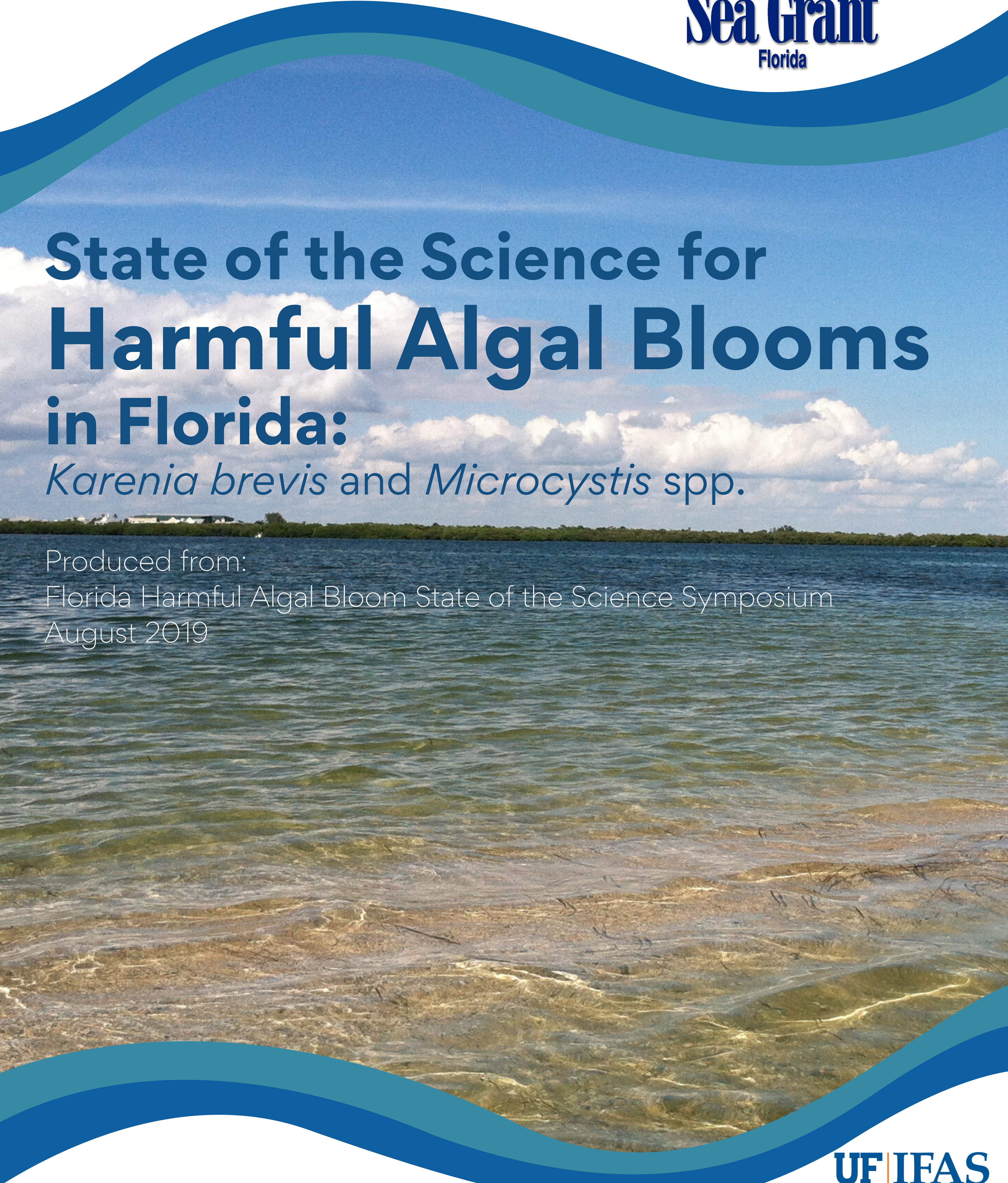
Sea Grant Florida



State of the Science for Harmful Algal Blooms in Florida:

Karenia brevis and *Microcystis* spp.

Produced from:
Florida Harmful Algal Bloom State of the Science Symposium
August 2019

UF | IFAS UNIVERSITY of FLORIDA

Contents

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Introduction

This document presents the outcomes of the *2019 Florida Harmful Algal Bloom State of the Science Symposium* held August 20 & 21 in St. Petersburg, Florida. The symposium, hosted by the Florida Sea Grant College Program and the University of Florida's Institute of Food and Agricultural Sciences, brought together harmful algal bloom (HAB) experts to discuss the current state of HAB research in Florida. The symposium was supported by the Florida Sea Grant College Program and National Oceanic and Atmospheric Administration (NOAA) National Centers for Coastal Ocean Science.

Seventy-five researchers from around the state and across the country attended the Florida Harmful Algal Bloom State of the Science Symposium to discuss the current state of knowledge and recommend research priorities to improve levels of certainty regarding HABs in Florida. Participants represented 27 unique institutions encompassing academia, nonprofit organizations, local, state and federal agencies, allowing for a diverse and comprehensive assessment of the scientific research arena.

The purpose of the symposium was fourfold:

- Facilitate information exchange and networking opportunities among Florida's harmful algal bloom scientists.
- Assess the current state of knowledge for Florida HABs with a focus on *Karenia brevis* and *Microcystis aeruginosa*.
- Identify data gaps and prioritize research needs for moving the state of the science forward.
- Facilitate better public outreach and communication from the scientific community.

