Remote Sensing Technologies to Monitor Harmful Algal Blooms in Offshore Aquaculture

Devan Nichols and Timothy Hogan

Harmful algal blooms (HABs) consist of aggregations of algae that range in size from microscopic single-celled organisms (microalgae) to large seaweeds (macroalgae). HABs can have lethal and sub-lethal effects on aquatic life, including deoxygenation (caused by the depletion of oxygen via the bacterial decomposition of algae), ichthyotoxicity (from phycotoxins produced), or physical interference (clogging or damaging of gills), emphasizing the importance of HAB monitoring at or near these sites. The HABs that garner the greatest concern are those that can produce high levels of toxins and those that create enough biomass to deplete oxygen levels and lead to the suffocation and death of aquatic life.

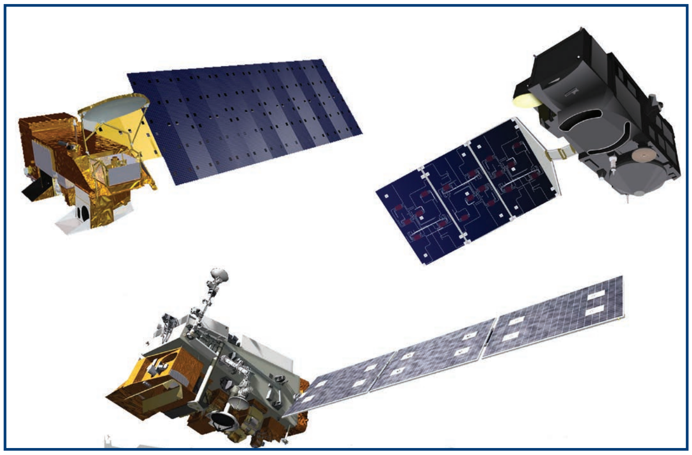

FIGURE 1. *Various sensors aboard satellites that are used for monitoring HABs globally. Clockwise from top left: a MODIS sensor onboard the Terra satellite (en.wikipedia.org/wiki/Terra_(satellite), top right: a OLCI sensor onboard the Sentinel 3 satellite (en.wikipedia.org/wiki/Sentinel-3), bottom: a VIIRS sensor onboard the JPSS satellite (commons.wikimedia.org/wiki/File:NOAA-20_JPSS-1_spacecraft_model_1.png).*

There are over 5,000 species of phytoplankton but fewer than 80 of those are known to be toxic (National Research Council 1999). This article pays special attention to those toxic species that can cause illness and death to humans and marine life and those that cause an array of economic impacts to aquaculture. Estimates of actual impacts are few, in part because these economic losses are difficult to quantify. However, on a global scale, HABs result in approximately $8 billion/year of losses because of mass mortalities of finfish, shellfish harvesting bans due to accumulation of phycotoxins and human health issues.

According to the Harmful Algal Event Database (HAEDAT), a Meta database containing records of HABs dating back to 1985, there is a significant increasing trend in all HAB events globally. Part of this observed HAB expansion simply reflects a better realization of the true or historic scale of the problem, long obscured by inadequate monitoring. Other contributing factors include the dispersal of species to new areas, the discovery of new HAB poisoning syndromes or impacts, and the stimulatory effects of human activities like nutrient pollution, aquaculture expansion and ocean warming, among others (Anderson *et al*. 2021). The continued diversification of harmful phytoplankton species and toxins represents a growing challenge to resource managers in terms of monitoring and management; therefore, trends need to be considered regionally and at the species level moving forward.

Currently almost every state in the US experiences some kind of HAB event and, with climate change, these blooms are predicted to increase in both frequency and severity. This increase in HABs, along with the push to move aquaculture facilities farther offshore, creates a need for remote sensing technologies that can monitor effectively at these offshore locations. The growing interest to move large-scale aquaculture operations farther offshore requires creative solutions to address the challenges of the harsh and/or exposed environment. Daily monitoring of net pen sites, including for HABs, becomes increasingly challenging.

