OCEAN ENTERPRISE INITIATIVE

Dialogues with Industry

Harmful Algal Blooms (HABs) Summary Report

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Executive Summary

The Marine Technology Society (MTS), Global Ocean Observing System (GOOS), National Oceanic and Atmospheric Administration (NOAA), United States Integrated Ocean Observing System (IOOS), and Industry (Kongsberg Discovery and L3Harris), lead the Ocean Enterprise Initiative, which focuses on understanding how to mature the Ocean Enterprise market sector.

The second *Dialogues with Industry* (hereafter *Dialogues*) series, focused on harmful algal blooms (HABs), consisted of three curated dialogues held in January and February 2025. The HABs *Dialogues* explored and defined market dynamics, identifying barriers and opportunities. The discussions focused on maturing the public/private/academic partnership, enhancing capability, and expanding capacity to meet the growing societal need for actionable, fit-for-purpose ocean data. This effort is driven by regional requirements and specific use cases.

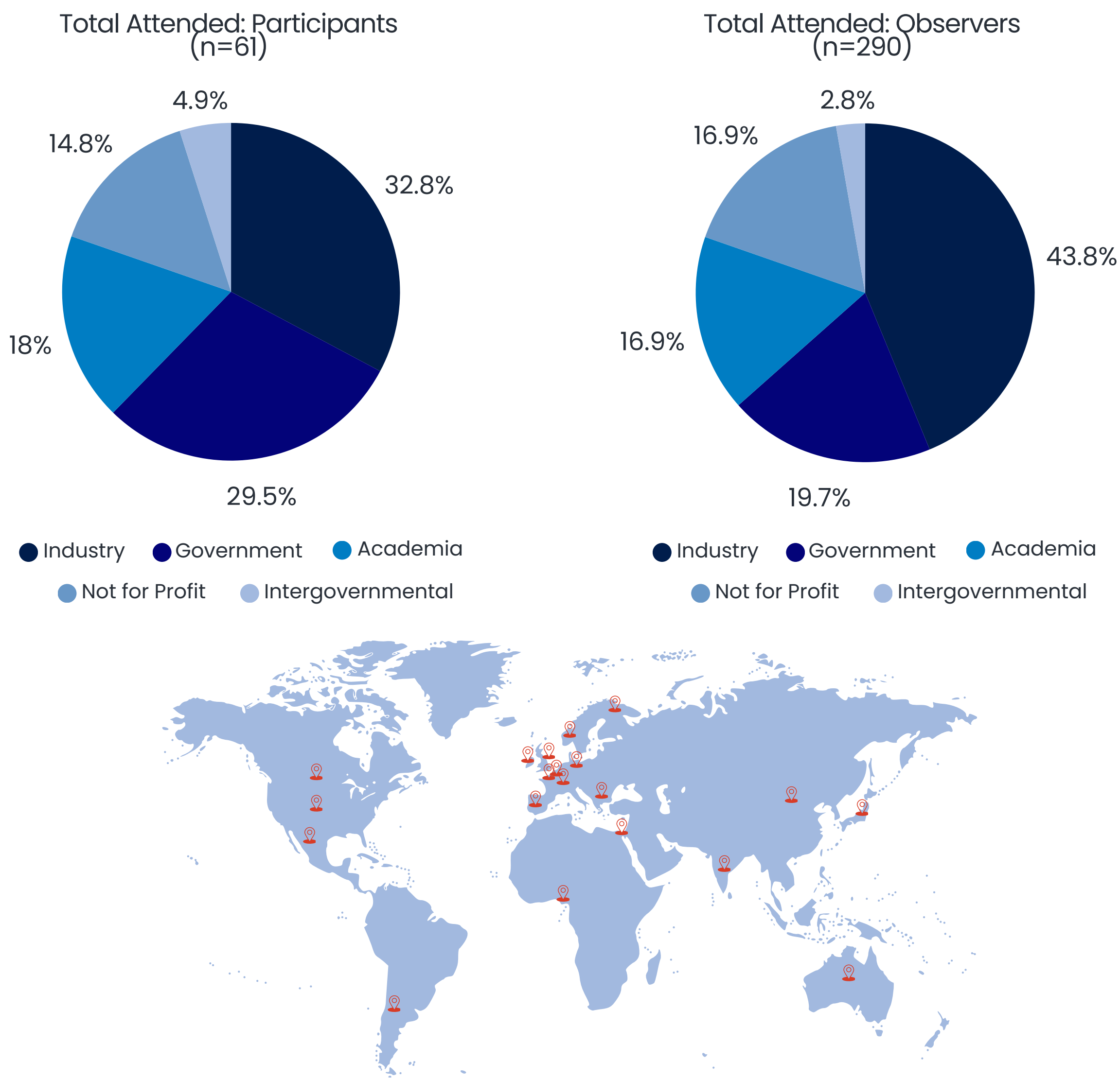

Figure 1: *This graphic visualizes the sectors represented by the participants and observers. The lower figure represents the geographic reach of the Dialogues.*

The HABs *Dialogues with Industry* – Summary Report synthesizes the three dialogues and aligns the results with the [*Dialogues with Industry* Roadmap](). The results of the HABs *Dialogues* fit within the priority areas defined in the Roadmap:

- Improving the Marketplace
- Collaboration to Grow and Impact Change
- Shaping the Future

Twenty-one action pathways were identified under eight of the challenges from the *Dialogues with Industry* Roadmap and are depicted in Figure 2 below.