Process

The symposium focused on *Karenia brevis* and *Microcystis* spp. and addressed five major aspects of HAB research including **bloom initiation, development, and termination; prediction and modeling; detection and monitoring; mitigation and control;** and **public health**.

The format for the symposium included one to two formal invited presentations summarizing the current state of the science for each bloom species and each focus area, followed by facilitated discussion. Facilitated discussion sought to capture group consensus regarding *what we know*, *what we think we know*, and *what we need to know* relative to the bloom species and focus area being discussed. *What we need to know* identified research needs and were prioritized by participants using TurningPoint voting technology. Ranked *research priorities* were then grouped by relatedness or dependency, when applicable.

In this report, we present consensus summaries for each bloom species by focus area. Each consensus summary includes *what we know* as a concise synopsis, followed by *what we think we know* and *what we don't know* in bulleted statements, and *research priorities* in tabular form. In all tables, priorities that received majority votes are displayed by rank percentage with all other priorities listed below. Research priorities grouped by relatedness are indicated by more than one priority in a row or by dependency as indicated by bullets.

The consensus summaries presented here represent the current state of knowledge as identified by symposium participants during the presentations and facilitated discussion. For this reason some summaries lack *what we think we know* or *what we don't know* statements. The information presented in this document reflects the general consensus of symposium participants.

HAB Summary

In 2018, Florida experienced concomitant *Karenia brevis* red tide and *Microcystis aeruginosa* cyanobacteria blooms bringing focus and attention to water quality and HABs in the state. Following these events, the Governor's Executive Order 19-12 established the Blue-Green Algae Task Force and revived the state's Harmful Algal Bloom Task Force to provide technical expertise and recommendations to reduce the adverse impacts of future blooms.

HABs are the rapid and substantial increase in algae biomass in aquatic systems that result in harm. Though notable in their duration and intensity, the 2018 blooms were not singular events for Florida which experiences a variety of HABs in its marine and fresh waters. To provide the most timely and relevant guidance for the state's task forces, the State of the Science Symposium focused on *K. brevis* and *Microcystis* spp., primarily *M. aeruginosa*. However, symposium participants recognized that there are numerous HAB species of concern and there are many commonalities pertaining to causes, impacts, and management.

The prevalence and intensity of HABs is increasing globally. Shifts in demographics and land use are confounded by the direct and indirect impacts of climate change. Florida is experiencing, or can expect to experience, increased temperatures, decreased pH, changes in circulation, coastal inundation, and precipitation. Increased rainfall will result in accelerated nutrient delivery, while periods of drought may lead to conditions that favor bloom formation. As HABs are likely to continue to increase both locally and globally there is a need to address all sources of nutrients along the entire fresh to saltwater continuum and to better understand the role of mixotrophy.

A suite of research recommendations arose that address these commonalities and broad themes. Foundationally, for many species bloom concentration and numeric thresholds need to be defined as does what qualifies as a bloom of concern. Similarly, consistent methodologies for determining cell counts need to be established.

The following research priorities were identified during the symposium. They pertain to HABs in general or to multiple HAB organisms. Additional research priorities for both *K. brevis* and *Microcystis* spp. are addressed in the respective sections.

HAB Research Priorities

Bloom Initiation, Development & Termination

1. Evaluate bloom termination (including environmental and ecological factors such as predation, hypoxia, etc.) and what is released when a bloom dies
2. Identify and understand the role of nutrient sources supporting blooms, specific gaps include:
   - Linkages to eutrophication
   - Benthic-pelagic coupling (internal cycling)
   - River influences (including iron)
3. Understand bloom triggers via experimental work (lab, mesocosm, and field experiments) and predict their movement, behavior, and termination
   - Identify direct link between HABs and climate change, such as increased water temperatures

4a. Clarify the relationship between blue-green algae and red tide
4b. Examine the inter-relationship between bloom species

5. Determine if blooms are more common or more intense

*Priorities are ranked in order though specific percentages are unknown due to technology error. Research priorities were grouped by relatedness as indicated by more than one priority in a row or by dependency as indicated by bullets.

Bloom Prediction & Modeling

1. Develop models than can separate point source and non-point sources of pollution	100%
2. Examine the relationships between water quality and bloom predictions	

Priorities that received majority votes are displayed by rank percentage with all other research priorities listed below a solid line.

Bloom Detection & Monitoring

1. Conduct more comprehensive and consistent monitoring (biology, chemistry, and physics), including: ▪ High resolution, *in situ* monitoring of bloom dynamics	46%
2. Form partnerships (government, academic, and industry) to develop monitoring programs that will be comprehensive and non-overlapping. All types of HABs could be monitored during well-designed monitoring programs	24%
3a. Develop affordable/effective field tests that are able to measure cells and toxins simultaneously 3b. Understand the fate and effects of HAB toxins	17%
4. Plan for comprehensive statewide monitoring and mitigation response	
5. Invest in updated and cost effective monitoring technology	
6. Determine the fate of the bloom organic matter	
7. Increase the rate of taxonomic identifications	

Priorities that received majority votes are displayed by rank percentage with all other research priorities listed below a solid line. Research priorities were grouped by relatedness as indicated by more than one priority in a row, or by dependency as indicated by bullets.

Bloom Mitigation & Control

1. Conduct pilot studies (lab, mesocosm, small areas) to mitigate blooms using new technologies	34%
2. Conduct coastal watershed investments/restoration activities that would reduce the occurrence, duration, and severity of future blooms	32%
3. Plan for comprehensive statewide monitoring and mitigation response	20%
4. Create a business or political model that funds or implements a mitigation or control solution ▪ Conduct a cost benefit analysis to promote the business model	14%

Priorities that received majority votes are displayed by rank percentage. Research priorities were grouped by dependency as indicated by bullets.

