ACT WORKSHOP: BIOSENSORS FOR HARMFUL ALGAL BLOOMS

EXECUTIVE SUMMARY

The Alliance for Coastal Technologies (ACT) convened a Harmful Algal Bloom Biosensor Workshop in Solomons, MD on March 20-22, 2002. The workshop was designed to bring together three distinct communities for open discussion of mechanisms necessary for development of harmful algal blooms (HAB) Biosensors. Participants included 1) researchers responsible for most recent sensor development in basic research programs, 2) coastal managers responsible for safeguarding coastal resources, public health, and local economies, and 3) industry representatives with experience in the commercial production of new technologies for coastal monitoring and assessment. Focused discussions within and between the three communities identified problems to be addressed in coastal areas, technologies and approaches in hand or available in the near term, and processes required for identifying commercial success in production and distribution of these new technologies to coastal management communities.

Specific workshop recommendations that acknowledge the immediate needs for accelerating access of coastal management communities to HAB biosensors included the following:

- Deploy existing sensors that are currently available (assembled in suites or arrays) and platforms that allow step-wise or event triggered sampling for periodic events, such as HABs, in coastal waters;
- Define environmental conditions preceding HABs, critical for sensor development and production;
- Define spatial and temporal scales for HAB sampling, for effective and useful sensor application;
- Assess critical needs and purchasing power of coastal managers to identify specific commercial instruments to be produced;
- Conduct field tests of newly developed sensors in order to identify detection limits, operation procedures, and biofouling limitations;
- Develop formal procedures for resolving patent rights and distribution, between academic institutions developing technologies and firms producing commercially available products;
- Identify and initiate specific funding opportunities to assure technique development, from initial idea through initial commercial production; and
- Compile and maintain a list of available sensors for general access, describing measured parameter, detection limits, distributors, costs, maintenance, and environments successfully and unsuccessfully assayed.

Many of these activities will be addressed by organizations such as ACT. As an initial effort, the Biosensors for Harmful Algal Blooms Workshop participants encouraged ACT to consider undertaking this role for the coastal communities. ACT could, in turn, organize and administer a working group specific to the recommendations of this workshop on HAB Biosensors.

Overall, many basic biosensor technologies are here, rapidly expanding, and simply require a stronger formal mechanism to assure commercial distribution to coastal management communities. ACT can guide this effort and provide the initial infrastructure for undertaking these identified activities.

ALLIANCE FOR COASTAL TECHNOLOGIES

The Alliance for Coastal Technologies (ACT) is a NOAA-funded partnership of research institutions, state and regional resource managers, and private sector companies interested in developing and applying sensor technologies for monitoring and studying coastal environments. ACT provides a mechanism for standardizing approaches to coastal monitoring and sensor technologies by functioning as:

- an unbiased, third-party testbed for evaluating new and developing coastal sensor and sensor platform technologies,
- a comprehensive data and information clearinghouse on coastal technologies, and
- a forum for capacity building through a series of annual workshops and seminars on specific technologies or topics.

The ACT workshops are designed to aid resource managers, coastal scientists, and private sector companies by identifying and discussing the current status, standardization, potential advancements, and obstacles in the development and use of new sensors and sensor platforms for monitoring and predicting the state of coastal waters. The workshop goals are both to help build consensus on the steps needed to develop useful tools and to facilitate the critical communications between the various groups of technology developers, manufacturers, and users.

ACT is committed to exploring the application of new technologies for monitoring coastal ecosystem and studying environmental stressors that are increasingly prevalent worldwide. For more information, please visit www.actonline.ws.

> ACT Headquarters is located at the Chesapeake Biological Laboratory and is staffed by a Director, Chief Scientist, and several support personnel. There are currently five ACT Partner institutions around the country with sensor technology expertise, and that represent a broad range of environmental conditions for testing. The ACT Stakeholder Council is comprised of resource managers and industry representatives who ensure that ACT focuses on service-oriented activities. Finally, a larger body of Alliance Members has been created to provide advice to ACT and will be kept abreast of ACT activities.