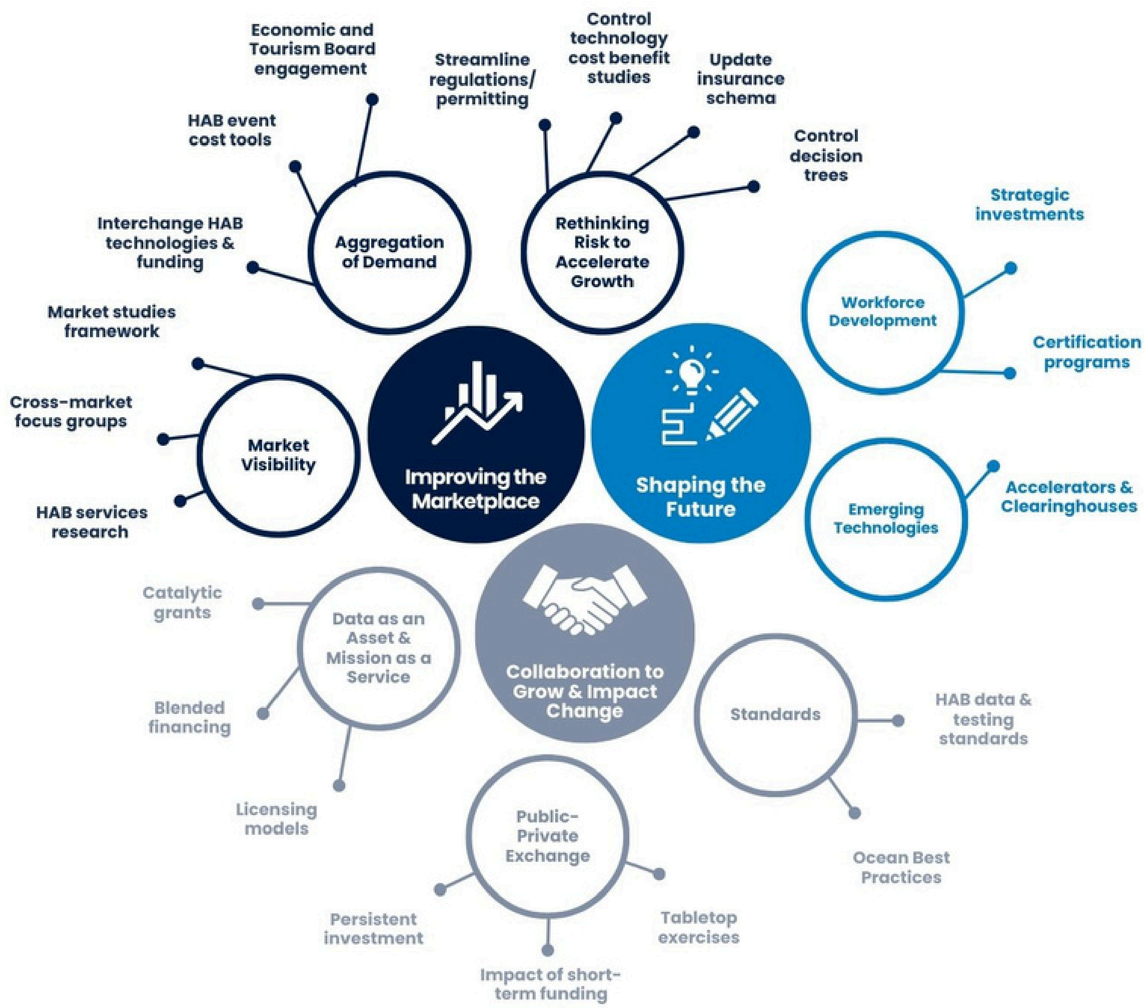

Figure 2: *This graphic was designed to connect the key outcomes of the HABs discussions while mapping back to the Roadmap challenges. These high-priority action pathways are identified with the challenges they are addressing and associated with the three priority areas: Improving the Marketplace, Collaboration to Grow and Impact Change, and Shaping the Future.*

The document was developed at the strategic implementation level and is dependent on collaboration across the Ocean Enterprise for success. It is important that these action pathways are **linked to other initiatives**. This effort is not about starting new efforts but rather coalescing the Ocean Enterprise around existing efforts. Only if a gap is identified should a new effort be started. Appendix 1 outlines the existing entities that are already engaged in HABs, and all collaborators are welcome.

About the *Dialogues with Industry*

The *Dialogues with Industry* is a flagship series of curated dialogues under the Ocean Enterprise Initiative. It is an international forum that brings together representatives from new and established companies, academic institutions, and government agencies to discuss the opportunities and challenges across the entire Ocean Information Value Chain, which is essential to achieving the goal of a mature Ocean Enterprise.

The Ocean Enterprise is a nested component of the ocean economy within the realm of maritime monitoring, mainly focused on the fields of ocean observing, forecasting, and services spanning public, private, and academic sectors. Members of the Ocean Enterprise provide observation, infrastructure, measurement, forecasting, and operational services to inform marine decision-making.

The "Ocean Information Value Chain" is a conceptual framework that outlines the transformation of ocean observations into products and services that deliver information to decision-makers. The framework comprises several components that interconnect to deliver information to end-users, who derive benefits from these information products. The Ocean Information Value Chain approach allows us to illustrate the importance of ocean information and related services.

The *Dialogues with Industry* series is distinct from other industry engagement efforts because it brings together the components of the Ocean Enterprise with facilitated discussions across the Ocean Information Value Chain, depicted in Figure 3. The three *Dialogues* focused on the main components of the Ocean Information Value Chain, namely (1) Instrument Provisioning, (2) User-Driven Ocean Information, and (3) Advancing Control Technologies.

