E-ISSN: 2347-5129
P-ISSN: 2394-0506
(ICV-Poland) Impact Value: 76.37
(GIF) Impact Factor: 0.549
IJFAS 2025; 13(4): 300-307

www.fisheriesjournal.com
Received: 05-08-2025
Accepted: 07-09-2025

Zubair AA
Assistant Professor, MES Ponnani College, Ponnani South, Malappuram Kerala, Kerala, India

Corresponding Author:
Zubair AA
Assistant Professor, MES Ponnani College, Ponnani South, Malappuram Kerala, Kerala, India

Aquatic one health framework: Integrating ocean ecosystems and human well-being

Zubair AA

DOI: https://www.doi.org/10.22271/fish.2025.v13.i5d.3171

Abstract
The concept of linkages between human, animal and environmental health is particularly relevant in the marine realm. The Aquatic One Health (AOH) was introduced as a developing concept with emphasis on overcoming the limitations of One Heath theory in view of raising awareness to specific challenges and potential opportunities highlighted in relation to those species dwelling in the oceans. The Paule D.M. report: The Aquatic One Health A framework for promoting the economic benefits of aquatic health knowledge 2015-2025 Summary this overall view paper summaries the status of AOH at present, its utilizations as well as its difficulty in practices form 2015 to 2025. Using case study examples that describe efforts to monitor marine mammal health and monitor harmful algal blooms, and to understand the health impacts of marine pollution on the public and animals, as well as tracking zoonotic disease emergence, we show why an integrated approach to human health and marine health is necessary. This review summarizes critical research gaps, challenges to implementation, and future opportunities in this domain. Our results suggest that the Aquatic One Health concept can provide a strong framework for tackling complex marine health issues but needs stronger cross-sectorial support, better surveillance and more intensified policy integration. We argue that its application is essential for maintaining marine ecosystem health and the provision of benefits to humanity in the face of an everchanging environment.

Keywords: Aquatic One Health, marine ecosystems, public health, environmental health, marine mammals, ocean pollution, climate change, zoonotic diseases, surveillance systems, transdisciplinary research

1. Introduction
The world's oceans: feeding humanity and maintaining life on earth The world's oceans span ~71% of the Earth's surface, utterly dominate its hydrological cycle, harbor 97% of its water, and constitute the largest contiguous ecosystem on our planet [1]. The services of these marine ecosystems include climate regulation, oxygen production, carbon sequestration, food provision and economic resources for billions of people worldwide. Nevertheless, marine ecosystems are now experiencing more anthropogenic impacts than they ever have before, with climate change, pollution, overfishing and habitat destruction, in addition to emerging infectious diseases that threaten marine life along with human populations reliant on the ocean [2].

In the past conservation of marine ecosystem and public health have been managing independently with poor access to environment, animal, human health. Such silo-management has failed to address the highly integrated, emergent challenges faced by marine ecosystems in the 21st century. The introduction of the One Health concept, acknowledging that human, animal and environmental health are interdependent [3], has facilitated a more holistic approach to health problems.

Applying the One Health approach to aquatic ecology - Aquatic One Health (AOH) is a relatively new but emerging field, which aims to focus on specificities and challenges, related with aquatic ecosystems. Marine ecosystems present dynamic boundaries, highly complex 3D habitat architectures, and high levels of connectivity at phenomenal spatial scales and host predominantly marine organisms that possess unique physiological adaptations influencing disease transmission and environmental health dynamics [4].

This review has been conducted with the goal of synthesizing established knowledge regarding Aquatic One Health, including its theoretical underpinnings, practical implementation, and research prospects. We review seminal cases and use cases from 2015-2025, as well as implementation challenges and opportunities to date - concluding with recommendations for the field that are based on evidence. We propose through this analysis that the Aquatic One Health paradigm is an indispensable departure from traditional thinking in response to complex issues at the convergence of marine science and public health.

2. Theoretical Foundations of the Aquatic One Health Framework

2.1 Evolution from Terrestrial One Health

The One Health approach was developed on the premise that human health, animal health and environmental health are interconnected and the resolution of complex public health challenges calls for coordinated, multispectral and interdisciplinary action [5]. One Health emerged predominantly as a concept for terrestrial issues, in particular with respect to zoonotic diseases and antimicrobial resistance, but has gradually grown to include wider environmental health problems.

The extension of One Health paradigm to aquatic contexts acknowledges the range of unique conditions separating marine from terrestrial environments. Oceans show high connectivity over very large spatial scales, as currents act to readily transport pathogens, pollutants, and other health-relevant factors across national borders. The 3-dimensional structure of marine environments results in intricate vertical gradients between species, environmental exposure and pathways to human health outcomes [6].

