S. W. (2015). Automated acoustic localization and call association for vocalizing humpback whales on the Navy's Pacific Missile Range Facility. *The Journal of the Acoustical Society of America, 137*(1). https://doi.org/10.1121/1.4904505

Hodgson, A. J., Kelly, N., & Peel, D. (2023). Drone images afford more detections of marine wildlife than real-time observers during simultaneous large-scale surveys. *PeerJ, 11, e16186.* https://doi.org/10.7717/peerj.16186

Hodul, M., Knudby, A., McKenna, B., James, A., Mayo, C., Brown, M., Durette-Morin, D., & Bird, S. (2023). Individual North Atlantic right whales identified from space. *Marine Mammal Science, 39*(1). https://doi.org/10.1111/mms.12971

Horne, N., Culloch, R. M., Schmitt, P., Lieber, L., Wilson, B., Dale, A. C., Houghton, J. D. R., & Kregting, L. T. (2021). Collision risk modelling for tidal energy devices: A flexible simulation-based approach. *Journal of Environmental Management, 278.* https://doi.org/10.1016/j.jenvman.2020.111484

Horton, T. W., Oline, A., Hauser, N., Khan, T. M., Laute, A., Stoller, A., Tison, K., & Zawar-Reza, P. (2017). Thermal Imaging and Biometrical Thermography of Humpback Whales. *Frontiers in Marine Science, 4.* https://doi.org/10.3389/fmars.2017.00424

Houegnigan, L., Merino, E. R., Vermeulen, E., Block, J., Safari, P., Moreno-Noguer, F., & Nadeu, C. (2022). Wildlife and Marine Mammal Spatial Observatory: Observation and automated detection of Southern Right Whales in multispectral satellite imagery. *bioRxiv*, 2022.2001. 2020.477141. https://doi.org/10.1101/2022.01.20.477141

Howe, B. M., Miksis-Olds, J., Rehm, E., Sagen, H., Worcester, P. F., & Haralabus, G. (2019). Observing the Oceans Acoustically. *Frontiers in Marine Science, 6.* https://doi.org/10.3389/fmars.2019.00426

Juhel, J. B., Marques, V., Polanco Fernandez, A., Borrero-Perez, G. H., Mutis Martinezguerra, M., Valentini, A., Dejean, T., Manel, S., Loiseau, N., Velez, L., Hocde, R., Letessier, T. B., Richards, E., Hadjadj, F., Bessudo, S., Ladino, F., Albouy, C., Mouillot, D., & Pellissier, L. (2021). Detection of the elusive Dwarf sperm whale (Kogia sima) using environmental DNA at Malpelo island (Eastern Pacific, Colombia). *Ecol Evol, 11*(7), 2956-2962. https://doi.org/10.1002/ece3.7057

Kapoor, S., Kumar, M., & Kaushal, M. (2023). Deep learning based whale detection from satellite imagery. *Sustainable Computing: Informatics and Systems, 38*. https://doi.org/10.1016/j.suscom.2023.100858

Kaschner, K., Quick, N. J., Jewell, R., Williams, R., & Harris, C. M. (2012). Global coverage of cetacean line-transect surveys: status quo, data gaps and future challenges. *PLOS ONE*, *7*(9), e44075. https://doi.org/10.1371/journal.pone.0044075

Katona, Z., Ziabari, S. S. M., & Nejadasl, F. K. (2024). MARINE: A Computer Vision Model for Detecting Rare Predator-Prey Interactions in Animal Videos. *arXiv preprint*. https://doi.org/10.48550/arXiv.2407.18289

Kemper, G., Weidauer, A., & Coppack, T. (2016). Monitoring seabirds and marine mammals by georeferenced aerial photography. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *41*, 689-694. https://doi.org/10.5194/isprs-archives-XLI-B8-689-2016

Khan, C. B., Goetz, K. T., Cubaynes, H. C., Robinson, C., Murnane, E., Aldrich, T., Sackett, M., Clarke, P. J., Larue, M. A., White, T., Leonard, K., Ortiz, A., & Lavista Ferres, J. M. (2023). A Biologist's Guide to the Galaxy: Leveraging Artificial Intelligence and Very High-Resolution Satellite Imagery to Monitor Marine Mammals from Space. *Journal of Marine Science and Engineering*, *11*(3), 595. https://doi.org/10.3390/jmse11030595

Kinzey, D., Olson, P., & Gerrodette, T. (2000). *Marine mammal data collection procedures on research ship line-transect surveys by the Southwest Fisheries Science Center.* (LJ-00-08, 1-31). S. A. R. NOAA.