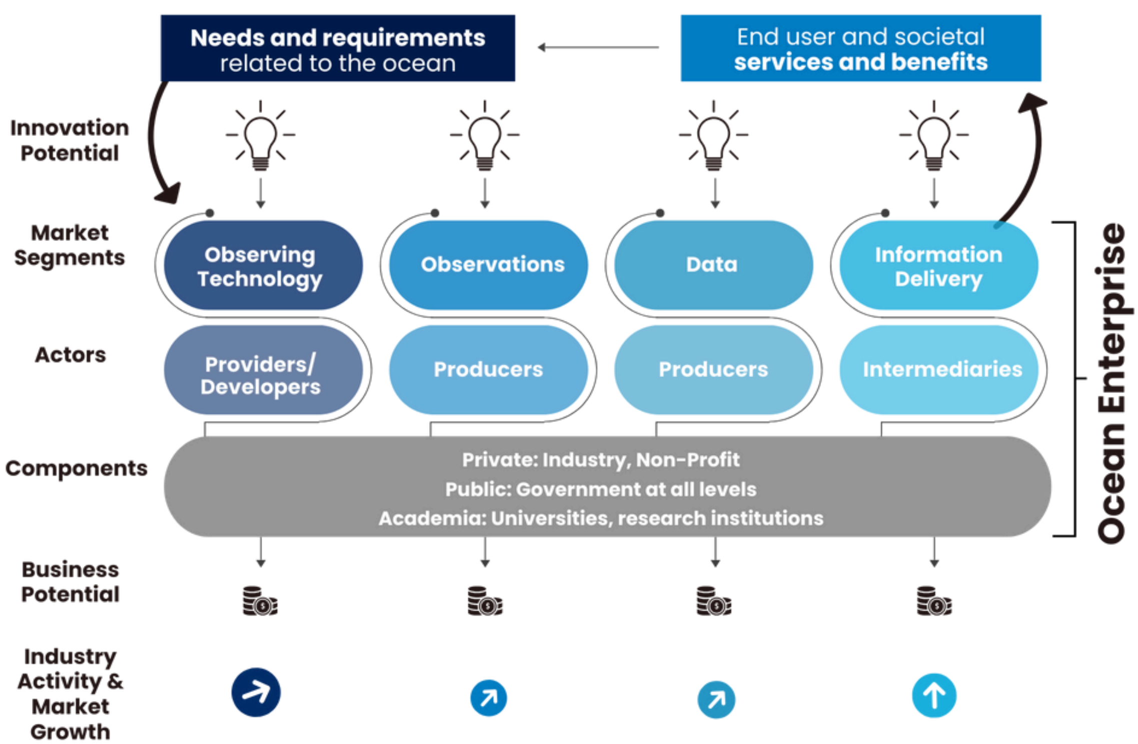

Figure 3: *This graphic visualizes the Ocean Enterprise and its interconnected components and activities across the Ocean Information Value Chain. The blue discs visualize the current level of private industry involvement in the segment, i.e., they offer an estimate of the current relative market size. The arrows indicate our estimate of private industry growth potential in each area (vertical is high). All market segments have the potential for innovation and commercial exploitation.*

Structure of the Document

The document links the action pathways to the challenges and priority areas. The priority areas are those within the Roadmap, but issues are tailored to those discussed within the HABs *Dialogues*. The tables present the challenge areas within the priority areas and include:

- **Challenge:** Elaborates on the ocean challenge.
- **Success Indicators:** Defines key indicators to evaluate success.
- **Action Pathways:** Suggested actions to move ahead.

The challenges associated with each of the priority areas are as follows:

- **Improving the Marketplace** focuses on improving the market visibility, aggregation of demand, and rethinking risks to accelerate growth.
- **Collaboration to Grow and Impact Change** focuses on data as an asset and missions as a service, private-public exchange, and standards.
- **Shaping the Future** focuses on workforce development and emerging technologies.

This is illustrated in Figure 1 in the Executive Summary. As each challenge is scoped, additional action pathways will be identified to achieve the success indicators. Appendix 2 arrays the key takeaways from the three *Dialogues* under the challenge areas.

Improving the Marketplace

The HAB sensor and platform market continues to evolve and grow, with consistent and predictable demand for ubiquitous, cost-effective, reliable, easy-to-use, multi-targeted sensing systems. However, because HAB impacts are localized, authorities set requirements levels too low, and impacted resources are managed independently, sensor requirements are developed in a highly segmented fashion, leading to inefficiencies within and across agency jurisdictions and market sectors, leading to inconsistencies within and across jurisdictions. As a result, industries have yet to develop a reliable supply for such systems. For both HAB sensor and control technologies, due to the varying market demands across multiple sectors, geographic regions, organisms, and toxins make a single solution unlikely. Greater coordination is needed to scale these markets effectively.

The global market for HABs monitoring needs to be clearly defined based on return on investment (ROI). A significant issue is that the full size of the market for HAB downstream services is currently unknown, making it difficult for private sector innovators to develop business plans that attract investors.

Downstream services are the value-added products and information that have been derived from the processing and analysis of *in situ*, laboratory and satellite data. Having some idea of the number of potential users, the range of potential applications, and the capacity of users and their willingness to pay would allow evaluation of the potential ROI. For HAB control, education and influence from both industry and community are needed. Valuing the avoided costs of HAB impacts prevented or mitigated is another element of defining the marketplace. Like the first *Dialogues* series, there are not enough credible market studies or impact studies that the private sector can use to secure investment funds to scale this market. Researchers and industry leaders need to establish independent data, papers, and results that demonstrate the actual significance, value, and quantifiable mitigation outcomes achieved—essentially conducting a cost-benefit analysis.

Aggregation of demand is one of the most significant issues. However, the localized nature of HAB impacts means that demand is currently 'myopic'. Governments and communities aren't seeing the bigger picture, limiting the ability of industry, supported by academia, to respond at a scale that would be commercially viable. There are drivers of this demand in aquaculture, tourism, health, and other sectors, but the challenges of implementing observation, monitoring, and control make HABs a niche market.

The greatest pull is from the government sector relates to food consumption and public health, but there is a potential for advancing private sector engagement through two government actions: (1) setting requirements for sensors, platforms, and services and (2) setting standards. The participants noted that government should not "do everything" using public funding but rather called for government to show leadership in aggregating demand and setting integrated requirements and data standards, thereby creating an environment conducive to private sector and academic investment and innovation.

Three significant risks were identified in advancing this market sector. The regulatory regime is fragmented, burdensome, and lengthy. This relates to the need for agreed to standardized metrics for test kits, better understanding of control methodologies, and separate testbeds from affected resources (e.g., an aquaculture farm). The second risk is that the insurance sector does not recognize and reduce rates for the farmers who have employed control methods. The third risk is associated with HAB control, overcoming the negative perception of control methodologies, and the need to ensure that methods are environmentally friendly.