Public Health

1. Improve knowledge of and evaluate human and ecosystem health impacts, both short and long-term	70%
2. Conduct long-term, longitudinal health studies on the chronic, low-level exposure to HAB toxins in humans including cumulative doses	
3a. Evaluate physical, mental, and social health risks for the public and those implementing control strategies 3b. Determine psycho-social impact on individuals living near blooms	
4. Identify human exposure to toxins through air and seafood vectors	
5. Evaluate mixed exposures	
6. Identify risk for all populations and occupations	
7. Develop interdisciplinary teams	
8. Understand dose response	

Priorities that received majority votes are displayed by rank percentage with all other research priorities listed below a solid line. Research priorities were grouped by relatedness as indicated by more than one priority in a row.

Karenia brevis - consensus statement and research priorities

Bloom Initiation, Development & Termination

Karenia brevis blooms follow a sequence of developmental stages that define a bloom. Blooms mostly occur in the fall although there is interannual variability. During initiation, *K. brevis* cells come from offshore and are transported shoreward. During the maintenance stage, cells are dispersed alongshore expanding their geographic range. Termination is defined by a population decreasing to background levels or advected out of the area. The exact mechanisms underlying each bloom stage and the transition from one stage to the next is still largely unknown, although progress has been made.

Image: *K. brevis* bloom
Credit: FWC Fish and Wildlife Research Institute

Initiation triggers for *K. brevis* blooms include physical, chemical, and biological drivers. Some upwelling is required for initiation; however, too much can favor other phytoplankton. *K. brevis* is ecologically flexible in terms of nutrients, temperature, salinity, and light; however, *K. brevis* growth is inhibited at 24 ppt and in lowlight.

K. brevis can utilize at least 13 different sources of nutrients, including multiple forms of both nitrogen (N) and phosphorus (P). The relative importance of the various nutrient sources is not known due to spatial and temporal variability. Ammonia (NH_4^+) is the preferred form of nitrogen; however, *K. brevis* will take up nitrate (NO_3) and urea when ammonia is limited. In the offshore initiation stage, nitrogen fixation by *Trichodesmium* can be a significant nutrient source for *K. brevis*.

K. brevis blooms are not new. Natural conditions exist in the Gulf of Mexico for blooms, however anthropogenic influences affecting Florida and the Gulf of Mexico, including climate change and increased nutrient inputs, may have direct and indirect impacts on *K. brevis* blooms.

There is clear evidence that cyanobacteria blooms are increasing with climate change. The marine cyanobacteria, *Trichodesmium* may be increasing due to climate change, leading to possible impacts on *K. brevis* bloom initiation.

What we think we know

- There is one offshore initiation zone, possibly quite extensive, along the west Florida shelf.
- Blooms tend to occur as a result of unique upwelling conditions.
- Estuarine cyanobacteria, such as *Synechococcus*, *Lyngbya*, *Lyngbya*-like, and *Microcystis,* may influence *K. brevis* blooms by providing a new source of nutrients, however the role of these cyanobacterial blooms in sustaining *K. brevis* is unknown.
- Some large blooms follow and/or occur in association with major runoff events.

What we don't know

Initiation

- What is the life cycle of *K. brevis* and are there seed populations and cysts?
- What is the role of P?
- What are the unique factors that determine the location of initiation?

Maintenance

- What is the role of nearshore nutrients in maintaining *K. brevis* blooms and how will a changing physical landscape change blooms?
- What is the role of mixotrophy?
- Does the microbial loop have a role in blooms?
- What is the interannual bloom variability, including what determines the years when there are super blooms?
- Will increases in cyanobacteria blooms due to climate change and increases in anthropogenic nutrients lead to more frequent or more severe *K. brevis* blooms?
- Are there linkages between freshwater Lake Okeechobee releases through the Caloosahatchee River and *K. brevis* blooms? Are the conveyance of *Microcystis* and nutrients from the lake to the estuary available and/or used by *K. brevis*?
- Are nutrients from the degradation of *Microcystis* used by *K. brevis*?
- Are there linkages between coastal cyanobacteria and *K. brevis* blooms?

Termination

- What ends a bloom? Is it physical, chemical, biological, or a combination?
- What is the role of nutrient impoverishment, bacteria and viruses?

Research Priorities: Bloom Initiation, Development & Termination

1. Geographically and temporally identify the initiation zone(s) of *K. brevis* blooms and the concentrations of *K. brevis* on the west Florida shelf; determine if nearshore initiation is possible	45%
2. Determine to what extent anthropogenic nutrients support the exacerbation of blooms once they get into the nearshore waters ▪ Track nutrient sources from the FL peninsula to the near-coastal shelf ▪ Develop a good nutrient budget with error bars	35%
3a. Geographically pinpoint what life stages of *K. brevis* are involved in initiating blooms 3b. Determine if any abiotic or biotic factors will disrupt the life cycle in the initiation phase 3c. Evaluate the ontogenetic stages of the organsim, including growth rates over the course of a bloom	
4. Determine the impact of major storms on existing and subsequent blooms	
5. Evaluate the development of a normal versus a super bloom	
6. Evaluate the ecosystem role that *K. brevis* may play (are there any adverse impacts without *K. brevis*?)	

Priorities that received majority votes are displayed by rank percentage with all other research priorities listed below a solid line. Research priorities were grouped by relatedness as indicated by more than one priority in a row, or by dependency as indicated by bullets.