Klinck, H., Mellinger, D. K., Klinck, K., Bogue, N. M., Luby, J. C., Jump, W. A., Shilling, G. B., Litchendorf, T., Wood, A. S., Schorr, G. S., & Baird, R. W. (2012). Near-Real-Time Acoustic Monitoring of Beaked Whales and Other Cetaceans Using a Seaglider™. *PLOS ONE*, *7*(5), e36128. https://doi.org/10.1371/journal.pone.0036128

Kowarski, K. A., Gaudet, B. J., Cole, A. J., Maxner, E. E., Turner, S. P., Martin, S. B., Johnson, H. D., & Moloney, J. E. (2020). Near real-time marine mammal monitoring from gliders: Practical challenges, system development, and management implications. *The Journal of the Acoustical Society of America*, *148*(3), 1215-1230. https://doi.org/10.1121/10.0001811

Kowarski, K. A., & Moors-Murphy, H. (2021). A review of big data analysis methods for baleen whale passive acoustic monitoring. *Marine Mammal Science*, *37*(2), 652-673. https://doi.org/10.1111/mms.12758

Lathlean, J., & Seuront, L. (2014). Infrared thermography in marine ecology: methods, previous applications and future challenges. *Marine Ecology Progress Series*, *514*, 263-277. https://doi.org/10.3354/meps10995

LeCun, Y., Bengio, Y., & Hinton, G. (2015). Deep learning. *nature*, *521*(7553), 436-444. https://doi.org/10.1038/nature14539

Lerczak, J. A., & Hobbs, R. C. (1998). Calculating Sighting Distances from Angular Readings During Shipboard, Aerial, and Shore-based Marine Mammal Surveys. *Marine Mammal Science*, *14*(3). https://doi.org/10.1111/j.1748-7692.1998.tb00745.x

Licciardi, A., & Carbone, D. (2024). WhaleNet: a Novel Deep Learning Architecture for Marine Mammals Vocalizations on Watkins Marine Mammal Sound Database. *IEEE Access*. doi: 10.1109/ACCESS.2024.3482117

Lonati, G. L., Hynes, N., Klymentieva, H., Warren, A., Zitterbart, D., Richter, S., Moore, M. J., & Davies, K. T. A. (2025). Drone-based infrared thermography to measure the intranasal temperature of baleen whales. *International Journal of Remote Sensing*, *46*(1). https://doi.org/10.1080/01431161.2024.2399326

Lü, Z., Shi, Y., Lü, L., Han, D., Wang, Z., & Yu, F. (2024). Dual-Feature Fusion Learning: An Acoustic Signal Recognition Method for Marine Mammals. *Remote Sensing*, *16*(20), 3823. https://doi.org/10.3390/rs16203823

Luczkovich, J. J., Sprague, M. W., Krahforst, C. S., Corbett, D. R., & Walsh, J. P. (2012). Passive acoustics monitoring as part of integrated ocean observing systems. *The Journal of the Acoustical Society of America*, *132*(3_Supplement).https://doi.org/10.1121/1.4755027

Macaulay, J., Gordon, J., Gillespie, D., Malinka, C., & Northridge, S. (2017). Passive acoustic methods for fine-scale tracking of harbour porpoises in tidal rapids. *The Journal of the Acoustical Society of America*, *141*(2), 1120-1132. https://doi.org/10.1121/1.4976077

Macaulay, J., Kingston, A., Coram, A., Oswald, M., Swift, R., Gillespie, D., & Northridge, S. (2022). Passive acoustic tracking of the three-dimensional movements and acoustic behaviour of toothed whales in close proximity to static nets. *Methods in Ecology and Evolution*, *13*(6), 1250-1264. https://doi.org/10.1111/2041-210x.13828