Challenge: Market Visibility

The HABs *Dialogues* identified three challenges related to the market economy. The first challenge is that the full size of the HABs market is unknown; the second is the need to diversify the market; and the third is the need for market analysis to understand and share technology.

A significant issue is that the full size of the market for HAB downstream services is currently unknown, making it difficult for private sector innovators to develop investable business plans. Having some idea of the number of potential users, the range of potential applications, and the capacity of users to pay would allow potential return on investment to be evaluated. Therefore, determining the size of the HAB downstream services market is considered a significant opportunity. Developing the tools to assess the cost of a bloom's impacts is a related issue.

The disparity in the market levels leaves the impression that the market is not of sufficient breadth or depth for commercial sustainability. This was clear in the difference in market levels when looking at the shellfish farms that face high barriers to entry due to small farm economics and regulatory costs. This is compared to the finfish sector, which is made up of larger corporations that have experienced significant funds loss due to HAB events.

There was a consensus that HABs are a niche market that needs to be diversified. Diversifying both missions and data comes with a significant price tag. Investment is required to drive down the costs of developing and manufacturing sensors and to develop more multi-parameter sensors. Further, a market is required to justify the costs of producing sensors. One possible solution is to leverage adjacent markets. Suppose HAB detection methods can be low-cost and deployable at scale. In that case, they may also be attractive to public health pathogen (e.g., vibrio bacteria) monitoring and other similar efforts, providing that detection of these new targets can be easily integrated into the sensor technology.

There is a need for a consolidated market report specifically for the aquaculture sector to show current users the available technology that might be targeted for adopters. This could include industry representatives such as current multinational companies or businesses trying to expand. There is a need for better market size information breakdown of the sectors and the adjacent markets, looking at the regulations and the standards competition, what's already out there, and current techniques and best practices. These reports must also present realistic analyses of how conservative some of these markets are and identify potential routes to the market. If sales increase because of dedicated marketing reports, the user base and variety of use cases increases, which will drive further investment and innovation.

Success Indicators

- Determination of the global market size for monitoring and control technologies for HABs.
- Establishment of a systematic, repeatable method to continuously update the value of the industry component of the HABs market.
- Creation of a location where curated market reports are accessible.

Action Pathways

- Professional societies, like the Marine Technology Society, as well as intergovernmental programs like Intergovernmental Oceanographic Commission (IOC)/Food and Agriculture Organization (FAO) - Intergovernmental Panel on Harmful Algal Blooms (IPHAB), GOOS, and the UN Decade (e.g., Harmful Algae Bloom Solutions (HAB-S) Programme, in partnership with the International Society for the Study of Harmful Algae (ISSHA), could set up focus groups to develop concrete steps to resolve challenges in scalability, cross-market reach, and regulatory regimes across the Ocean Enterprise.
- Creating a structured framework for conducting market studies will encourage investments from both public and private sectors to support these analyses. The framework would facilitate standardization of studies.
- Complete market research, including socio-economic parameters, to define regional, national, and international markets for downstream HAB services.

Challenge: Aggregation of Demand

Aggregating market demand for ocean observing technology, data, and information can create markets large enough to attract industrial involvement, development investment, and financing. The heterogeneity of industry sectors was again raised as a key challenge in aggregating demand. Tourism and recreation are huge sectors compared with shellfish aquaculture, but they have very different needs and very different business and cost models. The importance of defining and valuing the total addressable market for HABs was again discussed as a threshold issue. As part of this discussion, it was noted that we do not currently have the tools to determine the cost associated with a HAB event.

For a market pull, the perspective on monitoring and management must extend beyond looking for a specific HAB species or toxin. A shift from HAB-specific monitoring and sensors to more holistic observing efforts and related data/information products could aggregate demand across multiple sectors or end users, inherently increasing value.

Well-established markets respond favorably to predictable demand signals from large customer bases. Regarding HABs, the primary demand still comes from the public sector, which is responsible for food safety/security and human safety. In many cases, sensor developers are also reliant on government funding for their sustainment. The private sector needs to communicate that the dependency on jobs is tied to government funding, which is a critical aspect of communicating the value of the Ocean Enterprise.

Currently, requirements and standards for HAB sensors, platforms, and services are often set case by case at a specific or localized level, making it difficult for industry and academia to respond at scale. Despite the best efforts of all involved, this 'many to many' approach does not provide sufficient scale to attract the investment required. A government-led 'one to many' approach to HABs, with regulatory backing for integrated requirements, would aggregate demand and provide the economies of scale required to focus on private sector and academic investment and innovation.

Examples of current activities focused largely on the human health impacts of HABs, with tourism and fisheries (both wild and farmed) benefiting from investment in services dependent upon HAB data. Shellfish aquaculture efforts are largely undertaken by small businesses and are highly regulated. The financial impact of HABs on finfish farming can be significant but is infrequent at the farm level, where the issues manifest and are managed, further entrenching a fragmented approach. The impacts of HABs on other valuable industries, such as coastal tourism and water provision (including through desalination), have been documented in each sector but are not currently considered in an integrated fashion, making it difficult to describe a larger market. These and other impacted industries may have the capacity to invest, but it is currently challenging for them to engage with the issue of HABs at an Ocean Enterprise level.

Specifically, when it comes to HAB control technologies, there is a disconnect between the drivers and the push for implementation: While drivers across the aquaculture, tourism, desalination, and nuclear sectors were identified, the push for control technology implementation has not been realized. Factors contributing to the lack of implementation include (1) lack of market analysis for control compared to response, (2) lack of budgets within local and regional governments, and (3) lack of understanding of available control methodologies, and how and when to best employ them. Working with Economic Development Agencies, Tourism Boards, and other Associations can influence the acceptance of control methodology to put ownership and control in the hands of managing authorities, which is important for promoting acceptance. Part of this is an evolution in thinking about what constitutes green infrastructure – from 'build it, and they will come' to 'manage it, and they will come.'

Success Indicators

- A global HAB monitoring system is defined, and progress in implementing that system is measurable.
- An Ocean Enterprise Interchange for requirements, technologies, and public and private funding opportunities has been identified.
- HAB control technologies are implemented in the coastal waters and demonstrate a positive impact.