Bloom Prediction & Modeling

Florida red tide, caused by the toxic dinoflagellate *K. brevis*, is naturally occurring. *K. brevis* typically blooms along the west Florida shelf in the fall. Based on cell counts from 1953-2015 (FWC data), a spatial order exists for west Florida shelf ecology supporting the hypothesis that red tide initiates offshore and is transported to the coastline via Ekman layer transport under an upwelling circulation. The pattern of red tide occurrence offshore and alongshore is determined by ocean circulation.

Most of the west Florida shelf is characterized as oligotrophic or nutrient deplete. Bloom initiation along the west Florida shelf is associated with inorganic nutrients brought up from the deep ocean dependent upon the location and intensity of the loop current. The west Florida shelf pressure point, northwest of the Dry Tortugas, is critical in determining these water properties. Winds are also a factor for west Florida shelf circulation. Transport to secondary and tertiary locations, the Florida Panhandle and east coast respectively, are dependent on winds, ocean currents, and upwelling conditions. Transport of *K. brevis* via upwelling conditions is supported by appearance of blooms after persistent upwelling events and is also suggested by elevated chlorophyll levels and lower dissolved oxygen near the bottom during intense blooms.

Tracking and predicting *K. brevis* blooms are interdisciplinary problems. Predictions require understanding, observations, and models. At the present, glider surveys provide a qualitative picture of temperature, salinity, chlorophyll, colored dissolved organic matter (CDOM), and oxygen, which are necessary across the hypothesized initiation region. Tracking and prediction improvements are made by supplementing glider surveys with cruises and strategically placed moorings to provide quantitative real-time nutrient and cell-count data.

Current models allow for geographically-specific short-term *K. brevis* red tide forecasting. Short-term forecasts are based on observations and two different circulation models. Stochastic events like storms play an important role in the interannual variability in blooms and need to be incorporated into models. Seasonal forecasts are in development still, but good progress has been made based on the mid-shelf nutrient conditions determined by the location and strength of the Loop Current. Model accuracy can be improved by including biological measurements and simulation data, though prior work suggests it is unlikely that *K. brevis* bloom prediction with a fully coupled biological model will be realized due to the necessity of multiple variables and parameterizations.

Satellite data can provide key information for various modeling efforts although there are some limitations that need to be recognized, and sensitivities and specificities that must be accounted for. For instance, *K. brevis* can only be detected by satellite when a certain cell density is present in surface waters (greater than approximately 50,000 cells/L). Satellite can detect variations in chlorophyll to about one Secchi depth; as a result, satellite imagery is not useful for tracking sub-surface distribution of *K. brevis* or low concentrations at the surface. Chlorophyll detection alone is also not specific to *K. brevis*, and color is not particularly useful because other algae such as diatoms and other dinoflagellates share similar pigments that do not appear to be distinguishable with existing imagery. Algorithm issues may result in false positives or interference from sediments, CDOM, and the bottom so the method and presentation must explicitly identify limitations, and issues of false positives and negatives. Currently, *K. brevis* imagery is best used for supporting monitoring and input into other models, and for blending with field observations to identify or confirm bloom patches as *K. brevis*. Once there is confidence that a satellite-detected bloom is *K. brevis*, the satellite data may be useful as input into other models.

The "new bloom" anomaly has been the conventional method for *K. brevis* bloom detection by satellite. This method relies on current satellite imagery and imagery from the previous 60 days. The difference of those two images identifies a bloom while eliminating any persistent false positives. This method is best for the beginning of a bloom and becomes ineffective during long duration blooms when high chlorophyll is no longer anomalous.

MODIS and Sentinel-3 products have a newer method that uses chlorophyll fluorescence. This method removes interference from CDOM and much of the interference from the bottom (although it will detect seagrass in shallow water) and works well during monospecific *Karenia* blooms in the fall. However, like chlorophyll, fluorescence is not specific to *Karenia*. Additionally, images generated using this method are treated as pixels, not features, making it good for chlorophyll concentration but not necessarily good for further identification of taxa.

What we think we know

- The initiation zone is 10-40 miles offshore and may be quite extensive.
- Northwest and southwest blooms share an initiation zone.
- The Loop Current is a factor in driving *K. brevis* blooms, through driving the west Florida shelf circulation.
- Upwelling is a key factor in the appearance of blooms at the coast.
- We can detect surface blooms of *K. brevis* (above 50,000-100,000 cells/L) pretty well from satellite most of the time.

What we don't know

- Is the existing microscopy-based bloom species identification sufficient for validating remote sensing data?

Prediction

- Is the nutrient flux from the deep ocean onto the continental shelf through the loop current larger than the flux coming off of the land?
- If *K. brevis* doesn't fluoresce similarly over time or if there is cloud cover, cells won't be accurately detected via satellite. How often does this occur?
- We cannot detect sub-surface *K. brevis* using satellite imagery and we don't know how much of a problem this is. Do blooms form at the bottom, in the water column, or at the surface (or are all three possible)?

Modeling

- We don't know what determines *K. brevis* red tide bloom termination.
- We don't know the extent to which human-derived factors exacerbate blooms.