2.2 Core Principles of Aquatic One Health

The Aquatic One Health framework is built upon four fundamental principles that distinguish it from traditional sectoral approaches

Interconnectedness and Interdependence: The structure acknowledges that the health of marine ecosystems, marine fauna, and human communities are inherently linked. Modifications in such a system element influence the other parts of the system through intricate ecological, physiological and socioeconomic routes irrespective of whether they intended or not. For instance, the geographic distribution of marine pathogens is likely influenced by climate-related ocean warming that not only affects health of marine animals, but also human exposure to illnesses caused by organisms in the sea [7].

Transdisciplinary Integration: Successful implementation of aquatic One Health necessitates integration across discipline lines including marine biology, oceanography, veterinary medicine, public health, toxicology, climate science and social sciences. Such transdisciplinary approaches are critical to understanding the complexities of the interactions that occur within marine socio-ecological systems and develop holistic solutions to health issues [8].

Systems Thinking: The framework promotes a systems perspective that accounts for the complex interactions, feedbacks, and emergent properties inherent in marine social-ecological systems. The approach recognizes that marine health issues cannot be understood or solved using a reductionist approach that addresses individual component parts in isolation [9].

Adaptive Management: Taking into account the constantly evolving character of the oceans and uncertainty resulting from complex systems, the Aquatic One Health framework calls for adaptive management solutions that accommodate changing conditions and new information. This recognizes the need for flexible monitoring systems, adaptive governance systems and iterative learning processes [10].

Table 1: Core principles of Aquatic One Health and why they matter

Principle	Definition	Why it matters	Marine example	Refs
Interconnectedness	Human-animal-environment health are inseparable.	Avoids siloed actions; improves decisions.	Warming shifts pathogens affecting seafood & wildlife.	3,7

2.3 Unique Characteristics of Marine Environments

There are several characteristics of marine environments that provide unique opportunities and challenges for the implementation of One Health:

Spatial and Temporal Scales: Marine ecosystems can operate over vast spatial scales, from local coastal areas to ocean basins, and over temporal scales from tidal cycles to multi-decadal climate regimes. This introduces difficulties in monitoring, attribution of causality, and coordination of managerial responses across multi-jurisdictional scales [11].

Connectivity and Transport: Ocean currents, tidal flow and animal migrations make for a highly interconnected marine system that allows the rapid dissemination of pathogens, toxins and other health-relevant factors. Such interconnectedness means that local health impacts may be far-reaching and effective management often necessitates co-ordination across wide geographical areas [12].

Physiological Adaptations: Marine organisms have developed unique physiological adaptations to their aquatic habitats. Modification of respiratory systems, osmoregulatory mechanisms, and metabolic pathways permit establishment of specific pathological areas of susceptibility, as well as responses to environmental stress and bioaccumulation of xenobiotics that are entirely different than those of terrestrial organisms [13].

3. Case Studies and Applications

3.1 Marine Mammal Health Surveillance

Marine mammals are important sentinel species for ocean health because they are apex predators, have long lifespans and reside in coastal areas, where they interact with humans [14]. The establishment of organized marine mammal health monitoring systems is among the more extensively mature prospective applications of One Health for aquatic species.

A Workshop Report titled, Marine Mammal Health Surveillance (2024) developed a cohesive national approach to health monitoring for marine mammals that is consistent with Aquatic One Health concepts [15]. The envisaged monitoring system harmonizes different components such as

standardised sampling protocols, priority pathogen as well as biotoxin monitoring, non-infectious disease indicators and coordinated laboratory support networking**.**

Key elements of this surveillance framework include

Standardized Sampling Approaches: Development of consistent methodologies for the collection of health data from marine mammal populations from different areas, species, and life stages, both opportunistically from stranded animals and systematically from live captured or biopsied animals [16].

Priority Species and Populations: Identification of focal species and populations for targeted monitoring according to conservation status, ecological significance, geographic distribution and sentinel value for ecosystem health. Priority species include coastal cetaceans, pinnipeds and polar marine mammals which are particularly sensitive to environmental change [17].

Table 2: Sentinel marine mammals and priority health indicators

Species/Population	Region	Indicator	Sampling	Sentinel rationale	Refs
California sea lion (*Z. californianus*)	U.S. West Coast	Domoic acid (HAB)	Strandings; necropsy; serum/urine	Coastal predator; early HAB warning	18,19,21

Integrated Disease Monitoring: On-going surveillance of both infectious and non-infectious diseases, including novel pathogens, exposure to biotoxins, diseases associated with contaminant exposure, and disease outcomes associated with climate change. This integrated approach acknowledges that the health of marine mammals is impacted by a number of different and frequently interacting stressors [18].