Action Pathways

- Establish an interchange of information based on requirements and available technologies, as well as funding opportunities to bring the sectors together.
- Support socio-economic research to develop the tools to determine the costs associated with a HAB event, and to improve estimates of aggregate annual HAB costs by nation and globally.
- Conduct focus groups with relevant Economic Development Agencies and Tourism Boards to understand the value of HAB mitigation (monitoring and forecasting) and accelerate the use of control technologies and document successful deployment targeting regions with HAB problems and where tested control technologies are available.

Challenge: Rethinking Risk to Accelerate Growth

Three risk areas were identified: a fragmented regulation regime; outdated insurance schemas; and a negative perception of control technologies.

Often, regulation drives demand for new HAB observing technology. That demand drives the perceived market for new HAB sensors, which will increase investment. That increase in investment lowers unit costs and hopefully lowers the threshold for adopting new observing technologies.

The regulatory environment is not homogeneous and is often influenced by cultural, political, and governmental factors. Regulations and permitting were identified as a big obstacle for commercialization. The lack of consensus across jurisdictions on the requirements to achieve permitting approval is a major issue for industry and academia working regionally, nationally, and globally. The length of time for permitting is stifling commercialization for HABs control technologies. Even when a particular method has been proven effective in a test case, getting approval for a larger-scale demonstration of the technology is challenging. If there is no perceived market or the people who need this do not have the money, industry will not invest in technological development.

It is essential to include regulators early in developing new technologies to ensure that once the technology is developed, the information derived from the sensor will be fit-for-purpose. Linked to this is the need to have agreed-upon performance and/or detection thresholds. Agreed upon thresholds for some toxins do not exist. Without regulation, it is very difficult for a sensor designer to move forward, particularly in biosensing, which needs to target a regulatory threshold or suitable detection range. If there is a good regulatory market or basis for the regulatory market, then it opens doors in terms of development.

An adjacent issue is how the regulatory framework has affected the stability of the rapid toxin test kits. Recently, a well-known and established company withdrew from the shellfish toxin testing the marketplace, which was a warning sign that after ten years of effort in optimizing an assay and gaining a large share of the market, this effort was ultimately deemed not critical to the company's bottom line. While some organizations certify the performance of test methods, the fees are too costly for most small businesses and must be subsidized with funding from grants or other sources. Another barrier is that there is little available data to guide the industry in deciding which kits are most fit-for-purpose, and which have met their needed performance criteria. However, entities such as the U.S. Interstate Shellfish Sanitation Conference provide an approval pathway for screening and regulatory applications.

The testing required by the regulatory standard is complex. The shellfish industry operates on a weekly testing schedule and is highly competitive. There is a potential opportunity to develop a toxin test kit that is easy and simple for farmers to interpret, providing them with an early read on risk as they await regulatory agency results. There is no universal enforcement of testing, which limits the commercial demand for limited commercial demand for independent test kits. This gap must be addressed to strengthen risk management practices.

The second risk involves the insurance sector. Finfish farming insurance is a global market, though one significant event can wipe out the premium pool for a year. This makes HAB-caused losses difficult to predict from an actuarial perspective.

The four biggest insurers monitored HABs for 20 years to understand and model the risks of HAB-related loss, but they did not sustain the program because it was not cost-effective for the sector. Innovative approaches currently being developed to finance resilience could provide guidance on how to deal with the complex problem of HABs. A second aspect is how the insurance sector views control technologies. Farmers across the aquaculture sector who have demonstrated a proven record of using effective HAB controls are not benefiting from lower insurance rates. There are relatively few underwriters who evaluate the market globally, spreading the risk evenly over farmers who employ control practices and those who do not.

The final risk is how HAB control technologies are perceived. There is often a negative perception of control technologies as they are linked to chemicals and misidentified as pesticides. A coordinated communication campaign is needed to overcome this negative perception. As the control technology sector is still emerging, there is a need to understand when, how, and which control methods to employ.

Success Indicators

- National to global regulations metrics and standards are developed and implemented.
- Insurance policies consider the implementation of HAB control technologies.
- Negative perceptions of control technologies have been overcome.

Action Pathways

- Work with regulatory agency permitting staff to understand regulations and explore ways to streamline the regulations. Help HAB scientists working on control to navigate regulatory processes and increase opportunities for HAB community and industry engagement and partnership including working with existing efforts such as the United States Harmful Algal Bloom-Control Technologies Incubator (US HAB-CTI), which is working on developing materials to identify and navigate permitting requirements.
- Organize small convenings with the appropriate global insurance corporations to establish favorable cost structures to incentivize control methodologies.
- Commission Cost-Benefit studies to cross-compare different types of control methods; to compare use of a control method to no control; and to compare employing cost control methods externally to an aquaculture farm or water treatment plant to respond to efforts either after a bloom in the case of the farm or within a treatment plant.
- Develop decision trees on when and how to employ HAB controls.

Collaboration to Grow and Impact Change

The preconditions for collaboration to grow and impact change are positive across HAB instrument provision, downstream services, and control technologies. There are many past and current examples of productive collaborations between academia, industry, government, and community. The localized nature of HAB impacts keeps current demand narrow in scope. As mentioned in the earlier Market Visibility section, significant challenges exist in sizing the market, aggregating demand, and managing risk.

As Market Visibility challenges are addressed, it is essential to ensure that the enablers of collaboration to grow and impact change are in place and that potential barriers are removed. Three issues emerged as important. New market models and business models are required to enable the private sector to participate fully in the HAB marketplace. More active engagement and exchange between the public and private sectors must be fostered. Related to both issues, more evident standards need to be implemented to provide common targets for instruments and services and create a 'level playing field' for competition.

Photo Source: NASA Earth Observatory (2011). The green scum shown in this image is the worst algae bloom Lake Erie has experienced in decades. Vibrant green filaments extend out from the northern shore.Image captured by the Landsat-5 satellite. Data provided courtesy of the United States Geological Survey.