Additionally, increased dissolved nutrient inputs, such as uneaten feed and fish waste have potential to affect phytoplankton prevalence, another reason increased monitoring is so important in these areas. However, there are currently no commercial offshore aquaculture facilities operating in U.S federal waters; therefore, further research is required to better understand the potential correlation between increased phytoplankton and the prevalence of offshore aquaculture facilities. As noted above, this perceived increase may be simply related to intensified monitoring efforts, indicating that blooms existed naturally without additional nutrient input.

Warming ocean temperatures, along with increased terrestrial nutrient input from runoff, including fertilizers and sewage are the most documented and studied causes of HABs. Additionally, not all algal blooms are harmful. Blooms can sometimes be good indicators of environmental change and also provide a rich food source for a multitude of aquatic species. Often, HABs are detected after the bloom has already occurred, limiting the effectiveness of management efforts.

Remote Sensing Technologies

Remote sensing is defined by the National Aeronautics and Space Administration (NASA) as "the process of gathering information about something without touching it." The power of remote sensing lies in its ability to provide spatial and temporal views of surface water quality and atmospheric parameters that are typically not possible with in situ measurement. Such technologies are important for offshore aquaculture because they can help minimize the need for on-site personnel and vessel-based monitoring, both financially burdensome. In contrast, remote sensing technologies send data directly to an operator onshore, who can monitor conditions in real time. As such, remote sensing is central in the development, implementation and control of HAB management strategies for offshore aquaculture. Remotely sensed data used for these purposes can be collected indirectly with satellite sensors in near-real time and directly with in-situ sensors.

The use of remote sensing technologies that can help monitor and predict HABs near offshore aquaculture facilities is an emerging field of research and could help provide valuable insight on bloom dynamics. This technology-based review aims to discuss current remote sensing technologies used to monitor HABs in offshore aquaculture facilities. In addition, we review advancements in predictive early warning systems (EWS) and mitigation strategies built on data from remote sensing technologies.

Satellite Sensor Measurements Used for HAB Detection

Satellites are the most widely used remote sensing platforms globally and can be used for long-term spatial and temporal monitoring of HAB trends. Satellite images provide information on the current location and size of a HAB and aid in bloom tracking over time. Satellites used for these purposes include Sentinel, Envisat, Landsat, Orbview, Terra, Pegasus and Aqua, among others. Data collected from these satellites are publicly available. Specialized sensors outfitted on satellites can indirectly measure environmental parameters used to detect HAB presence before they become visible to the naked eye (Fig. 1).

HAB-specific environmental parameters monitored include chlorophyll *a* levels (detected via ocean color), sea surface temperatures (SST, detected via reflectance data) and turbidity levels (detected via suspended particulate matter concentration, SPM). Table 1 is an exhaustive list of these sensors and their applications to HAB detection/monitoring. New sensors are continuously evolving. For example, researchers from the United States Geological Survey (USGS) are currently working on a technique called SMASH (spectral mixture analysis of surveillance of HABs) to determine the type of microbe in a bloom from a satellite image. This could help determine whether a bloom is made up of dangerous, toxin-producing species, which is crucial information for aquaculture producers in the development of effective management options.

Chlorophyll a. Satellite sensors that monitor ocean color can detect increases in phytoplankton density using fluorescence as a proxy for increased chlorophyll *a* levels. Chlorophyll *a* levels can also be used as a bioindicator of nutrient concentration (Fig. 2). Chlorophyll *a* data can also be used in a time-series analysis to help with the accuracy of predicting HAB occurrence temporally by indicating how concentrations change over time. Additionally, chlorophyll *a* levels can be used to create a red tide (a specific type of HAB) index models using satellite-derived data (Lee *et al*. 2021, Sakuno *et al*. 2019). However, chlorophyll *a* sensors can be impacted by cloud cover and are most valuable for detecting high-density blooms; smaller, less dense blooms are more difficult to detect.

Sea Surface Temperature. Phytoplankton and HAB growth and productivity are directly correlated with SST. Warmer temperatures prevent water from mixing, allowing phytoplankton to grow denser and faster (Izadi *et al*. 2021). Temperature sensors aboard satellites can measure the magnitude of energy reflecting from the sea surface at different wavelengths to determine when SST levels are within a range of concern for potential bloom occurrence.