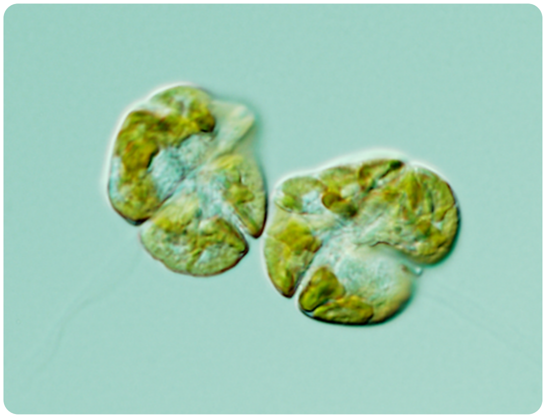

Image: *Karenia brevis* (light micrograph)
Credit: FWC Fish and Wildlife Research Institute

Research Priorities: Bloom Prediction & Modeling

1. Improve predictive capabilities ▪ Develop predictive model of a super bloom ▪ Need subsurface *K. brevis* measurements (there is nothing to correlate it to without) ▪ Evaluate the role of particulate nutrients from the Mississippi River Delta on *K. brevis* ▪ Understand the role of the Loop Current	67.5%
2. Tie predictions back to what society uses that information for. Determine what the best models are to get those predictions and evaluate the data gaps ▪ Develop/expand respiratory forecasts	32.5%

Priorities that received majority votes are displayed by rank percentage. Research priorities were grouped by dependency as indicated by bullets.

Bloom Detection & Monitoring

Southwest Florida has experienced *K. brevis* red tide blooms 57 of the past 66 years. Widespread impacts to fish and wildlife and humans necessitate comprehensive monitoring with microscopy, toxin testing, environmental sampling, remote sensing, and effects on ecological and ecosystem health. *K. brevis* detection and monitoring needs to incorporate the ecology of the species, particularly its bloom dynamics including initiation, bloom maintenance and growth, and termination. Monitoring also needs to incorporate baseline and background ecology during non-bloom periods and should extend into the offshore regions.

A comprehensive monitoring system currently exists, based on knowledge about the complexity of *K. brevis* that has been developed over many years. Sampling efforts are enhanced around bloom events, though routine monitoring occurs year-round statewide. Microscopy is currently the gold standard for evaluating *K. brevis* cell concentrations. However, new tools and technologies are being developed which will allow partners and citizen volunteers to participate in accurate data analysis as well as improve the timeliness of water sample collection and analysis. These tools, such as nucleic acid sequence-based amplification (NASBA; 1-100 cells/L) and HABScope (50K cells/L), are in various stages of validation and implementation.

In Florida, closures of shellfish harvest areas are currently tied to *K. brevis* cell counts. Shellfish harvesting areas are closed by the Florida Department of Agriculture and Consumer Services when cell counts reach 5,000 cells/L. An enzyme-linked immunosorbent assay (ELISA), which provides an overall estimate of brevetoxin content in shellfish or water samples, is another technology that can be shared with partners. This method was approved by the Interstate Shellfish Sanitation Conference (ISSC) in October 2017 as a limited use method and is now used to support the aquaculture industry.

Programmable hyperspectral seawater scanner or PHYSS (formally known as OPD and Brevebuster) provides *in situ* year-round detection. PHYSS differentiates between algal groups based on optical spectra.

Ocean gliders have sensors that help track chlorophyll from the surface to the bottom and can be outfitted with a PHYSS or other technologies to more specifically track red tide. Subsurface, offshore observations are critical for predicting bloom initiation as blooms occurring at or near the bottom are not detected by routine monitoring.

Solid phase adsorption toxin tracking (SPATT) is a passive sampling method for tracking toxins in the water over time using porous synthetic resins held in mesh bags attached to a mooring line and provides an integrated picture of toxin concentrations at various depths over time.

The Imaging FlowCytobot, which takes images of *K. brevis cells in situ*, is currently being used to learn more about the life cycle of *K. brevis*.

Multiple *Karenia* species can be involved in blooms, but *K. brevis* is the primary player in Florida. It is not known what role these other species play or why *K. brevis* is the dominant species in Florida. *K. brevis* is always toxic. An Imaging FlowCytobot has been successfully used to differentiate between different *Karenia* types in Alabama as well as in other systems for other HAB species (e.g., *Alexandrium* spp). *In situ* sensors are able to resolve life cycle dynamics as well as other characteristics, but this method requires data validation to determine their accuracy.

K. brevis monitoring and detection approaches should link these different tools and datasets together. An interdisciplinary observation network is needed to more fully resolve the life cycle of *K. brevis* and link bloom initiation, persistence, severity, and termination.

Having a central repository for monitoring data is critical for moving *K. brevis* science forward. The Gulf of Mexico Coastal and Ocean Observing System (GCOOS) aggregates and provides open-access data for public dissemination. Data is real time, near real time, or archival and it may be physical, chemical, or biological. Regional information coordination entity (RICE)—runs QA/QC so that all data used is certified and the equivalent of NOAA/NWS reliability. Numerous HAB products are currently hosted on the GCOOS website.

Considerations for increasing monitoring observations and incorporating new technologies include spatial coverage, temporal coverage, cost – initial and maintenance, specificity, regulatory concerns, and ease of use.

When it comes to monitoring, the best tools would be the most affordable with the highest specificity. Real-time HAB sensors are a priority; however, the tool used should be dependent on who the audience is and what the data is to be used for. For instance, the Beach Conditions Reporting System is not specific for scientific purposes, but it is very useful for beachgoers.

What we don't know

- There is more than one *Karenia* species in the Gulf of Mexico, with approximately 12- 13 species identified now globally. *K. brevis* dominates Florida blooms and occurs throughout the Gulf of Mexico, but these other species are often present in background concentrations. We do not know if and how changing temperatures and other environmental changes will alter the dominant *Karenia* species.