Macrander, A. M., Brzuzy, L., Raghukumar, K., Preziosi, D., & Jones, C. (2021). Convergence of emerging technologies: Development of a risk-based paradigm for marine mammal monitoring for offshore wind energy operations. *Integrated Environmental Assessment and Management*, *18*(4), 939-949. https://doi.org/10.1002/ieam.4532

Malinka, C., Gillespie, D., Macaulay, J., Joy, R., & Sparling, C. (2018). First in situ passive acoustic monitoring for marine mammals during operation of a tidal turbine in Ramsey Sound, Wales. *Marine Ecology Progress Series*, *590*, 247-266. https://doi.org/10.3354/meps12467

Mancia, A. (2018). New Technologies for Monitoring Marine Mammal Health. *Marine Mammal Ecotoxicology*. https://doi.org/10.1016/B978-0-12-812144-3.00011-5

Mandal, A., Ghosh, A. R., Mandal, A., & Ghosh, A. R. (2023). AI-driven surveillance of the health and disease status of ocean organisms: a review. *Aquaculture International 2023 32:1*, *32*(1). https://doi.org/10.1007/s10499-023-01192-7

Marine Mammal Protection Act of 1972, 16 U.S.C. §§ 1361–1423h (1972). National Oceanic and Atmospheric Administration. https://www.fisheries.noaa.gov/topic/laws-policies#marine-mammal-protection-act

Marine Works (Environmental Impact Assessment) Regulations 2007, SI 2007 No. 1518. UK Government. https://www.legislation.gov.uk/uksi/2007/1518/contents/made

Marotte, E., Wright, A. J., Breeze, H., Wingfield, J., Matthews, L. P., Risch, D., Merchant, N. D., Barclay, D., Evers, C., Lawson, J., Lesage, V., Moors-Murphy, H., Nolet, V., & Theriault, J. A. (2022). Recommended metrics for quantifying underwater noise impacts on North Atlantic right whales. *Marine Pollution Bulletin*, *175*, 113361. https://doi.org/10.1016/j.marpolbul.2022.113361

Marques, T. A., Thomas, L., Martin, S. W., Mellinger, D. K., Ward, J. A., Moretti, D. J., Harris, D., & Tyack, P. L. (2013). Estimating animal population density using passive acoustics. *Biological Reviews*, *88*(2). https://doi.org/10.1111/brv.12001

Mate, B., Mesecar, R., & Lagerquist, B. (2007). The evolution of satellite-monitored radio tags for large whales: One laboratory's experience. *Deep Sea Research Part II: Topical Studies in Oceanography*, *54*(3-4). https://doi.org/10.1016/j.dsr2.2006.11.021

Mattmüller, R. M., Thomisch, K., Van Opzeeland, I., Laidre, K. L., & Simon, M. (2022). Passive acoustic monitoring reveals year-round marine mammal community composition off Tasiilaq, Southeast Greenland. *The Journal of the Acoustical Society of America*, *151*(2). https://doi.org/10.1121/10.0009429

Mccafferty, D. J. (2007). The value of infrared thermography for research on mammals: previous applications and future directions. *Mammal Review*, *37*(3), 207-223. https://doi.org/10.1111/j.1365-2907.2007.00111.x

Michel, M., Guichard, B., Béesau, J., & Samaran, F. (2024). Passive acoustic monitoring for assessing marine mammals population in European waters: Workshop conclusions and perspectives. *Marine Policy*, *160*. https://doi.org/10.1016/j.marpol.2023.105983

Mills, E. M. M., Piwetz, S., & Orbach, D. N. (2024). Behavioral hotspots of bottlenose dolphins in industrialized ship channels. *Frontiers in Marine Science, 11.* https://doi.org/10.3389/fmars.2024.1334252

Napier, T., Ahn, E., Allen-Ankins, S., Schwarzkopf, L., & Lee, I. (2024). Advancements in preprocessing, detection and classification techniques for ecoacoustic data: A comprehensive review for large-scale Passive Acoustic Monitoring. *Expert Systems with Applications, 252.* https://doi.org/10.1016/j.eswa.2024.124220

National Academies of Sciences, E., and Medicine. (2017). *Approaches to Understanding the Cumulative Effects of Stressors on Marine Mammals.* The National Academies Press. https://doi.org/https://doi.org/10.17226/23479

National Environmental Policy Act of 1969, 42 U.S.C. §§ 4321-4370h (1969).