Turbidity. Satellites can also indirectly determine turbidity by measuring the suspended particulate matter concentration (SPM)

(CONTINUED ON PAGE 22)

TABLE 1. Current satellite sensors and the HAB parameters monitored.

Satellite Sensors	*HAB-related Variables Monitored*
MODIS – Moderate Resolution Imaging Spectro-Radiometer	SST, turbidity and ocean color to estimate algal biomass from chlorophyll pigments
MERIS – Medium Resolution Image Spectrometer	SST, turbidity and ocean color to estimate algal biomass from chlorophyll pigments (higher spatial resolution than MODIS)
VIIRS – NOAA Visible Infrared Imaging Radiometer Suite	SST, turbidity and ocean color to estimate algal biomass from chlorophyll pigments
OLCI – Ocean and Land Color Imager	Chlorophyll a and SST
GOCI – Geostationary Ocean Color Imager	SST, turbidity, and ocean color to estimate algal biomass from chlorophyll pigments
SeaWiFS – Sea-Viewing Wide Field-of-View Sensor	Ocean color to estimate algal biomass from chlorophyll pigments (no longer in orbit)
MSI – Multispectral Imager	Turbidity, SST, and ocean color to estimate algal biomass from chlorophyll pigments
OLI – Operational Land Imager	SST, turbidity, and ocean color to estimate algal biomass from chlorophyll pigments

based on light reflectance (Nazirova *et al*. 2021). Higher turbidity values, in conjunction with other remotely sensed data, may indicate an increase in phytoplankton biomass; however, there are depth limitations as these sensors can only penetrate surface waters (~10 m deep). To determine turbidity values in deeper waters, supplemental algorithms must be used in conjunction with remotely sensed data and direct in-situ measurements, such as a turbidity sensor mounted on a Conductivity, Temperature, Depth (CTD) instrument.

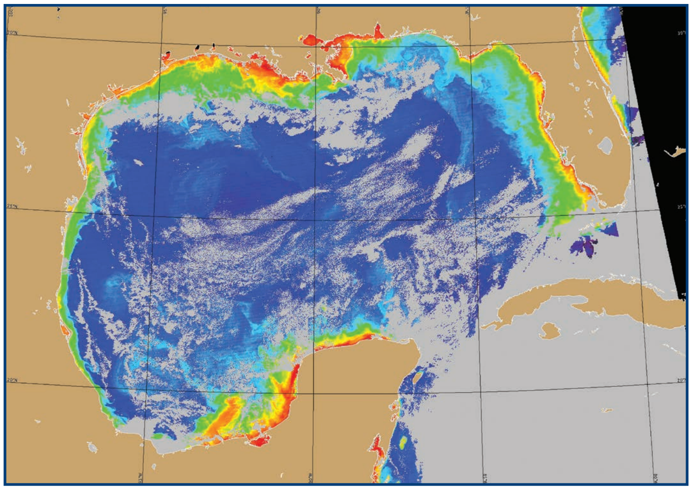

FIGURE 2. *Example of a satellite-derived image showing areas of elevated chlorophyll a (in red and orange) in the Gulf of Mexico taken using a MODIS sensor aboard the Aqua satellite (oceanservice.noaa.gov/podcast/may16/os17-hab-forecast.html).*

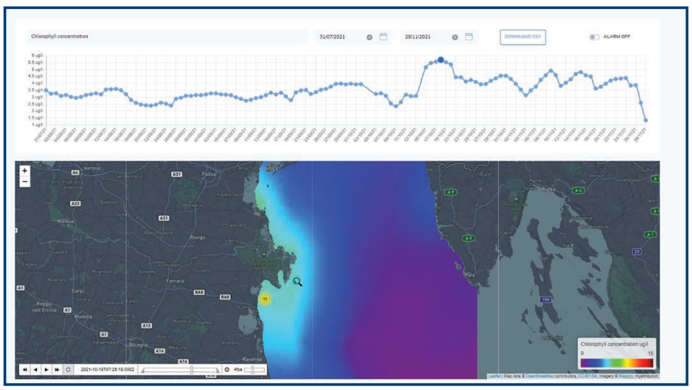

FIGURE 3. *A graphical user interface from ColomboSky's Aqua X Monitoring showing chlorophyll a concentrations on 18 October 2021 (image), as well as chlorophyll a concentrations over a four-month period (graph) in the northern Adriatic Sea. These interfaces provide convenient, real-time data that allow subscribers to better manage environmental threats to their facilities (Image: ColomboSky).*