The marine mammal health monitoring program already has provided valuable information on trends in ocean health. For instance, long - term Steller sea lion monitoring revealed a high incidence of domoic acid toxicity associated with harmful algal blooms and served as an early warning system for environmental changes that also affect human health, such as seafood consumption [19]. Likewise, monitoring of marine mammals in the Arctic has uncovered new infectious diseases which are related to climate change-driven changes in habitat [20].

3.2 Harmful Algal Bloom Surveillance and Response

Harmful algal blooms (HABs) are a prime example of Aquatic One Health threats since they impact the health of marine ecosystems, marine animals and humans in a complex cross-sectoral manner via various exposure routes [21]. The CDC's One Health Harmful Algal Bloom System (OHHABS) offers a model for integrated HAB surveillance and response.

Started in 2016, OHHABS is the sole national public health system to uniformly capture investment in HABs and associated human and animal disease [22]. The system is an example of Aquatic One Health in action - with a holistic surveillance system, multi-sectoral partnerships, and a focus on health impacts beyond species boundaries.

Table 3: Integrated HAB surveillance elements (OHHABS model)

Domain	Core metrics	Data source	Response trigger/action	Refs
Environment	Cells & toxins; species ID	Monitoring programs; field; remote sensing	Advisories; beach/harvest closures	22,23,25

Multi-Domain Data Integration: The OHHABS monitored environmental occurrence and toxin levels of harmful algal blooms (HABs), human health, animal health, and food safety. This integrative approach ensures a thorough evaluation of the effects of harmful algal blooms (HABs) on the human-animal-environment interface [23].

Collaborative Surveillance Network: The cooperation of state and territorial public health departments, environmental health agencies, veterinary health professionals, and academic researchers is a major component of the system. The results will be the multipronged protection of the public from dynamic and unpredictable harmful algae bloom (HAB) events [24].

Early Warning and Prevention: Through the synergistic combination of health monitoring and monitoring of the environment, OHHABS enables early warning of HAB-related health threats and preventive measures to be taken, such as beach closings, seafood harvest restrictions, and public health advisories [25].

A recent analysis of OHHABS data has indicated important patterns with respect to the occurrence of harmful algal blooms and health effects, including the geographical expansion of harmful algal bloom events, increases in the frequency of multi-toxin events, and new associations among climate variability and patterns of illness related to harmful algal blooms [26]. These results underscore the importance of integrated surveillance systems for understanding and responding to the complex problems with respect to environmental health.

3.3 Marine Pollution and Human Health

Marine pollution constitutes one of the most pervasive threats to the health of marine ecosystems and human health, with impacts delivered through a variety of pathways, including (but not limited to) direct exposure and bioaccumulation in the food chain, and disruption of ecosystem services [27]. The systematic review performed by Landrigan *et al*. (2020) indicated the urgent need for One Health approaches to tackle the complex and interlinked impacts of ocean pollution on human health [28]. Continents Marine chemical pollution with chemicals including heavy metals, persistent organic pollutants (POPs), pharmaceuticals, personal care products and emerging contaminants such as microplastics compounds the contamination of marine compartments. This pollutants biomagnifies the marine food webs and risk to both marine as well as human seafood consumers have been reported [29].

Microplastic Pollution: New findings have emphasized growing concern in microplastics as a threat to marine animal health and human health. Studies have reported microplastic ingestion in marine mammals with potential implications for inflammation, intestinal blockage and contaminant transfer [30]

The finding of microplastics in human tissues and the subsequent threat from seafood ingestion emphasizes the requirement to consider this emergent risk in a holistic manner [31].

Table 4: Marine pollutants (incl. microplastics) and exposure pathways

Pollutant	Sources	Marine fate/bioaccum.	Human exposure	Health concern	Refs
Microplastics	Consumer plastics; textiles	Ingestion; trophic transfer; sediments	Seafood; aerosols (coastal)	Inflammation; vector for chemicals/pathogens	30,31

Marine Endocrine Disruption: Marine environments act as reservoirs of endocrine-disruptive chemicals that may interfere with the reproductive health, development and immune profiles of marine species and mammals. The ubiquitous nature of these compounds in marine food webs provides exposure avenues connecting the health of marine ecosystems to the human health [32].

3.4 Climate Change in Relation to Marine Health

Climate change has been identified as one of the key drivers for changes in marine ecosystems, which cascade and impact on both marine animal and human health 33. Climate change in marine systems provides an example of where such integrated approaches are necessary as the influences of environmental change and ecosystem health on people's well-being becomes increasingly complex.

Ocean Warming and Acidification: Increased ocean temperatures and acidification influence marine organism physiology, the distributions of species, and ecosystem organization. These shifts impact pathogen dynamics, food web configuration and the provision of ecosystem services that are essential for human health and well-being [34].