Research Priorities: Bloom Detection & Monitoring

1. Improve routine monitoring of nearshore and offshore, particularly at depth ▪ Improve understanding of ecosystem stressors associated with red tide (e.g., hypoxia) ▪ Improve our detection capabilities ▪ Integrate the detection/monitoring of non-*Karenia* blooms into existing programs ▪ Increase tried and true sampling methods at more offshore stations ▪ Validate the accuracy of *in situ* sensors ▪ Develop new monitoring programs that build upon historic data sets so we do not lose old data ▪ Develop a local taxonomic image library with Imaging FlowCytobot and FlowCam technology ▪ Include dissolved oxygen measurements in monitoring ▪ Investigate connection with *Trichodesmium* blooms	100%

Research priorities were determined to all be dependent on *Improve routine monitoring of nearshore and offshore, particularly at depth* and thus received the total rank score of 100%.

Bloom Mitigation & Control

K. brevis red tides generally manifest as a nuisance to people once they are transported inshore, and the public would like to see some level of action to prevent, mitigate, or control blooms. There are promising strategies that are currently in use in other countries, but *K. brevis* is part of the natural system so we need to understand the role it plays in the ecosystem and be careful not to cause negative ecosystem effects. In the United States, very little has been accomplished in terms of *K. brevis* control due to environmental caution and few scalable technologies. Mitigation (defined here as strategies to minimize cells, toxins, and impacts) and control should be ecologically sound, economically feasible, and the exact triggers and issues we are trying to address – as well as the scale of these – should be stated. We must deal with cells and toxins and we want the cure to be no worse than the bloom-associated impacts.

There are four types of bloom mitigation and control strategies – avoidance, chemical, biological, and physical – as well as combinations of these types.

Avoidance is a key factor in reducing the impact of respiratory irritation and associated health risks. Currently, avoidance is a crude solution. The most common assumption is that if "red tide" is present, then the beach should be avoided. The existing NOAA HAB Bulletin provides a county-wide assessment day-by-day; essentially saying that there might (or might not) be a risk of low or high respiratory irritation today or tomorrow in each county. These county-wide forecasts have been shown to be correct at individual beaches only 20% of the time. A newer method, called the HABscope forecast uses detailed daily cell counts at individual beaches with improved models to give hourly forecasts at those beaches. Given the patchiness of blooms and variability of winds, the improved approach should provide a respiratory forecast that is more useful.

Chemical bloom mitigation and control include cleansing agents and algicides. Challenges to chemical mitigation and control are that methods may be toxic to other marine life, their persistence in the environment may lead to bioaccumulation in animals and different public health risks, or lysing of *K. brevis* cells could lead to a massive influx of brevetoxins into the ecosystem.

The first and last large-scale chemical control treatment of red tide in the U.S. occurred in 1957. Copper sulfate was dispersed across a 40 square kilometer area. This application succeeded in temporarily decreasing *K. brevis* cell concentrations; however, there was unknown but broad collateral damage as copper sulfate kills indiscriminately, especially invertebrates. Therefore, a review panel recommended against its use with future bloom occurrences.

Research in the 1960s examined 4,000 compounds to see which, if any, would kill *Karenia* cells at 10 parts per billion. Only one compound met the criteria for killing *K. brevis*, with low lethality of other species; however, that compound was deemed far too expensive to be used in any field application.

Biological bloom mitigation and control could include living docks and shorelines, macroalgal allelopathy, HAB-specific parasites, and algicidal bacteria. To date there have been no tests of biocontrol using introduced pathogens in the field even though research has shown high host specificity and rapid proliferation of some pathogens against some HAB species in lab studies. Challenges to biological mitigation and control includes adverse risks to other marine life, the fate of the toxin when the *K. brevis* cell is lysed, and resulting poor water quality.

Physical bloom mitigation includes the use of nanobubbles, bubble curtains – a physical barrier to keep HABs out of confined areas such as canals, or physical removal. Nanobubbles are bubbles less than 200 nanometers that oxidize pollutants and pathogens in the water. Cell and toxin removal is probably the most viable physical control method at the present time. This strategy utilizes clay flocculation. The combination of the clay particles and the ionic strength of seawater makes the cells aggregate. The resultant clay flocculant binds to *K. brevis* cells making them sink to bottom thereby removing the cells and a large percentage of the brevetoxin as well. Variations on this method have been successfully used against other types of HABs in Korea and China with low environmental impact.

Continuous monitoring is needed in order to develop strategies to minimize impacts to the public and to inform resource managers. Monitoring itself is a form of mitigation because it tells us where *K. brevis* (and thus brevetoxin) is and steps can be taken to avoid potential exposure. Monitoring provides information for forecasts that help the public avoid respiratory exposure and informs resource managers who take actions to protect the public from seafood poisonings.

A standard protocol for testing bloom mitigation products should be developed. Mitigation strategies should be considered in areas that are environmentally affected due to *K. brevis* blooms. These strategies must kill red tide cells, reoxygenate water and restore water to nontoxic conditions within 24-48 hours. A toolbox of potential mitigation strategies should be developed to address different adverse impacts, target what needs to be protected, and provide integrated information dissemination.

No single control method will work for all locations and multiple approaches need to be explored. Environmental compliance requirements limit what we can do but we should consider the impacts of the HAB against the impact of the control method. Scale and potential costs are high; large-scale application likely will not be possible, but targeted applications should be considered at critical times and places.