Satellite Data Analytics Service Providers

Given the challenges of managing large datasets, facility operators may rather choose to use a service provider. Service providers supply the satellite data and the most current (and often custom-designed) data analytics software to properly interpret it. In some cases, satellites are owned by service providers who offer subscription services to data users. In return, the subscriber receives real-time continuous monitoring of specific parameters of interest to the facility. The output of the data analysis will often be displayed in a convenient graphical user interface (Fig. 3) that displays real-time HAB data and allows the user to quickly and easily monitor and track HABs. The data can be accessed from laptops, cell phones or other remote devices. Most providers integrate various data streams to provide a reliable EWS using site-specific parameters. Alerts can be sent when anomalies are detected and mitigation recommendations can be provided. This allows subscribers to take action before experiencing negative impacts from an HAB on their facility. Examples of such satellite service providers include:

- ColomboSky's Aqua X Monitoring provides satellite technology for water quality monitoring and risk management in marine aquaculture.
- Satelytics Environmental Health Monitoring Program remotely measures phycocyanin, chlorophyll *a*, phosphorus and other contaminants.
- UMITRON Pulse provides a worldwide high-resolution satellite ocean data map for aquaculture farmers.
- CyANweb is a multi-agency project of the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the USGS, and the Environmental Protection Agency (EPA). This project detects and quantifies algal blooms using satellite data and then disseminates these data through a mobile application developed by the EPA to provide a web-based tool that can help identify when a HAB may be forming in lakes and reservoirs.
- S-3 EUROHAB is developing a web-based HAB and water quality alert system that uses satellite data to improve HAB monitoring methods in the French-English Channel and is capable of species-level identification of phytoplankton. These services are not yet commercially available.
- The Algal Bloom Monitoring System operated by NOAA's National Center for Coastal Ocean Science (NCCOS) routinely delivers near real-time products for use in locating, monitoring and quantifying algal blooms in lakes and coastal regions of the US using satellite imagery.

Drones

Remote sensing technologies such as a hyperspectral camera can also be deployed from drones. Drones can provide higher resolution images (up to 1 cm) than satellites but on a much smaller scale. Therefore, drones may be a more efficient means of tracking and monitoring HABs when there is a smaller area of interest, such as a small lake or pond, rather than a larger coastal area. Drones have advantages over satellites in that they are not hampered by cloud cover, can collect data on a more user-defined timescale and can be less costly to operate. Additionally, drones can be used with other sensors that satellites cannot use, such as water quality meters and equipment for collecting physical water samples. The combination of hyperspectral data from a water body and physical water samples allows ground-truthing of bloom composition, including phytoplankton species and toxin levels. This adds an additional level of accuracy and can aid in identifying more effective mitigation strategies. Use of a drone is driven in most cases by the required level of spatial resolution and economic needs.

In Situ Sensors

In situ remote sensing technologies can be deployed from a variety of different platforms, including mobile autonomous underwater vehicles (AUVs) or stationary moorings. They are mainly used for monitoring algae and their associated biotoxins and directly measure various environmental parameters in real time or near-real time that can be used for detecting HABs. These parameters include temperature, nutrient levels, chlorophyll *a*, pH, turbidity, dissolved oxygen, toxin levels, water depth, wind speed and currents. Specialized in situ sensors have become more commercially available; however, there are very few automated systems that would allow completely hands-off remote monitoring, which would be required for in-sea monitoring of HABs and toxins (McPartlin *et al*. 2016). Examples of some remote systems that can be considered fully automated and hands-off include 1) AquaMeasure sensors from Innovasea, 2) the MPC buoy from LG Sonic, 3) the Algae Tracker from AquaRealTime and 4) the FaaS (Fish-as-a-Service) from Aquaai Corporation.