Table 5: Climate drivers → mechanisms → marine & human endpoints

Driver	Mechanism (example)	Marine outcomes	Human outcomes	Refs
Marine heatwaves	Thermal stress; altered immunity	Mass mortalities; range shifts; predator collapse	Food security; HAB illnesses; economic loss	33,36

Sea level Rise and the Health of our Coasts: Sea level rise poses a growing threat to coastal communities, through increasingly frequent flooding, saltwater intrusion, and infrastructure damage. These impacts interact with human health through displacement, water and food security, as well as higher exposure to water-related diseases [35].

Extreme Weather: Climate change is driving up the number of extreme weather events like hurricanes, storm surges and marine heat waves. Such events can lead to large-scale die-offs of marine animals, perturb marine food webs and contribute to public health emergencies in coastal communities [36].

3.5 Emerging Zoonotic Diseases

Marine habitats harbor many zoonotic pathogens that can infect marine animals as well as humans **37**. The range expansion and transmission of marine zoonoses illustrate the importance of a "One Health" approach, whereby surveillance and response capacity is developed to account for a myriad of interactions among marine hosts, environmental factors, and human exposure.

Viral Zoonoses: Recent systematic reviews have also identified a high proportion of marine mammal mortality events resulting from zoonotic viral diseases, once again demonstrating the capacity for marine environments to act as drivers of emerging infectious disease [38]. Anthropogenic disturbances and climate change might increase the risk of viral spillover from marine wildlife to humans.

Bacteral Infections: The ocean is home to a variety of bacteria, some of which may be pathogenic and are capable of causing disease in marine animals as well as humans. The rise of antibiotic-resistant bacteria in the marine ecosystem is also becoming a more significant threat to both marine animal health and human [39].

Parasitic diseases: Parasites of the marine environment can infect both marine animals and humans from direct contact or consumption of contaminated seafood. Changes in marine conditions due to climate change appear to disrupt parasite life cycles and extend the geographical distribution of parasitic diseases [40].

4. Implementation Challenges and Barriers

4.1 Institutional and Governance Challenges

Jurisdictional Complexity: Marine ecosystems frequently are geographically divided between a range of legal systems, including national, state and local jurisdictions and even less well-defined practices such as those that apply in international waters through treaties. This jurisdictional complexity makes it difficult to coordinate integrated health surveillance and responses [41].

Sectoral Fragmentation: Conventional modes of managing have strongly separated institutions in human health, animal/ plant health and environment. Disassembling these silos and establishing effective mechanisms for coordination are challenging themes in the implementation of Aquatic One Health [42].

Resource Constraints: It will be cost and human resource intensive to realise the full potential of Aquatic One Health approach through surveillance, laboratory capacity, data management and coordination activities. Many countries have no financial capacity for multidimensional interventions [43].

4.2 Scientific and Technical Challenges

Gaps in monitoring and surveillance: Robust health surveillance in the marine environment is technically difficult because of its scale, difficulty of access and complicated three-dimensional nature of marine habitats. The existing monitoring system has large gaps in spatial and temporal coverage [44].

Attribution and Causality: There are challenges in attributing cause to change for environmental change and health within marine systems, as these are complex, multi-factorial issues which occur over long time scales with implications at the population level [45].

Data Integration and Standardization: Harmonizing data across sectors, disciplines and jurisdictiones requires standardized protocols, compatible Data systems, and functioning mechanisms for data sharing which often do not exist [46].

4.3 Capacity and Training Needs

Cross-disciplinary training: There is a limited pool of individuals who are trained across the multiple fields necessary to successfully implement Aquatic One Health. Creating educating activities and training programs that unites these fields is a big challenge [47].

Technical Capability: Much of the region does not have the technical capabilities for marine health surveillance, i.e. laboratory facilities, analysis and trained human resources. Creating such a reserve will necessitate significant investment and long-term commitment [48].

Communication and engagement: In order to implement Aquatic One Health effectively, good communication and engagement skills are needed in particular when it comes to working collaboratively across areas as well as hope for translating complex scientific messages into language that is understandable by different stakeholders [49].

5. Future Directions and Opportunities

5.1 Technological Innovations

Remote Sensing and Autonomous Systems Recent progress in satellite remote sensing, autonomous underwater vehicles, and sensor networks has been driving the development of capabilities to monitor marine environments as well as health indicators on large temporal and spatial scales [50].

Molecular Diagnostics: Rapid developments in molecular diagnostics such as environmental DNA (eDNA) and portable diagnostic devices are facilitating expansive, cost-effective surveillance of marine pathogens and health indicators [51].

Artificial Intelligence and Machine Learning: AI and machine learning methods hold promise of combining large multi-dimensional datasets and revealing hidden patterns and associations that would not be otherwise evident using traditional analysis [52].