What we think we know

- Bloom impacts could be exacerbated with the wrong type of intervention.
- Anthropogenic nutrients are exacerbating blooms in nearshore waters.

Research Priorities: Bloom Mitigation & Control

1a. Expand lab studies investigating the broad or specific impacts of red tide mitigation techniques on benthos, nekton, seagrasses, and corals 1b. Better understand the impacts of bloom control and mitigation technologies	38%
2. Use multiple approaches to control blooms (site-specific BMPs)	19%
3a. Determine via social-science studies what the public really wants (e.g., water quality or *Karenia* control, nutrient reduction, etc.) 3b. Determine the extent to which we should try to control a naturally occurring algae 3c. Develop performance measures to track progress	17%
4. Coordinate a data repository for all data collected regarding bloom control research by the various institutions and government agencies that can be accessed by all those interested in doing red tide research and mitigation	
5. Measure baseline biogeochemical parameters in sediments during natural blooms and during control experiments ▪ Evaluate the biogeochemical ramifications of materials put into the sediment; what happens to the benthos when red tide flocculate sinks to the sediments?	
6. Incorporate local ecological knowledge in understanding and mitigation of red tide	

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Public Health

K. brevis can cause neurotoxic shellfish poisoning (NSP) and aerosol-related brevetoxin induced respiratory irritation. There are also mental and social impacts associated with red tide. Exposure pathways for *K. brevis* include direct skin contact, ingestion of food, incidental ingestion, and inhalation of aerosols.

The risk for foodborne illness from brevetoxins is low because of ongoing shellfish monitoring in the state. Human illnesses from NSP in Florida are a required reportable disease. To date, there have been no known documented human fatalities from NSP. There have also been no documented NSP illnesses due to the consumption of legally harvested bivalves in Florida. However, NSP cases resulting from harvesting gastropods or from illegal recreational harvesting of bivalves have been reported. Potential victims of NSP are likely to be non-English speakers or visitors to the area unaware of the potential risks.

There are variations in toxin accumulation and depuration rates between molluscan species. Gastropods, such as conch and whelk, retain brevetoxins in the viscera for up to 8-months, whereas most bivalve species tend to depurate toxins much more quickly (weeks to months).

Dissolved brevetoxins in sea water are thought to associate with air bubbles that transport them to the sea surface, leading to aerosol exposure associated with sea breezes and breaking waves.

The symptoms of exposure to aerosolized toxins from *K. brevis* blooms are most severe for persons with respiratory illness, such as asthma. Respiratory irritation may linger in such susceptible populations, whereas acute symptoms in healthy people mainly subside as soon as they leave the exposure area.

Public health research should focus on prevention and improved treatment of impacts from exposure to *K. brevis* toxins; reducing impacts from exposure to *K. brevis* toxins resulting from health disparities due to race, ethnicity, or income; improving diagnostic testing accuracy; identifying high-risk subgroups; and improving early detection and prevention of *K. brevis*-related illness.

What we don't know

- How much brevetoxin is acceptable in recreational water?
- What are the long-term health risks from chronic foodborne brevetoxin exposure, including health effects from eating seafood containing low levels of brevetoxin?
- What are the long-term health risks from persistent aerosolized toxin exposures?
- What are the health risks associated with dermal irritation associated with red tide contaminated waters? Are the existing management actions as they relate to the amount of brevetoxin in recreational waters warranted?

Research Priorities: Public Health

1. Evaluate exposure or incidence rates for skin rashes, mucus membranes, dermis	33%
2. Determine the risk of chronic and low-level exposure from seafood	33%
3. Develop multi-lingual outreach materials	33%

Priorities that received majority votes are displayed by rank percentage.

Microcystis spp - consensus statement and research priorities

Bloom Initiation, Development & Termination

Cyanobacteria, also known as blue-green algae, are gram negative bacteria, with pigments in the thylakoids. Cyanobacteria have chlorophyll *a*, which unites all algae. This is why they are referred to as blue-green algae, despite being prokaryotic bacteria rather than eukaryotic algae. Sunlight and carbon dioxide dissolved in the water are used for photosynthesis.

Cyanobacteria are present in freshwater, estuarine, and marine environments, depending on the species. Cyanobacteria that form harmful algal blooms, including *Microcystis* spp. are primarily found in freshwater. Although *Microcystis* is a freshwater organism, it can tolerate salinities up to 18 ppt, with some colonies losing their integrity at 10 ppt. Salinity tolerance is species and strain dependent. Many cyanobacteria are able to regulate their buoyancy in the water column using gas vesicles. This vertical migration allows for optimization of light capture which gives them a competitive advantage over other phytoplankton and can lead to bloom initiation. *Microcystis* and other buoyancy regulating cyanobacteria accumulate and store carbohydrates during photosynthesis, causing them to sink to the lower part of the water column where nutrients are often recycled from sediments.

At any given time, there are a variety of phytoplankton, including bloom-forming species, in the water column. The triggers that allow one species to be selected and form a bloom over another species are complex, including nutrients,

Image: *Microcystis* bloom in the St. Lucie Estuary, 2004
Credit: Florida Sea Grant

light, stability of the water column, and interactions with other biotic members of the community. In general, cyanobacteria need both nitrogen and phosphorus; however, some cyanobacteria groups have the ability to use atmospheric nitrogen, removing this element as a limiting factor. *Microcystis* species are unable to do this and require an external source of nitrogen.