HAB BIOSENSORS

Recently, several natural resources such as shellfish, finfish and marine mammals, have been subjected to the recurring and expanding problem of deleterious harmful algal blooms (HABs). Several Federal programs – including the interagency ECOHAB program (Ecology and Oceanography of Harmful Algal Blooms) and NOAA's MERHAB program (Monitoring and Event Response for Harmful Algal Blooms) – provide funds for research and development on HAB related issues; other agencies support additional efforts through more general research programs such as EPA's STAR (Science to Achieve Results) program, NOAA's National and state Sea Grant programs, and the National Science Foundation. This recent commitment of resources has resulted in rapid development of several new technologies for the detection, identification, and assay of HAB species, toxins, and toxicities.

In general, these new technologies have remained research tools, used in on-going, science-based experiments and programs. As such, these technologies are typically not available or incorporated into coastal monitoring programs of states, counties, or local jurisdictions. This transition from specific use in individual scientist coordinated research to larger, routine coastal monitoring programs is a principal reason for convening the ACT Workshop of HAB Biosensors. By assembling appropriate scientists with their recently developed research tools, state management officials responsible for assessing living resource and coastal ecosystem health, and industry representatives interested in providing commercial products for private and public users, the ACT Workshop on HAB Biosensors proved an ideal forum to initiate the process towards new standardized technologies for routine use in coastal environments.

THE GLOBAL HAB PROBLEM

HABs have been problems for centuries, causing illness in populations near the Ancient Egyptian Nile, poisoning Spanish conquistadors in Florida in the 16th century, and more recently impacting important resources, local economies, and public health in most coastal nations. HABs also produce toxins, resulting in invertebrate, fish, bird, and marine mammal illnesses or death. Recent large mortalities have included sea lions, otters, and birds in California, whales in the Gulf of Maine, manatees along Florida's west coast, and dolphins in Florida's panhandle. Mass fish kills are frequently associated with HABs, either through toxicities associated with exposures to toxins or toxic materials from several species, such as Florida and Texas red tides, and *Pfiesteria* spp. in the mid-Atlantic region. Hypoxia/anoxia associated with respiratory demand and decomposition of blooms can also cause serious problems for, and significant mortality of, coastal organisms. Economic losses associated with HAB exposures include closures of many shellfish harvests, from the Alaskan-Washington-Oregon coasts where paralytic shellfish poisoning (PSP) and amnesic shellfish poisoning (ASP) occur regularly, to shellfish culture operations in California, and natural shellfish harvests for coastal Louisiana, Mississippi, and the Gulf of Maine states. Some shellfisheries have collapsed or are permanently closed because of HABs, including the bay scallop in eastern Long Island Sound where the brown tide organism has devastated local populations.

A recently compiled report, "Estimated Annual Economic Impacts from Harmful Algal Blooms (HABs) in the United States" (Anderson et al., 2000), summarizes the economic costs associated over a five year period in the coastal U.S. Averaging $40M annually, HAB impacts stress public resources by diverting local funds to coastal monitoring programs, health services, and public awareness documentation. Recreational businesses also suffer, through reduced boat charters, cancelled rentals for recreational boats and jet skis, and public avoidance of beaches and associated service industries. Seafood dependent firms are impacted by poor seafood sales, low restaurant visitation, and declining seafood processing. Single events can be long-lasting and expensive. For example, the Maryland *Pfiesteria* events of 1997 resulted in total economic losses estimated at $43M, from total fish mortalities estimated at less than 30,000.

Of greatest concern to coastal areas is potential threat to humans. Many HAB toxins cause human illness while several, with acute exposures to very high levels, can result in death. Red tides of Florida and Texas can produce respiratory distress in local populations, largely from aerosols generated from wind and breaking waves delivering the brevetoxins to near-coast populations. Other HAB species produce toxins responsible for gastrointestinal distress, such as nausea and diarrhea (e.g., exposure to *Dinophysis* toxins), temporary short-term memory loss, skin irritation, and irritated eyes (possibly *Pfiesteria*), and recurrent and long-term malaria-like symptoms (e.g., ciquatera-associated dinoflagellates). More debilitating illness can be experienced from the ingestion of domoic acid, the toxin produced from several species of the diatom *Pseudo-nitzschia*. At low concentrations, permanent short-term memory is lost while at very high dosages, death can occur. Several other dinoflagellates produce paralytic shellfish poisons (PSP), lethal at high concentrations if no respiratory assistance is provided shortly after exposure.