National Marine Fisheries Service. (2025). *50 CFR § 224.105 - Speed restrictions to protect North Atlantic right whales.* U.S. Government Publishing Office. https://www.ecfr.gov/current/title-50/chapter-II/subchapter-C/part-224/section-224.105

Nelms, S. E., Alfaro-Shigueto, J., Arnould, J. P., Avila, I. C., Nash, S. B., Campbell, E., Carter, M. I., Collins, T., Currey, R. J., & Domit, C. (2021). Marine mammal conservation: over the horizon. *Endangered Species Research, 44*, 291-325. https://doi.org/10.3354/esr01115

Norris, J., Evans, W., Sparks, T., & Benson, R. (1995). The use of passive towed arrays for surveying marine mammals. *The Journal of the Acoustical Society of America, 97*(5_Supplement). https://doi.org/10.1121/1.412715

Norris, T. F., Dunleavy, K. J., Yack, T. M., & Ferguson, E. L. (2017). Estimation of minke whale abundance from an acoustic line transect survey of the Mariana Islands. *Marine Mammal Science, 33*(2). https://doi.org/10.1111/mms.12397

Nosal, E.-M. (2013). Methods for tracking multiple marine mammals with wide-baseline passive acoustic arrays. *The Journal of the Acoustical Society of America, 134*(3). https://doi.org/10.1121/1.4816549

Nowacek, D. P. B., K.; Donovan, G.; Gailey, G.; Racca, R.; Reeves, R. R.; Vedenev A. I.; Weller D. W.; Southall, B. L. . (2013). Responsible Practices for Minimizing and Monitoring Environmental Impacts of Marine Seismic Surveys with an Emphasis on Marine Mammals. *Aquatic Mammals, 39*(4), 356-377. https://doi.org/10.1578/am.39.4.2013.356

Ollier, C. (2024). *Cetacean population monitoring: the merits and challenges of combining acoustic and visual data* La Rochelle Université].

Onoufriou, J., Russell, D. J. F., Thompson, D., Moss, S. E., & Hastie, G. D. (2021). Quantifying the effects of tidal turbine array operations on the distribution of marine mammals: Implications for collision risk. *Renewable Energy, 180.* https://doi.org/10.1016/j.renene.2021.08.052

Palagyi, T., Rice, A. N., & Palmquist, K. (2024). Use of Passive Acoustic Monitoring to Track Marine Mammals at Offshore Windfarm Sites. *International Oil Spill Conference Proceedings, 2024*(1). https://doi.org/10.7901/2169-3358-2024.1.329

Palka, D. (2000). *Abundance of the Gulf of Maine/Bay of Fundy Harbor Porpoise Based on Shipboard and Aerial Surveys during 1999* (Northeast Fisheries Science Center Reference Document 00-07). N. F. S. C. National Marine Fisheries Service.

Palomino-González, A., Kovacs, K. M., Lydersen, C., Ims, R. A., & Lowther, A. D. (2021). Drones and marine mammals in Svalbard, Norway. *Marine Mammal Science, 37*(4), 1212-1229. https://doi.org/10.1111/mms.12802

Parsons, E. C. M., Dolman, S. J., Jasny, M., Rose, N. A., Simmonds, M. P., & Wright, A. J. (2009). A critique of the UK's JNCC seismic survey guidelines for minimising acoustic disturbance to marine mammals: Best practise? *Marine Pollution Bulletin, 58*(5). https://doi.org/10.1016/j.marpolbul.2009.02.024