5.2 Policy and Governance Innovations

Coordinated Governance Framworks: Coordinated governance framworks, including those that have horizontal coherence among sectors and jurisdictions such as: ecosystem-based management approaches EBM [54, 55] and One Health governance systems [56] may promote better coordination and efficiency in the adjustment process.

International cooperation: Enhanced efforts are needed to develop global mechanisms for health surveillance and response for the marine environment, including sharing of data and coordinated monitoring programmes because of the transboundary character of marine systems [54].

Adaptive Management Systems: Adopting adaptive management methodologies, which are able to dynamically respond to gradients and change in conditions, including new information could increase the efficacy and resilience of aquatic OH programs [55].

5.3 Research Priorities

Systems-level Understanding: Research that progresses our understanding of the interactions in marine socio-ecological systems, such as development of integrated models predicting health outcomes under different scenarios [56].

Effectiveness of Interventions: This could include studies assessing the effectiveness of Aquatic One Health interventions such as surveillance, management and policy strategies [57].

Social and Economic Aspects: Studies on social and economic aspects of Aquatic One Health, such as costs and benefits of integrative approaches, the drivers for stakeholder engagement or change in behavior [58].

6. Recommendations

Drawing on our extensive examination of the Aquatic One Health framework, we make several recommendations towards furthering this essential area:

6.1 Surveillance and monitoring enhancement

Strengthen Integrated Surveillance Networks: Build integrated networks, such as those that harmonize environmental monitoring and marine animal health surveillance with human health surveillance at spatial and temporal scales appropriate to the challenge.

Standardize Protocols and Data Systems: Create standardized protocols for how data is collected, analyzed and shared in order to integrate effectively across sectors as well as across location.

Invest in Monitoring Infrastructure: Increasing investment into monitoring infrastructure such as laboratory capacity, field monitoring options and data management systems.

6.2 Enhance Institutional Coordination

Develop Coordination Mechanisms: Formal coordination mechanisms that facilitate the organization of relevant sectors and jurisdictions to develop implement, and assess Aquatic One Health programs.

Integrative Governance Frameworks: Aim for governance frameworks that are broader than the traditional sectoral silos and support cohesive decision-making.

Enhance International Cooperation: Boosting international collaboration for monitoring and response efforts for marine health, including data sharing agreements and collaborative surveillance programs.

6.3 Build Capacity and Expertise

Training Programs Development: Develop training programs that will develop trans-disciplinary capacity in Aquatic One Health.

Support Research and Development: Invest in research to

explore marine socio-ecological systems and the effectiveness of integrated health interventions.

Facilitate Innovation: Facilitate the development and adoption of new technologies and methodologies for marine health monitoring.

6.4 Engage Stakeholders and Communities

Enhance Communication: Facilitate communication mechanisms that strengthen stakeholder and demographic involvement in aquatic One Health efforts.

Support Participatory Models: Carry out participatory models in which communities and stakeholders are actively engaged to design, implement Aquatic One Health programs.

Tackle Social and Economic Factors: Factor in the social and economic aspects of marine health challenges, and make sure Aquatic One Health approaches are attuned to concerns about equity and justice.

7. Conclusion

The Aquatic One Health (AOH) paradigm is a fundamental shift necessary to address the complex, interrelated challenges facing ocean systems and humans in the 21st century. Our comparitive analysis shows that while there has been significant advancement in the conceptualization and operationalization of AOH, a lot of barriers still exist towards its institutional arrangements, command on science and resources.

The case studies reviewed in this analysis—marine mammal health monitoring, harmful algal bloom surveillance, marine pollution exposure, and emergent zoonotic disease—are indicative of the promise and obstacles to integrated approaches to marine health. These case studies illustrate that successful implementation of Aquatic One Health will necessitate ongoing sectoral collaboration, significant investment in surveillance and monitoring tools, and adaptive management strategies capable of addressing evolving conditions.

The successful implementation of the Aquatic One Health framework in future will rely on us to address these institutional, scientific and capacity challenges raised in this review. This will necessitate an unprecedented level of cooperation between disciplines, sectors and jurisdictions, as well as sustained investment in infrastructure and capacity to support the integrated approach.

However, the increasing acceptance of how interconnected are marine health with human health, and technology advances along with an increasingly widespread understanding about our need to conserve the sea, offer room for optimism. The Aquatic One Health concept provides a model for more efficient and sustainable options that safeguard not only the health of marine ecosystems, but also benefit human well-being.

With the world now entering a period of unique environmental change the timing couldn't be better for integrated thinking around marine health. The Aquatic One Health framework must serve as a vehicle to address this challenge, but its effectiveness will be shaped by how committed we are — collectively — to implementing the team- and discipline-based approaches that are integral to it.

The state of our oceans and the health of human societies are intertwined. By adopting the Aquatic One Health paradigm, it is possible to move toward a future in which both marine and human communities can flourish sustainably within healthy relationships with our world's aquatic systems.