> The overall impact of HABs can severely strain local resources because of cost associated with monitoring and survey requirements. In addition, HABs can cause economic hardships on local businesses. Thus the development and routine use of in situ detection capabilities is critical for many coastal regions.

RECENT HAB TECHNOLOGY ADVANCEMENTS

In the last five years, tremendous technological advances have been made in the detection of HAB species, toxins, and toxicities stemming from basic research programs in several academic and Federal laboratories. Partnerships with private industry as well as state and local government agencies have also led to significant progress. Nonetheless, these detection capabilities are used primarily as tools within the research community, and have yet to be incorporated into routine public or private coastal monitoring efforts. Specific areas of HAB technology advancement include: A. molecular-based detection, B. in situ and hand-held sensor platforms, C. detection of specific pigments, D. detection of the toxins, and E. in vitro bioassays.

A**.** *Molecular-based detection:* Molecular-based detection of individual HAB species has progressed extremely rapidly and there are now species-specific probes for numerous taxa common to waters of the U.S. and many other countries. Such probes encompass both antibodies targeting cell surface antigens and nucleic acid probes detecting intracellular genetic signatures. Among the species for which probes are currently available are several PSP toxin-producing *Alexandrium* species, brown tide taxa from Long Island and Texas, *Pfiesteria* and *Pfiesteria*-related species from the mid-Atlantic states and Florida, brevetoxin-producing red tide populations (*Karenia brevis*) from the Gulf of Mexico, several toxic and non-toxic *Pseudo-nitzschia* species, and other HAB taxa with smaller areas of impact (*Heterosigma*, *Karlodinium*, *Chattonella*). A few of these techniques have been used in the detection of HAB species in routine monitoring programs, which has permitted a much more rapid assessment of potential problems than does conventional microscopy. Examples include the laboratory-based immunological detection of the brown tide organism, *Aureococcus anophagefferens*, in Long Island and the mid-Atlantic and the detection of *Pfiesteria piscicida* and *P. shumwayiae* genomic sequences in the mid-Atlantic states.

B. *In situ and hand held sensors:* In addition to the laboratory-based application of molecular probes, a considerable effort is underway to format these methods for placement on both in situ and hand-held sensor platforms. The deployment of in-water sensors for individual HAB species is being tested with an Environmental Sample Processor (ESP) prototype developed at the Monterey Bay Aquarium Research Institute. Using a water tight submerged system with software controlled pumping, filtering, and sample processing, the ESP is capable of autonomously conducting rRNA probe sandwich hybridization assays and sending the digitized data to a land-based laboratory via radio modem. The ESP also has sample archival capabilities, providing material for toxin testing, microscopic examination, and additional genetic analyses. Individual populations of *Pseudo-nitzschia* and several other taxa (*Heterosigma*, *Alexandrium*) are being detected during instrument deployments in coastal waters of Monterey Bay, the Pacific Northwest, and the Gulf of Maine. While the ESP shows great promise as an in situ sensor for HAB species, the instrument configuration is currently being redesigned and prototype testing is still underway, with general, routine access to the system not likely for several years. Molecular probe-based sensors for HAB species are also being developed by scientists at the Alfred Wegener Institute in Bremerhaven, Germany for use with hand-held DNA microchip readers employing electrochemical detection and sandwich hybridization. Such systems show good potential for use in both laboratory- and field-based detection of HAB species within the next couple of years.

C. *Detection of specific pigments:* The detection of specific pigments associated with HAB species has also proven valuable for assessment of bloom populations. Optical signatures for *K. brevis* have proven important in research-based detection of this red tide organism, through the analysis of a unique accessory pigment. Further, satellite-based detection of the organism has been developed for tracking bloom distributions off western Florida, using a species-specific algorithm developed in NOAA's National Centers for Coastal Ocean Sciences. A similar approach is being explored for West coast *Pseudo-nitzschia* species.