Challenge: Data as an Asset and Mission as a Service

SSome regulatory-driven markets exist to protect public health from known HAB impacts. Such markets can provide an informative signal for guiding sensor development. Regulatory limits are often unclear (e.g., anatoxin-a), or sensor development is immature (e.g., ciguatoxins). Non-regulatory markets also exist to understand the role of HAB species and plankton in general in supporting healthy ecosystems and how they respond to change. Other market sectors are more financially motivated to develop HAB sensors and solutions to support the optimal production of farmed seafood products (e.g., salmon aquaculture).

Across regulatory, non-regulatory, or financially driven markets, it is worth exploring untapped opportunities for public-private collaboration in HAB technologies and data generation. Further discussion is needed to explore the potential for a "mission" or "data" as a service concept, including whether the market sectors that can benefit from actionable HAB data (e.g., shellfish growers, finfish farmers, water treatment, and desalination facilities) would be receptive to a third party providing the sensors and missions and/or data services.

Several models could be considered, such as 'mission' as a service, where a private company takes on the cost and risk of operating a platform, but the paying entities control the data. Another model is a private company that collects the data and provides a value-added product to the customer. Another model would be the public sector maintaining a scale of production and local operators co-pay for deploying instruments. This could be done using a tax and credit system for a consortium of users where the co-pay amount could be based on the business size.

Startups have much more flexibility in their business and licensing models, particularly with more and more data going to the cloud. This is promising for the future of the Ocean Enterprise as many new companies will hopefully be established. Startups using cloud-enabled technologies can be very agile in structuring data and services in ways that work for their clients. Sensor and platform companies are now focused on telemetry systems and the presentation of data, including analysis tools and data processing, in a simplified package, and they have ready access to the contemporary technologies required.

Downstream HAB services by the consulting industry are typically in response to a single client's terms and conditions and views about restricting access to data and products. This business model is at odds with the approach of data or software as a service. Shifting to an end-user license agreement model, already used in the land remote sensing sector, or adopting the radio occultation purchase model could provide adaptable solutions.

Success Indicators

- Increased private sector provision of instrument/sensor missions and data services delivering actionable HAB data across multiple market sectors.
- Some startups in the Ocean Enterprise include HAB missions and services as part of their product offering.
- New, end-to-end solutions are available, combining platforms, sensors, data processing, and analysis tools in a simplified package.

Action Pathways

- Grants to catalyze early-stage collaboration between private sector innovators and academic and government research institutions to foster early-stage collaboration to realize the upside potential of HABs.
- ·Greater use of blended finance approaches to mitigate the risk of government seed grants ending before products and services are fully market-ready, with potential investors being engaged at an earlier stage to maximize the chances that small-to-medium enterprises (SMEs) can deliver their innovations to the market.
- Broader use of end user licensing agreements, which could be modeled after the land remote sensing industry, the purchase of radio occultation data, and or the open-source licenses in the software industry.

Challenge: Public/Private Exchange

SSustained and coordinated investment in public weather services underpins the growth and expansion of private sector missions and services now seen as an integral part of the global Weather Enterprise. It provides a model for the Ocean Enterprise to foster greater engagement between the public and private sectors. Operational marine environmental monitoring services, including HABs, are not yet at the standard of weather, and biological and ecological processes are inherently more difficult to monitor. The societal need for such services is however very high, and rapid advances in sensors, platforms, telemetry, data processing and analysis (including machine learning and artificial intelligence), visualization, and decision support provide confidence that societal benefits will be realized with sustained focus on public/private exchange.

There is a need to continue advancing operational HAB observing systems to accelerate research and unlock new opportunities for industry and public-private partnerships: Efforts supported by time-limited funding (e.g., research projects or annually renewed pilots) have demonstrated the effectiveness of HAB observing systems to help mitigate impacts and need to continue. Maturing innovations and successful pilots into operational HAB observing systems will sustain these benefits and provide a basis for the private sector to develop value-added products and services to keep pace with the expanding global HAB problem.

The most continuous and consistent investment has been from the public sector, which has driven the development, testing, and piloting of HAB sensors and regional observing systems. This sustained investment in operational HAB observing systems benefits impacted industries. Engagement between public and private sector partners helps generate data and systems that support ecosystem research, regulatory actions, and business decisions. There are a variety of end users that would benefit from coordinated ocean observations and data. Innovative thinking is needed to design and manage these systems and incorporate public-private partnerships. Governments cannot fund the whole bill. Yet, governments often can manage aspects such as data collection, analysis, maintenance, and distribution. However, public-private partnership funding may be necessary for the system to be sustainable and flexible enough to adopt technological advances.

Success Indicators

- Industry advocacy for sustained investment in operational HAB observing systems based on socio-economic benefits to impacted industries and regional communities.
- Private sector developed HAB products and services built on publicly funded operational observing systems being delivered and used by impacted industries and communities.
- Public-private partnerships established that develop value-added products and services to keep pace with the expanding global HAB problem.

Action Pathways

- ·Create a discussion paper on the potential cost of continual short-term thinking about key observing infrastructure to society.
- Create tabletop exercises involving local and national government to understand the impact of HAB occurrences better, the need for HAB monitoring and services, and the planning for response.
- Communicate the need for persistent government investment in core services and data that are the foundation of the private sector to create derived products and applications to meet the needs of individual user groups with specific user requirements.

Challenge: Standards

Participants in the inaugural *Dialogues* series identified the need for standards, and it was raised again in this follow-on series. The lack of standards is a barrier to a thriving and expanding private sector engagement. For the private sector, there is no defined and common target to achieve for data or instruments provided. For the public sector, there is no measure or 'standard' to hold private sector providers accountable for delivery. The private sector has indicated that standards, if used well, can create a 'level playing field' for competition, such that achieving the standard would mean that the data/instrumentation is fit-for-purpose.

Standards for validating, formatting, and organizing HAB data must be developed, implemented, and communicated. In addition, data sets, especially those generated by imaging sensors, are enormous and often require further processing and analysis. Support is needed to maintain a supply of certified reference materials for toxin-specific sensors and standards for validated image classifiers. Consideration of integrating data collection by various national, subnational, or private sector entities is needed. Further, focusing on international and national bodies that promote collaboration can help the field adapt as standards change with new legislation, instruments, or methodologies.