Pierpoint, C., Oliver, E., Scala, L., & Hedgeland, D. (2021). An acoustic survey of beaked whale distribution at São Tomé and Príncipe, Gulf of Guinea, using an unmanned surface vessel. *African Journal of Marine Science, 43*(4). https://doi.org/10.2989/1814232X.2021.1982769

Piwetz, S., Gailey, G., Munger, L., Lammers, M. O., Jefferson, T. A., & Würsig, B. (2018). Theodolite tracking in marine mammal research: From Roger Payne to the present. *Aquatic Mammals*, 44(6), 683. doi: 10.1578/AM.44.6.2018.683

Potter, J. R., Thillet, M., Douglas, C., Chitre, M. A., Doborzynski, Z., & Seekings, P. J. (2007). Visual and Passive Acoustic Marine Mammal Observations and High-Frequency Seismic Source Characteristics Recorded During a Seismic Survey. *IEEE Journal of Oceanic Engineering, 32*(2), 469-483. https://doi.org/10.1109/joe.2006.880427

Poupard, M. F., M., Schluter; J., Marxer, R.; Giraudet, P.; Barchasz, V.; Gies, V.; Pavan, G.; Glotin, H. (2020). *Real-time passive acoustic 3D tracking of deep diving cetacean by small non-uniform mobile surface antenna* In ICASSP 2019-2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP) doi: 10.1109/ICASSP.2019.8683883

Premus, V. E., Abbot, P. A., Kmelnitsky, V., Gedney, C. J., & Abbot, T. A. (2022). A wave glider-based, towed hydrophone array system for autonomous, real-time, passive acoustic marine mammal monitoring. *The Journal of the Acoustical Society of America, 152*(3). https://doi.org/10.1121/10.0014169

Reynolds, S. A., Beery, S., Burgess, N., Burgman, M., Butchart, S. H. M., Cooke, S. J., Coomes, D., Danielsen, F., Minin, E. D., Durán, A. P., Gassert, F., Hinsley, A., Jaffer, S., Jones, J. P. G., Li, B. V., Aodha, O. M., Madhavapeddy, A., O'Donnell, S. A. L., Oxbury, W. M.,...Sutherland, W. J. (2025). The potential for AI to revolutionize conservation: a horizon scan. *Trends in Ecology & Evolution, 40*(2). https://doi.org/10.1016/j.tree.2024.11.013

Richter, S., Yurk, H., Winterl, A., Chmelnitsky, E., Serra, N., O'Hara, P. D., & Zitterbart, D. (2024). Coastal Marine Mammal conservation using thermal imaging-based detection systems. *bioRxiv*. https://doi.org/10.1101/2023.08.25.554754

Ross, S. R. P.-J., O'Connell, D. P., Deichmann, J. L., Desjonquères, C., Gasc, A., Phillips, J. N., Sethi, S. S., Wood, C. M., & Burivalova, Z. (2023). Passive acoustic monitoring provides a fresh perspective on fundamental ecological questions. *Functional Ecology, 37*(4). https://doi.org/10.1111/1365-2435.14275

Ryder, M., Booth, C., Oedekoven, C., Marques, T., Joy, R., & Harris, D. (2024). Passive Acoustic Monitoring Power Analysis: A Tool for Designing an Acoustic Monitoring Program. In *The Effects of Noise on Aquatic Life: Principles and Practical Considerations* (pp. 1995-2010). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-50256-9_140

Sanganyado, E., Bi, R., Teta, C., Moreira, L. B., Yu, X., Yajing, S., Dalu, T., Rajput, I. R., & Liu, W. (2021). Toward an integrated framework for assessing micropollutants in marine mammals: Challenges, progress, and opportunities. *Critical Reviews in Environmental Science and Technology, 51*(23). https://doi.org/10.1080/10643389.2020.1806663

Sanguineti, M., Guidi, C., Kulikovskiy, V., & Taiuti, M. G. (2021). Real-Time Continuous Acoustic Monitoring of Marine Mammals in the Mediterranean Sea. *Journal of Marine Science and Engineering, 9*(12). https://doi.org/10.3390/jmse9121389