D. *Toxin detection:* In addition to the detection of HAB species, detection of the toxins produced by these organisms is of critical importance to HAB monitoring programs. The fact that cellular toxicity can fluctuate widely depending on the ambient environmental conditions, makes it essential that both species and their toxins be monitored concurrently to assess the potential impact on fishery or aquaculture resources. HAB toxin detection and quantification is readily accomplished in the laboratory with sensitive analytical techniques (e.g., HPLC, mass spectrometry) that are presently available for all of the major algal toxin classes; however, application of such methods to in situ platforms presents a considerable challenge. Nonetheless, progress is being made in this area, with the deployments of underwater mass spectrometers being conducted by the Center for Ocean Technology at the University of South Florida. These instruments have yet to be configured for algal toxin detection, but their ability to detect natural and anthropogenic compounds in seawater suggests a high likelihood of success for HAB-related applications. Although use of these systems in research programs is likely within the next couple of years, incorporation into routine monitoring efforts would be considered a long-term goal.

E. *In vitro bioassays:* Finally, in addition to analytical approaches, HAB toxins and HAB-produced compounds can be detected with various in vitro bioassays, including those based on a toxin's functional activity (e.g., cell-based assays, receptor assays) and those relying on the structure of a toxin molecule (e.g., immunoassays). Functional assays, such as receptor binding assays, are available for the major toxin classes and show good agreement with live animal bioassays in estimating the human toxic potency of contaminated seafood products. Other cell-based assays (e.g., reporter gene assays) have proven effective in assessing the activity of unknown toxins, such as those associated with *Pfiesteria* spp. Nevertheless, the properties that make functional assays very effective and reliable are also the primary obstacles to formatting these methods for in situ use. It is an inability to maintain the functional integrity of receptors or cells under the conditions experienced on in-water platforms that makes in situ deployment of these assays unlikely in the near future. In contrast, the principal components of structural assays, such as antibodies or other toxin binding proteins, are quite stable under conditions outside the controlled laboratory environment. Several versions of these assays, which are also available for most toxin classes, have been successfully formatted as laboratory- and field-based detection kits (e.g., MIST Alert; Jellett BioTek), but have yet to be incorporated into any routine monitoring programs. Work is also currently underway to configure immunoassays for the ESP in situ platform which, when coupled with the probe-based detection of HAB species on this instrument, will yield a concurrent assessment of the organisms and their toxins. In-water toxin detection onboard the ESP will focus first on research-based applications with broader, monitoring applications to follow.

GOALS FOR THE ACT HAB BIOSENSOR WORKSHOP

The HAB Biosensor Workshop was convened March 20-22, 2002 in Solomons, Maryland to explore and discuss HAB related sensor technologies. The workshop was organized by Dr. Kevin Sellner, Director of Chesapeake Research Consortium. Dr. Bill Dennison, Vice President of UMCES Center Administration, served as Facilitator. Sponsored by ACT and NOAA's Center for Coastal Ocean Research in the National Ocean Service, the Chesapeake Biological Laboratory of the University of Maryland Center for Environmental Science and the Chesapeake Research Consortium co-hosted the workshop. Researchers active in molecular, optical, and chromatographic technologies developed for HABs and associated environmental conditions, public officials from several state monitoring programs responsible for overseeing HAB-related activities, and industry representatives involved in commercial production of a suite of monitoring technologies met to discuss possibilities for transforming recently developed research tools into commercially-available, in situ capabilities for routine use in coastal areas impacted by HABs.

Workshop participants (Table 1) were first tasked to identify problems (Table 2) in current HAB detection, approaches (Table 3) and obstacles (Table 4) to solving these problems, and the feasibilities of short (<5 years) and long-term (5-10 years) solutions (Table 5). Breakout group discussions led to the identification of six specific issues that needed to be addressed for the successful development of useful HAB technologies:

- Spatial and temporal scaling/problems in scaling;
- HAB-specific sensors;
- Organism versus toxin measurement;
- Cost and ease versus accuracy and precision;
- Multi-adaptive sampling technology; and
- Integration/intercalibration interfacing of sensors.

> Note on Scaling:
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> HABs typically occur at irregular intervals and locations, prohibiting pro-active focused sampling in time and space. "Hot spot" predictability is region specific, requiring sampling approaches that combine in situ capabilities with a need for portability.