References

1. National Ocean Service. How much of the ocean have we explored? National Oceanic and Atmospheric Administration. 2021. https://oceanservice.noaa.gov/facts/exploration.html. 15 October, 2025.
2. Halpern BS, Frazier M, Potapenko J, Casey KS, Koenig K, Longo C, *et al*. Recent pace of change in human impact on the world's ocean. Scientific Reports. 2019;9(1):11609. https://doi.org/10.1038/s41598-019-47201-9.
3. World Health Organization. One Health. 2017. https://www.who.int/news-room/q-a-detail/one-health. 15 October, 2025.
4. Norman SA, Thomas AC, Dubpernell S, Heise K, Saliki J, Cline M, *et al*. Editorial: Aquatic one health—the intersection of marine wildlife health, public health, and our oceans. Frontiers in Marine Science. 2023;10:1227121. https://doi.org/10.3389/fmars.2023.1227121.
5. Zinsstag J, Schelling E, Waltner-Toews D, Tanner M. From "one medicine" to "one health" and systemic approaches to health and well-being. Preventive Veterinary Medicine. 2011;101(3-4):148-156. https://doi.org/10.1016/j.prevetmed.2010.07.003.
6. Bossart GD. Marine mammals as sentinel species for oceans and human health. Veterinary Pathology. 2011;48(3):676-690. https://doi.org/10.1177/0300985810388525.
7. Burge CA, Eakin CM, Friedman CS, Froelich B, Hershberger PK, Hofmann EE, *et al*. Climate change influences on marine infectious diseases: implications for management and society. Annual Review of Marine Science. 2014;6:249-277. https://doi.org/10.1146/annurev-marine-010213-135029.
8. Plön S, Rowat D, Johnson C, Tempier M, Fonseca L, Beltran S, *et al*. Towards sustainability and beyond with Ocean Health Science. npj Biodiversity. 2025;4(1):23. https://doi.org/10.1038/s44185-025-00091-9.
9. Ostrom E. A general framework for analyzing sustainability of social-ecological systems. Science. 2009;325(5939):419-422. https://doi.org/10.1126/science.1172133.
10. Holling CS. Adaptive Environmental Assessment and Management. John Wiley & Sons; 1978.
11. Levin SA. The problem of pattern and scale in ecology. Ecology. 1992;73(6):1943-1967. https://doi.org/10.2307/1941447.
12. Cowen RK, Sponaugle S. Larval dispersal and marine population connectivity. Annual Review of Marine Science. 2009;1:443-466. https://doi.org/10.1146/annurev.marine.010908.163757.
13. Somero GN. The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine 'winners' and 'losers'. Journal of Experimental Biology. 2010;213(6):912-920. https://doi.org/10.1242/jeb.037473.
14. Moore SE. Marine mammals as ecosystem sentinels. Journal of Mammalogy. 2008;89(3):534-540. https://doi.org/10.1644/07-MAMM-S-312R1.1.