Satterlee, K., Watson, S., & Danenberger, E. (2018). New Opportunities for Offshore Oil and Gas Platforms – Efficient, Effective, and Adaptable Facilities for Offshore Research, Monitoring, and Technology Testing, IEEE Conference Publication. IEEE Xplore. *OCEANS 2018 MTS/IEEE Charleston.* https://doi.org/10.1109/OCEANS.2018.8604935

Scala, L., Pierpoint, C., Teilmann, J., Petersen, K. V., Narramore, J., & Morris, J. (2017). Middelfart listening station: A Static Acoustic Monitoring Solution for Monitoring Harbour Porpoise & Ship Traffic in a Marine Protected Area. ECO Magazine, 34-37. http://digital.ecomagazine.com/publication/?i=443941&article_id=2905963&view=articleBrowser&ver=html5#{

Sehnal, L., Brammer-Robbins, E., Wormington, A. M., Blaha, L., Bisesi, J., Larkin, I., Martyniuk, C. J., Simonin, M., & Adamovsky, O. (2021). Microbiome Composition and Function in Aquatic Vertebrates: Small Organisms Making Big Impacts on Aquatic Animal Health. *Frontiers in Microbiology, 12*. https://doi.org/10.3389/fmicb.2021.567408

Senevirathna, J. D. M., & Asakawa, S. (2021). Multi-Omics Approaches and Radiation on Lipid Metabolism in Toothed Whales. *Life 2021, Vol. 11, Page 364, 11*(4). https://doi.org/10.3390/life11040364

Sheehan, E. V., Bridger, D., Nancollas, S. J., & Pittman, S. J. (2020). PelagiCam: a novel underwater imaging system with computer vision for semi-automated monitoring of mobile marine fauna at offshore structures. *Environmental monitoring and assessment*, *192*(1), 11. https://doi.org/10.1007/s10661-019-7980-4

Shiu, Y., Palmer, K. J., Roch, M. A., Fleishman, E., Liu, X., Nosal, E.-M., Helble, T., Cholewiak, D., Gillespie, D., Klinck, H., Shiu, Y., Palmer, K. J., Roch, M. A., Fleishman, E., Liu, X., Nosal, E.-M., Helble, T., Cholewiak, D., Gillespie, D., & Klinck, H. (2020). Deep neural networks for automated detection of marine mammal species. *Scientific Reports 2020 10:1, 10*(1). https://doi.org/10.1038/s41598-020-57549-y

Smith, H. R., Zitterbart, D. P., Norris, T. F., Flau, M., Ferguson, E. L., Jones, C. G., Boebel, O., & Moulton, V. D. (2020). A field comparison of marine mammal detections via visual, acoustic, and infrared (IR) imaging methods offshore Atlantic Canada. *Marine Pollution Bulletin, 154*, 111026. https://doi.org/10.1016/j.marpolbul.2020.111026

Sousa-Lima, R. S., Norris, T. F., Oswald, J. N., & Fernandes, D. P. . (2013). A Review and Inventory of Fixed Autonomous Recorders for Passive Acoustic Monitoring of Marine Mammals. *Aquatic Mammals, 39*(1), 23-53. https://doi.org/10.1578/am.39.1.2013.23

Species at Risk Act, S.C. 2002, c. 29. Government of Canada. https://laws.justice.gc.ca/eng/acts/s-15.3/

Stewart, J. B., Hudson, J. M., Sherbo, B. A. H., & Watt, C. A. (2024). Estimating beluga whale abundance from space: using drones to ground-validate VHR satellite imagery. *Remote Sensing in Ecology and Conservation, 10*(6). https://doi.org/10.1002/rse2.396

Stöcker, C., Bennett, R., Nex, F., Gerke, M., Zevenbergen, J., Stöcker, C., Bennett, R., Nex, F., Gerke, M., & Zevenbergen, J. (2017). Review of the Current State of UAV Regulations. *Remote Sensing 2017, Vol. 9, Page 459, 9*(5). https://doi.org/10.3390/rs9050459

Stupariu, M.-S., Cushman, S. A., Pleşoianu, A.-I., Pătru-Stupariu, I., & Fürst, C. (2021). Machine learning in landscape ecological analysis: a review of recent approaches. *Landscape Ecology, 37*(5), 1227-1250. https://doi.org/10.1007/s10980-021-01366-9