> Note on Integration:
>
> One approach to explore is the implementation of several technical demonstrations using current sensors, leading to repackaging of existing technologies and phasing in new technologies as they are developed.

WORKSHOP RECOMMENDATIONS

Discussions of the six critical issues in HAB sensor development by new breakout groups led to a variety of suggestions that were synthesized into the Workshop Recommendations.

Recommendation 1. Achieve strong collaborative links between technology industry, environmental managers, and harmful algal bloom researchers.

The strengths inherent to each group of meeting participants need to be combined to produce a coordinated, focused approach to developing sensors and technologies useful in environmental management. The following approaches should be initiated to begin this collaboration, with ACT possibly facilitating many of the activities.

- *Form and convene sensor focus groups:* These focus groups combining researchers, managers, and industry representatives will explore in more detail research and development options for new generation of sensors, including identifying proving ground/testing for sensors and possible funding sources. This group should identify priorities of managers and researchers, perhaps overseeing user surveys, to analyze 'needs'. The focus groups should also assume a proactive role in marketing technologies (not brands but approaches) with listings of products for undertaking specific monitoring

- *Sensor comparisons:* As new techniques are developed for the identification of cells, toxins, or toxicities, it is important to compare existing methods with the new techniques for an individual species, a toxin, or for the sensitivity of each species' toxicity. Information for cross-comparisons can be provided via list server groups or an established web site such as that of ACT.

- *Additional regional meetings and workshops:* To continue the critical dialog and exchange of information, additional working sessions with the three diverse groups and special sessions on HAB technologies at specific national/international meetings would be useful.

- *Industry contacts:* A point-of-contact database should be developed, to identify primary contacts within each company for specific sensor interests. ACT could also expand its Alliance Membership to include additional international corporations serving monitoring and coastal issues.

- *Global links:* As HABs are a global problem, and many nations are focusing resources on coastal detection, formalizing international communication is likely to yield rapid dissemination of information, stimulating more rapid advancements and limiting redundant efforts. ACT through its Headquarters at CBL might provide contacts with the European community while west coast ACT Partners could focus on contacts within the Pacific Rim.

- *Data processing links:* Develop, perhaps through specific agency (e.g., NSF) initiatives, data processing capabilities for distributing information and processing data. One example is HABSOS, currently being implemented in the Gulf of Mexico.

Recommendation 2: Introduce rapid and efficient existing and future harmful algal bloom biosensors into monitoring, assessment, and research programs.

The incorporation of new technologies into monitoring programs must be based on practical needs of environmental managers and researchers and hence the market potential for developing products. Without a potential for profit, commercial distribution of any technique is impossible. Hence, the specific 'needs' analysis (see ***Recommendation 1*** above) should include surveys of what and how frequently the managers and researchers need to measure a parameter, and what is 'affordable' for these measurements.

Once specific needs are identified for technology development, ACT can serve the important role of testbed for evaluating existing sensors as well as developing instruments. ACT could coordinate testing through coupling pilot studies of the technologies in ongoing monitoring or research programs. Further, through the pilot studies, ACT could coordinate industry-testing and evaluation protocols development for new technology to assist the general use of new technologies and provide feedback to the industry on operation manuals.

New technology development also suffers from a recurrent problem, sustained funding from inception to implementation. Although some public programs are now in place that encourage the development and use of research tools for specific applications (e.g., the Monitoring and Event Response for HAB [MERHAB] Program in NOAA/NOS), models for sustained funding are rare. Efforts should be made to foster a formal mechanism for long-term support of new technology development and use, through partnerships linking scientific products, identified management priorities for the coastal zone, and government-industry financial resource support to actually produce a reliable technology for routine incorporation in coastal zone monitoring.

Basic research-generated techniques often remain in academic institutions or research programs, used by the researchers for specific needs of a project or discipline. Linking management needs identified from the user survey with specific research assays in use in cutting-edge research programs would be of great value. Further, once a research technique has been identified, ACT could familiarize the industry with need and possible market to foster technique development, pilot testing, and eventual sale and distribution.

Recommendation 3: Foster near real-time biosensor data collection and processing supporting harmful algal bloom management and research.