The government has a key role in setting the required data standards. A lack of access to data from disparate sources constrains the development of HAB services. The government is distinctively placed to set the standard for data to be findable, accessible, interoperable, and reusable (FAIR) by default through its roles as both a regulator and a facilitator of industry development. The Global Telecommunications System (GTS) for weather observations provides a vision to aspire to, and the IOC-FAO IPHAB can support the development of FAIR data standards to help enable such a vision.

Standards around HAB control testing metrics and types of testing were also discussed. Issues raised included cell reduction versus toxin reduction standards, replicated trials, including 'no treatment' control, and relative impact of alternative treatments.

Success Indicators

- Larger, longer-term, more spatially expansive HAB datasets are findable, accessible, interoperable, and reusable (FAIR).
- Requests for Proposals (RFPs) for HAB missions and services have defined and common targets that provide a 'level playing field' for industry and quantitative evaluation criteria for industry, government, and academic users.
- New HAB services are available based on access to data from disparate sources that conform to FAIR principles.

Action Pathways

- ·The IOC-FAO IPHAB can support the development of FAIR data standards to help enable such a vision.
- Work with the Oceans Best Practices effort as a repository of HABs practices and standards.

Shaping the Future

TThe growth of the Ocean Enterprise market is dependent on the availability of a highly skilled and diverse workforce that can meet future demands, as well as a capacity to exploit emerging technologies that can enhance the value and impact of ocean data, information, and knowledge.

Broadly, the Workforce Development challenges facing the HAB sector are no different from those faced by the Ocean Enterprise. The technical and quantitative skills required are in high demand across various industries and sectors, many of which can offer higher remuneration levels (e.g., IT, Finance, etc.). The distinctive issue for the HAB workforce is the importance of specialist expertise in algal taxonomy and natural products\toxin chemistry.

Similar and related challenges arise in emerging technologies. Many issues around emerging HAB technologies are relevant to other areas of marine environmental monitoring. However, the precision required to determine the likelihood and consequence of what algal blooms are harmful in space and time is a distinctive HAB requirement.

Photo Source: Southby, J. (2024). Students on research vessel. MTS Summer Workshop, Northwestern Michigan College, Traverse City, MI.

Challenge: Workforce Development

Generating reliable and effective HAB data streams that meet user needs requires specialist expertise, especially in taxonomy and natural products\toxin chemistry experienced with algae. The combination of an aging expert scientific workforce, opportunities for skilled staff outside of traditional science, and rapid uptake of new technologies (including Artificial Intelligences (AI)) suggests a shift in the balance between specialization and generalization in the future HAB workforce.

In the future, there may be less traditional, specific expertise and more general, problem-agnostic expertise facilitating faster uptake of new technologies and approaches to the problem of HABs.
Microcredentials and short courses will have a key role in cross-fertilization of expertise at appropriate levels.

Success Indicators

- Maintenance of core specialist expertise in taxonomy and natural products\toxin chemistry experienced with algae.
- HAB-specific microcredentials and short courses being delivered and taken up.
-

Action Pathways

- Capitalize on and create partnerships between existing groups like IOC-FAO IPHAB, MTS and national HAB-focused government, academic, and private sector groups and communities of practice (e.g., US NHABON or industry user groups like McLane Labs IFCB User Group) to build support for strategic workforce investments needed to tackle HABs and other pressing and complex ocean-based challenges.
- Sustain and expand support for harmful algae training and certification programs (e.g. Bigelow Laboratory's annual Karen A. Steidinger Marine Harmful Algae Taxonomy Course) and (e.g. IOC UNESCO trainings.)

Challenge: Emerging Technologies

TThe growth of the Ocean Enterprise market is inhibited by the slow adoption of emerging technologies, which are necessary to ensure systems evolve for the improved delivery of public services. A distinctive HAB requirement is the precision required to determine the likelihood and consequence of which algal blooms are harmful in space and time.

The current HABs observing systems are costly and complex. The cost of sensors, data management, and data interpretation expertise are barriers to advancing technologies. Current instruments like the Environmental Sample Processor (ESP) and the Imaging FlowCytobot (IFCB) have enabled observing HAB events and assessing their associated toxin levels and should remain a mainstay of monitoring, but they are unaffordable in large quantities.

Driving down the cost per observation needs to remain a priority for private sector developers. There is a demand for affordable instrumentation at the farm site level, including undertaking an internet-of-things testing on a farm rather than waiting for toxin test results from governmental laboratories.

Thinking about HABs at a larger or regional scale means that sensors will need to be able to detect a wider range of HAB species.In response, the sensor developers can think about sensor technologies that can be 'tuned'. For example, with a broadly based capability to measure the spectral absorption of species, different sample processing methods could be triggered by the detection of different species in an ESP. Their design could have a set of standard sensors, but they can respond to species of interest at the local level.

AI presents both challenges and opportunities. Early-career professionals who have grown up with AI offer fresh perspectives on how it can address gaps in workforce development. In the medium to long term, the demand for experts may decrease as AI models become more advanced, though such models are still far from ready and human-in-the-loop validation will likely still be required at some level. Participants emphasized the need for AI standards to build trust and confidence among users, and investors, ensuring they can reliably depend on AI-driven products and services. Beyond training AI, rigorous validation is essential to support its adoption and attract capital investment.

The role of satellite remote sensing had a low profile in the *Dialogues* on instrument provision and user-driven ocean information but had much higher prominence in the dialogue on control technologies. One possible explanation is that all available information is potentially useful in a HAB control situation, and satellite remote sensing data has high spatial and temporal availability. Satellite and airborne (e.g., drone-based) remote sensing and modeling tools from current and future missions are important in HAB surveillance, monitoring, forecasting, and situational awareness, especially given the rapid advances in hyperspectral imaging that may allow discrimination of different HAB classes. There are limitations (sub-surface, identification at species level), and it is necessary to complement remote sensing with in-water sampling and observations when required.