More advanced in situ sensors can detect a variety of organisms (Scholin *et al*. 2017), including individual species of phytoplankton and algal toxins in real or near real-time using a variety of imagery techniques, molecular probes and/or environmental DNA (eDNA). Examples include 1) the Imaging Flow Cytobot and the Phytoplankton Sampler from McLane Research Laboratories, Inc., East Falmouth, MA, 2) the Environmental Sample Processor from the Monterey Bay Aquarium Research Institute and NOAA and fabricated by McLane Research Laboratories and 3) the phytO-ARM (phytoplankton observing for automated real-time management) from the Woods Hole Oceanographic Institution.

These in situ sensors are commercially available and are helpful for determining the species of phytoplankton present and providing information on bloom specifics, including types and levels of toxins produced. Additionally, in situ sensors can be used to track phytoplankton growth and spread patterns, resulting in time-series data that can be used to refine future bloom predictions. Examples of various in situ sensors can be seen in Figure 4.

The eDNA Sampler from Dartmouth Ocean Technologies, Inc. also has the capability to detect species of interest using eDNA from collected water samples. While the detection of fluorescence levels indicating high phytoplankton biomass is in real time, the post-processing of eDNA for species identification occurs approximately three hours after collection. This technology may be more economically feasible for smaller-scale aquaculture facilities, as compared to more advanced sensors. This is considered a small (7 in diameter, 24 in long) in situ sampler rather than a sensor and can be deployed on a variety of platforms.

FIGURE 4. *A variety of in situ sensors used to monitor HABs. Top left: A third-generation ESP (shown in bottom left of photo) from MBARI prior to its placement in a long-range autonomous underwater vehicle (LRAUV) and MBARI's LRAUV travelling across the surface of Lake Erie during a large algal bloom (photos: Ben Yair Raanan 2019, MBARI 2018). Top right: The MAZU, an untethered robot fish from the Aquaai Corporation (photo: Liane Thompson, www.aquaai.com/). Bottom left: The MPC Buoy from LG Sonic (photo: www.lgsonic.com/nysdec-will-use-mpc-buoys-to-combat-algae/). Bottom right: The Algae Tracker from AquaRealTime (photo: www.algaetracker.com/how-it-works).*

Early Warning Systems

Early warning of the timing, location and magnitude of HABs and their associated biotoxins is of great value to coastal zone managers and the aquaculture industry, informing business planning and ensuring the protection of both human and fish health (Anderson *et al*. 2001, Davidson *et al*. 2021). EWS provide a window of opportunity for users and regulatory agencies to take preventive actions against impending threats. The creation of EWS would not be possible without incorporating remotely sensed data. Although the science of forecasting HABs is dynamic, there have been recent advancements in the creation of EWS using satellite imagery, in situ data and machine-learning (ML) based approaches in tandem, a technique that has been applied to a variety of blooms (Hans *et al*. 2006, Fernandez-Salvador *et al*. 2021, Yerrapothu 2021). Current site-specific EWS using the most advanced technologies can predict the occurrence of HABs from 7-14 days in advance, allowing operators sufficient time to implement the mitigation strategies. Researchers continue to strive to create advanced EWS that can detect HABs as they form, as well as identify a variety of phytoplankton species. In addition to incorporating remotely sensed data, another vital component of EWS includes the creation and use of numeric models.

Numeric modeling relies on the input of various remotely sensed data and uses computational algorithms to predict the movement of water and/or waterborne particles over time. Numeric modeling is a critical component of an EWS because it provides the means to predict the spread and transport of a bloom. Typical inputs for a numeric model include density of particles, algal cells, initial location of the bloom, water depth/bathymetry, water temperature and salinity (which affects particle buoyancy), current speed and wind direction. Numeric modeling of HABs is crucial to the development of EWS, which provides actionable information to facility operators facing impending blooms.