The need to provide timely, understandable, and factual information to decision makers and the public is critical. This includes information distributed over the web, which in some cases can be provided in real time (e.g., Gulf of Maine Ocean Observing System, Chesapeake Bay Observing System, and USF Coastal Ocean Monitoring and Prediction System). Environmental weather reporting including integrated, synthesized visuals would prove invaluable for local citizens and water-related industries. These could be supplemented by small, regular outputs such as fact sheets or hand-outs.

Of obvious concern and primary focus would be the sensors and data processing required to ensure real-time data delivery. For sensors, issues such as biofouling would need to be addressed. Biosensors should also have autocalibration capability, to reduce field visits and equipment maintenance. Data collected in situ would ideally require automated processing from existing or new platforms and use developing data transfer technologies.

Finally, it is critical to the translation of research technologies into reliable and routine monitoring tools that sustained funding models be explored and implemented, to ensure long-term abilities from technology inception through routine use. ACT might aid this process by facilitating wide-ranging partnerships between public agencies, industry, and the research community to assure fiscal probabilities for technique incorporation into coastal monitoring programs.

Recommendation 4: Develop an integrated, tiered approach of coupled environmental and harmful algal bloom biosensor technologies to early detection and forecasting.

There are a number of existing platforms and monitoring approaches in place that provide the foundation for step-wise expansion and inclusion of HAB biosensors. The research and management communities strongly advocated development of consensus schemes on ways to adapt current monitoring technologies through time with new, more focused sensors including HAB biosensors. Drivers for the approaches might be species-specific or process focused for a specific area. A baseline would be describing a suite of sensors available for most systems, a common denominators focus, on which other sensors and technologies might be added. It is critical to include bio-optical sensors and integration with remote sensing capabilities in development of the tiered monitoring approach, as these two technologies are well developed, easily accessible, and can provide broad spatial coverage.

Examples of specific technical recommendations:

- Detect species and cell abundance
- Detect toxin and toxin concentration
- Use autonomous and mobile field sensors and platforms
- Develop high frequency sampling
- Develop biofouling resistance
- Adapt molecular techniques for in situ detection
- Develop solid state in situ sensors
- Use lab validation/verification of in situ sensor data

Once sensors are identified for specific species or regions, controller technology should be incorporated that would permit multi-tasking and instrument selection based on specific environmental cues detected with the standard array of sensors in the package. The obvious problem of scaling becomes an issue, but the consensus building teams, might provide guidance on spatial and temporal scales to sample, again species- or locale-specific. Various arrays of sensor packages could be developed in a networked system, leading to forecasting capacities in coastal areas. Test sites should be explored, perhaps where other observing systems are in place, permitting building on existing programs (e.g., HABSOS for the Gulf of Mexico or developing a HABSOS program for the ECOHAB focused Gulf of Maine region).

The overriding principle is focused, planned expansion of existing programs and platforms that would permit multi-assessments of basic environmental factors that might trigger sampling of more specific HAB-related phenomena in coastal waters. This approach complements the recent focus on coastal observing systems and provides a specific justification for multiple detection arrays throughout coastal environments of the U.S. and other nations.

SPECIFIC RECOMMENDATIONS FOR ACT IN HAB BIOSENSOR DEVELOPMENT

The development of reliable, in situ HAB biosensors, for species, toxins, and toxicities, will require several critical steps. The workshop participants felt that ACT could provide an important role by providing a unique service to the research, management, and industrial communities not currently available through any other program, organization, or agency.

Specifically ACT could:

- Help coordinate the assembly of in situ sensor technology inventories to identify existing and new HAB technologies for possible routine use in coastal monitoring programs.

- Convene focus groups to prioritize immediate, short-term, and longer-term HAB sensor needs. In this endeavor, ACT could help oversee surveys of management needs for coastal states and regions to provide industry realistic priorities for sensor development based on possible markets, funds available within the states, and frequency/use of the technology in monitoring programs.

- Facilitate the distribution of information to and between researchers, managers, industry, and agencies, to encourage R&D and rapid inclusion of new products in public monitoring programs.

- Conduct demonstrations and verifications of HAB sensors and expanded sensor arrays. ACT can conduct technique-specific product testing (beta tests) for review of new technologies, coordinate sensor-standard method comparisons, and disseminate results to the general community.