Suarez-Bregua, P., Álvarez-González, M., Parsons, K. M., Rotllant, J., Pierce, G. J., & Saavedra, C. (2022). Environmental DNA (eDNA) for monitoring marine mammals: Challenges and opportunities. *Frontiers in Marine Science, 9*. https://doi.org/10.3389/fmars.2022.987774

Szesciorka, A. R., Severy, M., Ampela, K., Hein, C., Richlen, M., Haxel, J., & Clerc, J. (2025). *Evaluating tools and technologies for monitoring baleen whales during offshore wind foundation installation* (PNNL-37249; NREL/TP-5000-92549). Pacific Northwest National Laboratory & National Renewable Energy Laboratory. https://tethys.pnnl.gov/publications/baleen-whale-monitoring-technologies-report

Thode, A. (2004). Tracking sperm whale (Physeter macrocephalus) dive profiles using a towed passive acoustic array. *The Journal of the Acoustical Society of America, 116*(1). https://doi.org/10.1121/1.1758972

Thode, A., Širović, A., & Bayless, A. S. (2021). *Optimization of towed passive acoustic monitoring (PAM) array design and performance study (Passive Acoustic Monitoring Study)* (OCS Study BOEM 2021-086). Bureau of Ocean Energy Management, U.S. Department of the Interior.

Todd, N. R. E., Cronin, M., Luck, C., Bennison, A., Jessopp, M., & Kavanagh, A. S. (2020). Using passive acoustic monitoring to investigate the occurrence of cetaceans in a protected marine area in northwest Ireland. *Estuarine, Coastal and Shelf Science, 232.* https://doi.org/10.1016/j.ecss.2019.106509

Torres, L. G., Nieukirk, S. L., Lemos, L., & Chandler, T. E. (2018). Drone Up! Quantifying Whale Behavior From a New Perspective Improves Observational Capacity. *Frontiers in Marine Science, 5.* https://doi.org/10.3389/fmars.2018.00319

Tsokana, C. N., Symeonidou, I., Sioutas, G., Gelasakis, A. I., & Papadopoulos, E. (2023). Current Applications of Digital PCR in Veterinary Parasitology: An Overview. *Parasitologia, 3*(3), 269-283. https://doi.org/10.3390/parasitologia3030028

Tucker, J. (2023). Extending aerial surveys beyond target marine mammal species: An application of strip transect methodology to humpback whale and dugong abundance estimation in Exmouth Gulf, Western Australia. https://doi.org/10.25958/n9g8-sh89

Valsecchi, E., Tavecchia, G., Boldrocchi, G., Coppola, E., Ramella, D., Conte, L., Blasi, M., Bruno, A., & Galli, P. (2023). Playing "hide and seek" with the Mediterranean monk seal: a citizen science dataset reveals its distribution from molecular traces (eDNA). *Sci Rep, 13*(1), 2610. https://doi.org/10.1038/s41598-023-27835-6

van der Schaar, M., Andre, M., Delory, E., Gillespie, D., Rolin, J.-F., Van der Schaar, M., Andre, M., Eric, D., Gillespie, D., & Rolin, J.-F. (2017). *Passive Acoustic Monitoring from Fixed Platform Observatories.* https://repository.oceanbestpractices.org/handle/11329/1465

van Geel, N. C. F., Risch, D., Benjamins, S., Brook, T., Culloch, R. M., Edwards, E. W. J., Stevens, C., & Wilson, B. (2022). Monitoring cetacean occurrence and variability in ambient sound in Scottish offshore waters. *Frontiers in Remote Sensing, 3.* https://doi.org/10.3389/frsen.2022.934681

Van Parijs, S. M., Clark, C. W., Sousa-Lima, R. S., Parks, S. E., Rankin, S., Risch, D., & Van Opzeeland, I. C. (2009). Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. *Marine Ecology Progress Series, 395.* https://doi.org/10.3389/fmars.2021.760840