Examples of Current and In-Development Early Warning Systems

NOAA's National Centers for Coastal Ocean Science (NCCOS) launched a new program in 2021 called the Aquaculture Phytoplankton Monitoring Network (AQPMN). NCCOS is working directly with the commercial aquaculture sector to focus on species of phytoplankton known to be harmful to common shellfish and

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finfish species in aquaculture. This program aims to provide aquaculture facility operators with a minimum of two weeks advanced warning of dangerous levels of toxic phytoplankton. The AQPMN is partnered with the East Coast Shellfish Growers Association and The Nature Conservancy's Shellfish Growers Climate Coalition on this initiative. This partnership will allow rapid expansion of the program into aquaculture farms already dealing with environmental and water quality issues.

Additionally, NCCOS has multiple HAB Forecasting Systems that offer short-term (hourly to weekly) forecasts to identify potentially harmful blooms, their location, size, trajectory and respiratory risk, as well as longer-term seasonal forecasts that predict the severity of HABs for the bloom season in a particular region. These forecasting systems are currently available for Texas, Florida, the Gulf of Maine and Lake Erie. The systems incorporate satellite and/or field collected data to monitor conditions daily and issue regular forecasts of blooms. Forecasting systems are currently under development for Chesapeake Bay, Alaska and Lake Okeechobee regions.

C-Harm (California Harmful Algae Risk Mapping) HAB Forecasts are part of the Integrated Ocean Observing System (IOOS) and generate nowcasts and forecasts up to three days in advance of a HAB caused specifically by the species *Pseudo-nitzschia* in California and southern Oregon. Satellite observations of ocean color, surface salinity, temperature and currents are used to measure phycotoxins, specifically domoic acid, to predict the likelihood of a bloom in these regions.

Blue Lion Labs, a Canadian-based startup, in collaboration with the marine technology group OTAQ, located in the UK, is developing artificial intelligence technology that will be used to create a fully-automated EWS for detecting HABs using imaging technology to identify individual phytoplankton to the species level. These data will then be analyzed using a variety of ML methods to deliver real-time data on the species composition of the bloom. This level of detail will help operators implement the most efficient mitigation techniques. This partnership hopes to achieve commercialization of their product in the near future.

Innovasea's cloud-based software can deliver real-time data on harmful plankton concentrations. This software uses data from a suite of aquaMeasure sensors to track spatial and temporal trends, providing a better idea of which plankton species are likely to appear, and how species distributions and concentrations change over time. In the future, these data can be used to predict the size and location of blooms. Although this technology is not yet predictive, an EWS is currently under development.

Mitigation Strategies

After receiving an alert regarding an onset of a HAB, there are operational procedures that facility managers can implement to protect living assets. As is always the case, mitigation methods are extremely site- and facility-specific and can vary based on location, equipment used and specific characteristics of the HAB itself — size, shape, depth and toxin levels. In some cases, facility managers alerted to a potential HAB threat may react by harvesting stock earlier, taking stock from an unaffected area or, when feasible, towing net pens to a refuge area, a common mitigation strategy practiced worldwide. Towing net pens is challenging and stock can be lost as a result of ripped nets and loss of cages from wave or towing forces beyond the design tolerance of pens. Employing boats with sufficient towing capacity to move larger net pens can also be very costly. Additionally, identifying suitable refuge areas that do not interfere with marine navigation or present unmitigable risk to infrastructure or stock can prove challenging (Anderson *et al*. 2001).

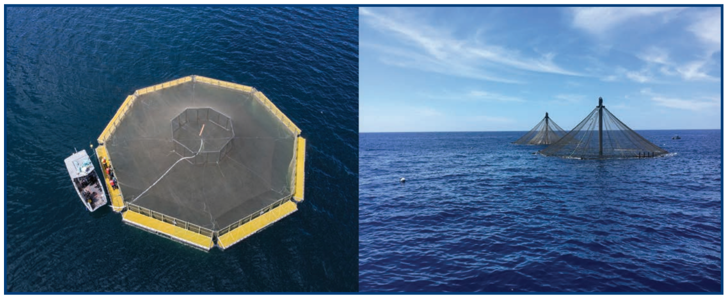

FIGURE 5. *The Evolution pen (left) and the SeaStation pen (right) from Innovasea that can be submerged to a pre-determined depth to potentially avoid physical injury to the stock or algae-related hypoxia from a HAB.*