15. Marine Mammal Commission. Marine Mammal Health Surveillance Workshop Report. 2024. https://www.mmc.gov/wp-content/uploads/Marine-Mammal-Health-Surveillance-Workshop-Report.pdf. 15 October, 2025.
16. Gulland FMD, Hall AJ. Is marine mammal health deteriorating? Trends in the global reporting of marine mammal disease. EcoHealth. 2007;4(2):135-150. https://doi.org/10.1007/s10393-007-0097-1.
17. Simeone CA, Gulland FMD, Norris T, Rowles TK. A systematic review of changes in marine mammal health in North America, 1972-2012: the need for a novel integrated approach. PLoS One. 2015;10(11):e0142105. https://doi.org/10.1371/journal.pone.0142105.
18. Harvell CD, Montecino-Latorre D, Caldwell JM, Burt JM, Bosley K, Keller A, *et al*. Disease epidemic and a marine heat wave are associated with the continental-scale collapse of a pivotal predator (Pycnopodia helianthoides). Science Advances. 2019;5(1):eaau7042. https://doi.org/10.1126/sciadv.aau7042.
19. Lefebvre KA, Quakenbush L, Frame E, Huntington KB, Sheffield G, Stimmelmayr R, *et al*. Prevalence of algal toxins in Alaskan marine mammals foraging in a changing arctic and subarctic environment. Harmful Algae. 2016;55:13-24. https://doi.org/10.1016/j.hal.2016.01.007.
20. VanWormer E, Gulland FMD, Johnson CK, Huggins J, Kock R, Lavigne DM, *et al*. Viral emergence in marine mammals in the North Pacific may be linked to Arctic sea ice reduction. Scientific Reports. 2019;9(1):15569. https://doi.org/10.1038/s41598-019-51699-4.
21. Anderson DM, Glibert PM, Burkholder JM. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. Estuaries and Coasts. 2012;35(2):704-726. https://doi.org/10.1007/s12237-012-9475-3.
22. Centers for Disease Control and Prevention. About the One Health Harmful Algal Bloom System (OHHABS). 2024. https://www.cdc.gov/ohhabs/about/index.html. 15 October, 2025.
23. Roberts VA, Vigar M, Backer LC, Veytsel GE, Hilborn ED, Hamelin EI, *et al*. Surveillance for harmful algal bloom events and associated human and animal illnesses—One Health Harmful Algal Bloom System, United States, 2016-2018. MMWR Surveillance Summaries. 2020;69(8):1-22. https://doi.org/10.15585/mmwr.ss6908a1.
24. Backer LC, McNeel SV, Barber T, Kirkpatrick B, Williams C, Chen J, *et al*. Recreational exposure to microcystins during algal blooms in two California lakes. Toxicon. 2010;55:909-921. https://doi.org/10.1016/j.toxicon.2009.07.006.
25. Fleming LE, Kirkpatrick B, Backer LC, Walsh CJ, Nierenberg K, Clark J, *et al*. Initial evaluation of the effects of aerosolized Florida red tide toxins (brevetoxins) in persons with asthma. Environmental Health Perspectives. 2011;119(8):1176-1182. https://doi.org/10.1289/ehp.1002912.
26. Gobler CJ. Climate change and harmful algal blooms: insights and perspective. Harmful Algae. 2020;91:101731. https://doi.org/10.1016/j.hal.2019.101731.
27. Islam MS, Tanaka M. Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis. Marine Pollution Bulletin. 2004;48(7-8):624-649. https://doi.org/10.1016/j.marpolbul.2003.12.004.
28. Landrigan PJ, Rigaud A, Silva MH, Messerlian C, Bellinger DC, Wright RO, *et al*. Human Health and Ocean Pollution. Annals of Global Health. 2020;86(1):151. https://doi.org/10.5334/aogh.2831.
29. Tornero V, Hanke G. Chemical contaminants entering the marine environment from sea-based sources: a review with a focus on European seas. Marine Pollution Bulletin. 2016;112(1-2):17-38. https://doi.org/10.1016/j.marpolbul.2016.06.091.
30. Zantis LJ, Carroll EL, Nelms SE, Bosker T. Marine mammals and microplastics: a systematic review and call for standardisation. Environmental Pollution. 2021;269:116142. https://doi.org/10.1016/j.envpol.2020.116142.
31. Ragusa A, Svelato A, Santacroce C, Catalano P, Notarstefano V, Carnevali O, *et al*. Plasticenta: first evidence of microplastics in human placenta. Environment International. 2021;146:106274. https://doi.org/10.1016/j.envint.2020.106274.
32. Diamanti-Kandarakis E, Bourguignon J-P, Giudice LC, Hauser R, Prins GS, Soto AM, *et al*. Endocrine-disrupting chemicals: an Endocrine Society scientific statement. Endocrine Reviews. 2009;30(4):293-342. https://doi.org/10.1210/er.2009-0002.
33. Poloczanska ES, Brown CJ, Sydeman WJ, Kiessling W, Schoeman DS, Moore PJ, *et al*. Global imprint of climate change on marine life. Nature Climate Change. 2013;3(10):919-925. https://doi.org/10.1038/nclimate1958.
34. Doney SC, Ruckelshaus M, Duffy JE, Barry JP, Chan F, English CA, *et al*. Climate change impacts on marine ecosystems. Annual Review of Marine Science. 2012;4:11-37. https://doi.org/10.1146/annurev-marine-041911-111611.
35. Nicholls RJ, Cazenave A. Sea-level rise and its impact on coastal zones. Science. 2010;328(5985):1517-1520. https://doi.org/10.1126/science.1185782.
36. Oliver ECJ, Donat MG, Burrows MT, Moore PJ, Smale DA, Alexander LV, *et al*. Longer and more frequent marine heatwaves over the past century. Nature Communications. 2018;9(1):1324. https://doi.org/10.1038/s41467-018-03732-9.
37. Waltzek TB, Cortés-Hinojosa G, Wellehan JFX Jr, Gray GC. Marine mammal zoonoses: a review of disease manifestations. Zoonoses and Public Health. 2012;59(8):521-535. https://doi.org/10.1111/j.1863-2378.2012.01492.x.
38. Vigil K, Fiorello CV, Mazet JAK, Goldstein T. A systematic review on global zoonotic virus-associated marine mammal mortality events. One Health. 2024;18:100678. https://doi.org/10.1016/j.onehlt.2024.100678.
39. Watts JE, Schultz ST, Huber ME, Riley LW. The rising tide of antimicrobial resistance in aquaculture: sources, sinks and solutions. Marine Drugs. 2017;15(6):158. https://doi.org/10.3390/md15060158.
40. Marcogliese DJ. The impact of climate change on the parasites and infectious diseases of aquatic animals. Revue Scientifique et Technique. 2008;27(2):467-484. https://doi.org/10.20506/rst.27.2.1820.
41. Young OR. Governing Complex Systems: Social Capital