Van Parijs, S. M., Baker, K., Carduner, J., Daly, J., Davis, G. E., Esch, C., Guan, S., Scholik-Schlomer, A., Sisson, N. B., & Staaterman, E. (2021). NOAA and BOEM Minimum Recommendations for Use of Passive Acoustic Listening Systems in Offshore Wind Energy Development Monitoring and Mitigation Programs. *Frontiers in Marine Science, 8.* https://doi.org/10.3389.fmars.2021.760840

Verfuss, U. K., Aniceto, A. S., Harris, D. V., Gillespie, D., Fielding, S., Jiménez, G., Johnston, P., Sinclair, R. R., Sivertsen, A., & Solbø, S. A. (2019). A review of unmanned vehicles for the detection and monitoring of marine fauna. *Marine Pollution Bulletin, 140,* 17-29. https://doi.org/10.1016/j.marpolbul.2019.01.009

Verfuss, U. K., Gillespie, D., Gordon, J., Marques, T. A., Miller, B., Plunkett, R., Theriault, J. A., Tollit, D. J., Zitterbart, D. P., & Hubert, P. (2018). Comparing methods suitable for monitoring marine mammals in low visibility conditions during seismic surveys. *Marine Pollution Bulletin, 126,* 1-18. https://doi.org/10.1016/j.marpolbul.2017.10.034

Vieira, S., de Varenne, F., Gaillard, S., Sousa-Lima, R., & Glotin, H. (2024). Sounds and DNA Reveal Marine Mammals in the Mediterranean Sea. https://doi.org/10.2139/ssrn.4898656

Wang, D., Shao, Q., Yue, H., Wang, D., Shao, Q., & Yue, H. (2019). Surveying Wild Animals from Satellites, Manned Aircraft and Unmanned Aerial Systems (UASs): A Review. *Remote Sensing 2019, Vol. 11, Page 1308, 11*(11). https://doi.org/10.3390/rs11111308

Whale Safe (n.d.). Whale Safe Project. https://whalesafe.com/

Würsig, B., Cipriano, F., & Würsig, M. (1991). Dolphin movement patterns: information from radio and theodolite tracking studies. In *Dolphin Societies: discoveries and puzzles* (pp. 79-112). University of California Press. https://doi.org/10.1525/9780520922051-005

Yaney-Keller, A., Mcintosh, R. R., Clarke, R. H., & Reina, R. D. (2025). Closing the air gap: the use of drones for studying wildlife ecophysiology. *Biological Reviews*. https://doi.org/10.1111/brv.13181

Yang, S., Jin, Y., Li, S., & Liu, Z. (2024). Integrated approaches for comprehensive cetacean research and conservation in the East China Sea. *Marine Pollution Bulletin*, 206. https://doi.org/10.1016/j.marpolbul.2024.116789

Zitterbart, D. P., Kindermann, L., Burkhardt, E., & Boebel, O. (2013). Automatic Round-the-Clock Detection of Whales for Mitigation from Underwater Noise Impacts. *PLOS ONE*, 8(8). https://doi.org/10.1371/journal.pone.0071217

Zitterbart, D. P., Smith, H. R., Flau, M., Richter, S., Burkhardt, E., Beland, J., Bennett, L., Cammareri, A., Davis, A., Holst, M., Lanfredi, C., Michel, H., Noad, M., Owen, K., Pacini, A., & Boebel, O. (2020). Scaling the Laws of Thermal Imaging–Based Whale Detection. *Journal of Atmospheric and Oceanic Technology*, 37(5), 807-824. https://doi.org/10.1175/jtech-d-19-0054.1

International HQ: 1 Birdcage Walk , London SW1H 9JJ • United Kingdom • **Tel:** +44 (0) 20 7382 2600
Asia-Pacific Office: 298 Tiong Bahru Road, #05-01 Central Plaza, Singapore 168730 • **Tel:** +65 6472 0096

Registered Charity No. 212992 • Founded 1889. Incorporated by Royal Charter 1933 • Licensed body of the Engineering Council (UK) and the Science Council

AMERICAS • EUROPE • MIDDLE EAST & AFRICA • ASIA PACIFIC

www.imarest.org