Success Indicators

- Successful development of generic sensors that can be triggered to detect HAB species and toxins of interest.
- HAB downstream services using AI are trusted to inform operational decision making (e.g., human health).
- Better utilization of satellite and airborne remote sensing in operational HAB monitoring.

Action Pathways

- Entrepreneurs, governments and professional societies should seek to participate in and foster the further development of incubators, accelerators and clearinghouses, which serve the interests to their membership in expediting access to information resources, mentorship and funding opportunities.

Going Forward

The *Dialogues with Industry* – HABs has been instrumental in defining and refining a set of clear priority actions that function across the ocean information value chain to lower barriers and increase opportunities for a public/private partnership in delivering HABs observing, services and control. The summary document is intended to be a resource for the Ocean Enterprise to help focus future discussions and the start of practical work. Some suggestions for going forward include:

1. **Work** with the Ocean Enterprise Initiative to define specific focus groups.
2. **Recruit** additional partners to provide advice on how to move HABs services to an operational footing.
3. **Identify** new platforms for discussing the importance of HAB monitoring and control.

The success of this effort will require continued support, interest and commitment to making the pathways effective and impactful across private, government, and science.

Appendix 1: International and National Response to HABs

The purpose of this appendix is to identify committees and organizations that have a role in overseeing policy, regulations and/or funding for HAB efforts. This is an area where the HAB stakeholders could work to identify additional response entities.

International
European Food Safety Authority (EFSA)
Food and Agriculture Organization of the United Nations (FAO)
International Atomic Energy Agency (IAEA)
International Council for the Exploration of the Sea (ICES) – IOC Working Group on Harmful Algal Bloom Dynamics (WGHABD)
International Society for the Study of Harmful Algae (ISSHA)
IOC-FAO Intergovernmental Panel on Harmful Algal Blooms
North Pacific Marine Science Organization (PICES)
World Health Organization (WHO)

United States State government agencies lead efforts overseeing human health, fisheries, and aquatic/marine resources.
Centers for Disease Control and Prevention (CDC)
Interagency Working Group on Harmful Algal Bloom and Hypoxia Research and Control Act (IWG-HABHRCA)
Interstate Shellfish Sanitation Conference (ISSC)
Interstate Technology and Regulatory Council (ITRC)
U.S. Environmental Protection Agency (EPA)
U.S. National HAB Committee (NHC)
U.S. National Office for Harmful Algal Blooms
U.S. National Shellfish Sanitation Program (NSSP)

Appendix 1: International and National Response to HABs

Canada Jurisdiction if shared between federal and provincial/territorial governments.	
Federal Government	**Provincial/Territorial Governments**
Environment and Climate Change Canada	Provincial Ministries of Environment
Fisheries and Ocean Canada	Municipalities
Health Canada	Public Health Units

European Union HABs management if primarily focused on on public health, with relevant regulations and directives from the European Commission, while national authorities and research initiatives play crucial roles in monitoring and research.	
National Authorities	**Research and Coordination**
Member states are responsible for implementing and enforcing EU regulations related to HABs, including monitoring and management actions.	Research and Coordination: The European Commission promotes research and networking across the EU.

Australia Jurisdiction is a shared responsibility, with local councils and state water authorities playing a key role in investigating outbreaks and alerting the public, while state-level departments (like environment, health, and agriculture) handle broader issues and scientific advice.	
State Level	**Local Level**
Department of Environment, Tourism, Science and Innovation, Department of Primary Industries , Queensland Health: (or similar), Department of Energy, Environment and Climate Action (DEECA)	Local councils are responsible for managing algal blooms in recreational waters, bathing reserves, and foreshores, often under the Public Health Act.

Appendix 1: International and National Response to HABs

China
Ministry of Natural Resources
State Oceanic Administration of China, which monitor and report on HAB event

Japan
Ministry of Environment (MoE)
Ministry of Agriculture, Forestry and Fisheries (MAFF)

Appendix 2: Key Takeaways

Priority Area: **Improving the Marketplace**

Market Visibility

- The Full Size of the HABs Market is currently Unknown
- Disparity in Market Size and Diversification
- Need for Market Analysis and Sharing of Technological Innovations

Aggregation of Demand

- Government has a Key Role in Setting Requirements
- There is a Disconnect between the Drivers and the Push for Implementation
- Integrating or 'Mainstreaming' HABs Into Environmental Monitoring

Rethinking Risk to Growth

- Permitting is a Big Obstacle for Commercialization
- The Insurance Industry has not kept pace with the Introduction of Control Methods
- Disaggregation of Regulatory Demand is an Impediment to Scaling Up
- Working with Development Agencies, Tourism Boards, and other Associations can Influence the Acceptance of Control Methodology
- Education and Outreach for Control Methodologies needed to Change Perception

Priority Area: Collaboration to Grow and Impact Change

Data as an Asset and Mission as a Service

- Startups can Create New Business and Licensing Models
- New Market Models can Create Demand

Public Private Exchange

- Advancing Operational HAB Observing Systems will Accelerate Research and Unlock New Opportunities for Industry and Public-Private Partnerships
- Sustainable Investment in Operational HAB Observing Systems will Benefit Impacted Industries

Standards

- Government has a Key Role in Setting Data Standards
- Establishing Standards is Crucial to Transform Data into User-Friendly Services

Priority Area: Shaping the Future

Workforce Development

- Workforce Shift between Specialist and Generalist Expertise
- Sustain and Expand Support for Harmful Algae Training and Certification Programs

Emerging Technology

- Sensor Technologies that can be Tuned

Appendix 3: Planning Team

The second Dialogue series, the writing of the background paper and use cases are the work of the planning under the auspice of the Ocean Enterprise Initiative. The authors and organizing committee core members would like to express our sincere gratitude to all the participants and observers of the Dialogues with Industry initiative. MTS efforts identified in this report are largely funded by the Department of Commerce NOAA – grant, in support of the Ocean Observing Community Engagement Framework Cooperative Agreement detailed in NA23NOS0120322.

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