for the Anthropocene. MIT Press; 2017.
42. Lebel L, Anderies JM, Campbell B, Folke C, Hatfield-Dodds S, Hughes TP, Wilson J. Governance and the capacity to manage resilience in regional social-ecological systems. Ecology and Society. 2006;11(1):19. https://doi.org/10.5751/ES-01606-110119.
43. Ruckelshaus M, McKenzie E, Tallis H, Guerry A, Daily G, Kareiva P, *et al*. Notes from the field: lessons learned from using ecosystem service approaches to inform real-world decisions. Ecological Economics. 2015;115:11-21. https://doi.org/10.1016/j.ecolecon.2013.07.009.
44. Duffy JE, Amaral-Zimmermann A, Gardner T, Golden HE, Karlson RH, Reed DC, *et al*. Envisioning a marine biodiversity observation network. BioScience. 2013;63(5):350-361. https://doi.org/10.1525/bio.2013.63.5.8.
45. Hill AB. The environment and disease: association or causation? Proceedings of the Royal Society of Medicine. 1965;58(5):295-300. https://doi.org/10.1177/003591576505800503.
46. Wilkinson MD, Dumontier M, Aalbersberg IJJ, Appleton G, Axton M, Baak A, *et al*. The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data. 2016;3(1):160018. https://doi.org/10.1038/sdata.2016.18.
47. Rabinowitz PM, Kock R, Kachani M, Kunkel R, Thomas J, Gilbert J, *et al*. Toward proof of concept of a One Health approach to disease prediction and control. Emerging Infectious Diseases. 2013;19(12):e130265. https://doi.org/10.3201/eid1912.130265.
48. Karesh WB, Dobson A, Lloyd-Smith JO, Lubroth J, Dixon MA, Bennett M, *et al*. Ecology of zoonoses: natural and unnatural histories. The Lancet. 2012;380(9857):1936-1945. https://doi.org/10.1016/S0140-6736(12)61678-X.
49. Lerner H, Berg C. A comparison of three holistic approaches to health: One Health, EcoHealth, and Planetary Health. Frontiers in Veterinary Science. 2017;4:163. https://doi.org/10.3389/fvets.2017.00163.
50. Muller-Karger FE, Hochberg EJ, Hu C, Liu Y, LaPointe BE, Muller-Karger CM, *et al*. Satellite sensor requirements for monitoring essential biodiversity variables of coastal ecosystems. Ecological Applications. 2018;28(3):749-760. https://doi.org/10.1002/eap.1682.
51. Thomsen PF, Willerslev E. Environmental DNA in ecology: achievements and prospects. Biological Reviews. 2015;90(3):751-777. https://doi.org/10.1111/brv.12132.
52. Reichstein M, Camps-Valls G, Stevens B, Jung M, Denzler J, Carvalhais N, Prabhat. Deep learning and process understanding for data-driven Earth system science. Nature. 2019;566(7743):195-204. https://doi.org/10.1038/s41586-019-0912-1.
53. Long RD, Charles A, Stephenson RL. Key principles of marine ecosystem-based management. Marine Policy. 2015;57:53-60. https://doi.org/10.1016/j.marpol.2015.01.013.
54. Rochette J, Bille R, Molenaar EJ, Gjerde KM, Lutchman I, Unger S, *et al*. Regional oceans governance mechanisms: a review. Marine Policy. 2014;50:212-237. https://doi.org/10.1016/j.marpol.2014.05.012.
55. Williams BK. Adaptive management of natural resources—framework and issues. Journal of Environmental Management. 2011;92(5):1346-1353. https://doi.org/10.1016/j.jenvman.2010.10.041.
56. Fulton EA. Approaches to end-to-end ecosystem models. Journal of Marine Systems. 2010;81(1-2):171-183. https://doi.org/10.1016/j.jmarsys.2009.12.012.
57. Rüegg SR, McMahon BJ, Häsler B, Esposito R, Nielsen LR, Ifejika Speranza C, *et al*. A systems approach to evaluate One Health initiatives. Frontiers in Veterinary Science. 2018;5:23. https://doi.org/10.3389/fvets.2018.00023.
58. Zinsstag J, Prudêncio D, Anvar M, Gilbert J, Whittaker M, Moolenaar R, *et al*. Mainstreaming One Health. EcoHealth. 2015;12(1):103-111. https://doi.org/10.1007/s10393-014-0960-5.