- Coordinate manual and protocol development for new HAB technologies derived from initial researcher-industry suggested practices, furthering the collaboration between the research and industrial communities.

- Identify new data transfer technologies to increase the delivery and receipt of integrated product output to as many web-based users as possible.

- Assume a coordination role for advancing HAB technologies. ACT's affiliations with research institutions, agencies, and industries place it in a unique position to assume many coordination roles for advancing coastal technologies. ACT could become a strong advocate for demonstrating the success of this type of partnership. Without continuous demonstration of the need and successes of these working relationships to the individual groups, participation will remain low. The continuous distribution of partnered material to individual groups within the partnership as well as those public groups (e.g., Congress) seeking definitive examples of successes in transferring basic research results to societal gain is a must for future and continued success.

CONCLUSIONS

HAB sensor development has progressed rapidly in the past decade, yielding many viable techniques employed routinely in on-going academic research programs. Application is far more limited in coastal monitoring programs critical to safeguarding public health, coastal resources, and local economies. This transition from research application to routine use in local to regional coastal assessments will require a much more developed collaboration among researchers, industry, and agencies. Research efforts should continue to identify environmental conditions responsible for bloom formation, permitting forecasting of blooms in space and time, and specific technologies elucidating bloom species, toxins, and toxicities. However, formal mechanisms must be established between public monitoring leaders and the commercial communities in order to permit rapid incorporation of the new research tools into specific products for routine use by the coastal management and assessment communities. Institutions like ACT can provide this service, ensuring identification and testing of appropriate research technologies for public use in coastal protection. An expanding partnership between the research community, public coastal monitoring representatives, and sensor industries must be implemented so the newest ideas can be coupled to the highest needs to yield commercially viable products for protecting our coastal areas and populations. ACT is in an ideal position to assume leadership in this effort, and provide opportunity and products for future coastal environments. ACT can encourage research, assist industry in identifying coastal management needs, and test developing sensor technologies to assist industry and coastal managers in obtaining specific affordable technologies for routine use in HAB-rich areas. The increasingly frequent and hazardous HAB impacts throughout our national waters warrant a focused, integrated response.

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The workshop attendees are thanked for their services to our community in dedicating their time, talents, and great effort in contributing to advancing the quality of environmental monitoring technologies.

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Table 2. The Problems associated with detecting harmful algae, their toxins, and their toxicities identified by HAB researchers, coastal resource managers, and industry representatives.

TOPIC	RESEARCHERS	MANAGERS	INDUSTRY
Problem 1: Some techniques available	Standards Availability: stable, certified, distributable (toxins, genomes, cultures)	Acute responses known but lack knowledge of impact from chronic toxin exposures	Genome techniques in place and some profiling and monitoring platforms are available
Problem 2: What, where?	Insufficient knowledge: where, when unknown so 'predicting' sampling is difficult; temporal and spatial unknowns large	Same, forcing functions unknown and hence episodic or aperiodic frequency and duration of HABs difficult for designing technologies; large areal coverage and remote locations	Same; HABs in layers a problem, sampling through a water column necessary? *In situ* sensing poor for spatial resolution
Problem 3: Taxon specificity	Roles of life history, stages unknown for many species	Which should public programs monitor?	Genome techniques identify organisms, not toxins
Problem 4: What to measure?	Cells or toxins, absolute or relative concentrations, numbers; food web transfer.	Public versus ecosystem health? Acute vs. chronic?	Layers, over a water column, cells, toxins?
Problem 5: Sampling Frequency?	Power requirements? Reagent stability? Portability? Waste generation?	Accuracy and timeliness of analysis for decision making	Understanding time scale between detection and response; sampling rate for high specificity probes too low
Problem 6: Biofouling	Always a problem; accuracy impact, impact on longevity of the sensor	Always; servicing a problem	Always; some techniques are available
Problem 7: Driver for product commercialization	Prioritization by management community	Spatial and temporal reproducibility at low expense; continuity of funding for purchasing technologies	What is it managers need and can afford?
Problem 8: Do nutrients matter?	Measure environmental factors leading to or associated with HABs	Usually some part of in place monitoring programs	Fairly standard measurements now

Table 3. Approaches towards detecting harmful algae, their toxins, and their toxicities identified by HAB researchers, coastal resource managers, and industry representatives.