Depending on the net-pen technology used, pens could also be lowered and raised in the water column to avoid contact with the HAB using airlift pumping technology. For example, Innovasea's Evolution pens and SeaStation pens (Fig. 5) can float on the surface when there are no environmental threats such as rough seas, storm surge or large algal blooms but then can be submerged to a pre-determined depth to avoid these threats. The ability of these net pens to sink to a regulated depth allows them to potentially avoid impacts to stock caused by HABs. Such net-pen technology allows operators to avoid the bloom, reducing the risk of physical injury to fish or to avoid algae-related hypoxia.

Less technologically advanced net pens often deploy perimeter skirts or tarps that are suspended vertically around the outside perimeter of the net pen to create a barrier between the sea and the stock inside in the pens. This method is typically practiced in tandem with other mitigation methods such as pump aeration to attempt to reduce fish kills.

Aeration and oxygenation systems can also be used to mitigate HABs. Aeration of net pens can help thin out and disperse large masses of algae when a bloom is detected. Aeration also improves water quality and increases water circulation, which adds oxygen and can help reduce dead zones inside of net pens. Examples of aeration systems currently in use to mitigate HABs include aquaControl technology from Innovasea, bubble tubing technology from Canadianpond, which can be used to create bubble curtains to deflect incoming HABs, as well as diffusers such as SalmoAir that create constant circulation of water and air inside net pens. Additionally, nanobubble technology from Moleaer provides multiple operational benefits for aquaculture facilities including HAB mitigation. Using nanobubbles, which are 2,500 times smaller than a grain of salt, as opposed to conventional aeration methods, allows for more efficient gas transfer and oxygenating areas more efficiently by allowing bubbles to stay in the water column for weeks without off gassing at the surface.

As the push to move aquaculture facilities farther offshore continues, so too does the need for technological advancements to properly monitor HAB risk at these sites. Remote sensing technologies have the potential to allow for the convenient, reliable, real-time monitoring of HABs that serve as an invaluable tool for offshore aquaculture facilities. HABs can be harmful to humans and aquatic life and cause major economic losses to aquaculture globally.

Additional mitigation strategies include using various techniques to try and sink the algae, thereby limiting the availability of sunlight for photosynthesis that kills algal cells before they can form blooms. The MPC buoy (Fig. 4) from LG Sonic is an example of a technology that uses ultrasonic frequencies to mitigate HAB development. The use of high frequency sound waves reduces the buoyancy of phytoplankton cells, causing them to sink to deeper waters, thereby preventing surface blooms. Additionally, a study by Kirke (2001) indicated that operation of low-powered surface pumps can transport algal cells to deeper waters, reducing the impacts of surface blooms. Lastly, clay application may be used to prevent algae from aggregating in surface waters by attaching to and sinking algae cells (Yu *et al*. 2017).

Summary

As the push to move aquaculture facilities farther offshore continues, so too does the need for technological advancements to properly monitor HAB risk at these sites. Remote sensing technologies have the potential to allow for the convenient, reliable, real-time monitoring of HABs that serve as an invaluable tool for offshore aquaculture facilities. HABs can be harmful to humans and aquatic life and cause major economic losses to aquaculture globally. The impacts of HABs are diverse, as are the causes and underlying mechanisms controlling blooms. As many HAB events are spatially and temporally variable, often differing in magnitude and location from year to year, useful HAB risk assessment requires greater temporal resolution than only seasonal. An understanding of the underlying ecology and drivers of bloom events, along with the observational platforms and predictive approaches to identify and forecast developing blooms, is therefore necessary for useful expert interpretation (Davidson *et al*. 2021). Recent advancements in the creation of EWS using remotely sensed data, in tandem with a variety of computational methods, have made it possible for operators to implement appropriate management strategies before HABs can inflict damage. However, further research is needed on species-specific detection methods for algae, overall regional trends in HAB development and the continued creation and improvement of predictive models and forecasting methods to extend warning times.

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