TOPIC	RESEARCHERS	MANAGERS	INDUSTRY
Approach 1: What to measure?	Focus on cell detection as first level of monitoring then introduce toxin detection	Based on 'event', 'trigger', 'sentinel', e.g., moving monitors like SUV, SAM (sensitive artificial sensors like mullet, mollucs), dead fish; rapid response teams	'Smart' bulk phase sampling: high frequency profiling using traditional sensors, these trigger biosensing with induction approach to address biofouling
Approach 2: How?	Integration with ocean observing systems and platforms of opportunity; this can include volunteer monitoring programs, ships of opportunity; addressing QA/QC issues for integrating information; incorporate biosensors as become available and dependable	Piggyback on existing programs, use initiatives that occur frequently to find new opportunities; explore new partnerships like volunteers, R&D for industry, NGOs	Explore remote sensing (aerial, satellite, ROV) coupled to *in situ* sampling; develop low cost disposable and high cost discrete capabilities

Table 4. Obstacles in developing biosensors for detecting harmful algae, their toxins, and their toxicities identified by HAB researchers, coastal resource managers, and industry representatives.

TOPIC	RESEARCHERS	MANAGERS	INDUSTRY
Obstacle 1: Sensor shortfalls	Some sensors inappropriate for routine use: sensitivity/selectivity 'at odds' with miniaturization; cross-contamination problems; reagent stability/internal calibration; power/energy requirements; sample collection/preparation	Cost/loss of instruments; real time?; temporal and spatial variability?; spatial coverage possible?	Cost/price for sensor use and sensor ownership; verification of product/technology; lack of standards/protocols within industry
Obstacle 2: Regulatory needs		Regulatory acceptance of sensors is a long process: requires several years of testing	Government budget system/cycle prohibits new technology use
Obstacle 3: Funding		Poor history of government infrastructure for implementation and program continuance; must educate government officials and cultivate the mass media, produce comprehensible fact sheets, web sites	Government budget system/cycle prohibits new technology use
Obstacle 4: Sensor-related needs	Sensors need a laboratory component to validate/verify sensor data; multiple sensors possible for detecting environmental variables associated with blooms? Automated sampling and archival? Some toxins unknown-need structures for sensor development		

Table 5. Feasibility in harmful algal bloom biosensor development identified by HAB researchers, coastal resource managers, and industry representatives.

TOPIC	RESEARCHERS	MANAGERS	INDUSTRY
Possibilities 1: Couple to existing activities	'Off the shelf' techniques can be used: satellite data, chem/phys sensor arrays; automated sampling is possible; laboratory-based immunological and genomic assays in place	Use stepwise approach of satellites, various platforms, water sampling, disease, epidemiology, including incorporation of newly available instrumentation; develop a table of toxin levels permitted in water; use screening from organisms to focus/implement toxin analyses	High frequency profiling using traditional sensors
Possibilities 2: Short-term activities	'Off the shelf' techniques can be used: satellite data, chem/phys sensor arrays; automated sampling is possible; laboratory-based immunological and genomic assays in place	Characterize 'events' with current technology; develop data warehousing and management; develop and use field kits for species, toxins	Multi-adaptive sampling technology (MAST); move DNA technology to *in situ*; create industry-wide sensor interface standard; biofouling 'avoidance'; demonstration projects using new deployment platforms
Possibilities 3: Long-term prospects	Unknown toxin structures, miniaturization will result in progress in the future	Web-based data management; real time information; transition from wet chemistry to solid state; use integrated detection systems (physical, chemical, biological in end-to-end approach); moving monitors; ultimate goal is detecting toxicity; accumulators developed for triggering biosensors; flow through, automated systems	Develop solid state sensors and bio-fouling immunity; routine integrated observations (e.g., GOOS, MOGOOS, etc.); toxin sensors

Alliance for Coastal Technologies Workshop Participants
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"Biosensors for Harmful Algal Blooms"

Photograph taken in front of the ACT Headquarters, which is located in the Coastal Technology Laboratory at the Chesapeake Biological Laboratory in Solomons, Maryland.