There are many external and internal sources of nutrients that can fuel cyanobacterial blooms in Florida. Cyanobacteria display a strong response to hydrologic forcing, such as water movement and flushing, including runoff from local basins. In the Lake Okeechobee basin, legacy nutrients, those nutrients from past contributions but which can be re-mobilized, are a particularly important source of nitrogen and phosphorus. Nutrient fluxes from lake sediments are enhanced under anoxic conditions.

Blooms are very complex, with daily, weekly, monthly and seasonal forcing functions, including light quantity and quality, stability of the water column, rainfall patterns and nutrient availability. We are currently unable to predict the timing or magnitude of a bloom, and not all blooms are visibly apparent.

Cyanobacteria are thermophiles; in warm waters that are high in nitrogen and phosphorus cyanobacteria can multiply quickly, forming blooms. There are several different genera that notoriously form harmful blooms, including *Microcystis*, *Dolichospermum*, and *Raphidiopsis* (formally *Cylindrospermopsis*). Each organism has an optimum rate of nutrient uptake and a concentration threshold efficiency to take up nutrients. Cyanobacteria blooms are often not monospecific, and shifts in the dominant phytoplankton bloom-forming species may occur with bloom progression. Shifts in community composition may include non-cyanobacterial phytoplankton such as diatoms. Not all cyanobacteria blooms occur at the surface. Bloom initiation and maintenance may occur at mid water or on the bottom, depending on the species, water clarity, and stratification.

Microcystis populations originate from overwintering in the sediments. Resuspension of these populations are triggered by increases in temperature, light, and anoxic conditions. *Microcystis* blooms may produce microcystin toxins, although the energetic cost of doing so is very expensive. Microcystins are about 14% nitrogen by mass, whereas *Microcystis* cells are approximately 7% nitrogen by mass. Thus, *Microcystis* needs excess nitrogen to make microcystins. Microcystins play an antioxidant role in the cells and complete reasons for toxin production are not yet fully understood.

There are many different strains of toxic and non-toxic *Microcystis*. Even those strains that can produce toxin do not always do so. Research suggests nitrogen availability drives what strains are present and how much toxin they are producing. Toxic strains require more nitrogen and nitrogen availability limits microcystin production such that the ratio of microcystin to *Microcystis* biomass decreases as toxic to non-toxic species shifts occur. There may also be toxin genes downregulation in certain strains. There are over 250 congeners of microcystin, and these may also change during the course of a bloom. Like *Microcystis*, microcystin toxicity is variable. Therefore, there is not a defined link between *Microcystis* biomass and toxin concentration nor with toxin concentration and toxicity.

Temperature is important in bloom termination, but the role of other factors, such as bacteria, predation, leaking cells and cell death are not well understood. There are always cells dying in a colony and they release toxins and nutrients into water column for others to utilize.

What we think we know

- Climate change is impacting blooms.
- Increased rain associated with climate change will drive more nutrients off the land, resulting in more nutrients, including urea, being driven to Lake Okeechobee.
- Most communities are dominated by a few types of bacteria.

What we don't know

- What does the community – bacteria, zooplankton, and other phytoplankton – look like before a bloom initiates?
- How do bacteria communities contribute to a bloom?
- What factors are involved in bloom termination?
- What are microcystin degradation rates?

Research Priorities: Bloom Initiation, Development & Termination

Priority	Rank
1. Understand the factors that contribute to initiation, persistence, severity, and decline of blue-green HABs	54%
2. Evaluate past and current hydrology and the effects of freshwater releases on blue-green algae in Lake Okeechobee	
3a. Determine what is responsible for variability in toxicity and toxin production 3b. Determine the function(s) of toxins	
4. Understand the movement of toxins into the environment, including air	
5. Determine variability of strain toxin levels and the relationship with N and P	
6. Determine the role of herbicides on bloom development	
7. Determine how to adequately measure bloom initiation	
8. Evaluate the role of viruses and viral interactions	
9. Assess food web ramifications and develop better ecological models	

Priorities that received majority votes are displayed by rank percentage with all other research priorities listed below a solid line. Research priorities were grouped by relatedness as indicated by more than one priority in a row.

Bloom Prediction & Modeling

Cyanobacteria, including *Microcystis aeruginosa*, are amenable to satellite or other remote sensing tools. Satellites can provide key data for various modeling efforts including model building and validation, although with models, hindcast validation does not equal a forecast.

Cyanobacteria have an absorption peak of about 680 nm and may have a secondary peak at 620 nm when phycocyanin is present. Satellites that can detect the reduced reflectance caused by absorption at these wavelengths can detect the presence of these cyanobacteria. Currently, the only routine operational sensor with these bands is the Ocean Land Colour Imager (OLCI) on the Copernicus Sentinel-3 satellites. OLCI has a 300 m pixel size, and so requires the waterbody to be greater than 600 – 900 meters across to allow extraction of information on blooms in the water. Other satellite sensors, such as the Multi-spectral imager (MSI) on the Sentinel-2, while having greater spatial resolution (10-20 m), has trade-offs. The MSI carries fewer bands than OLCI, and the bands are not specific to cyanobacteria. MSI can find scum and provide measurements for chlorophyll quantity but it cannot specifically identify cyanobacteria. The MSI also has a fixed repeated orientation, so some water bodies may be in sun glint for a few months around the solstice.

Blooms can be seen and quantified from satellite. Biomass and location can be monitored using lake circulation, and forecast three days out with current models. Satellites have been used to estimate chlorophyll in Florida lakes, resulting in bloom frequency models. A severity metric is also being created. In some Florida lakes, such as Lake Apopka, phosphorus load is related to bloom formation and satellites can see the associated variations in bloom intensity, potentially allowing them to provide data to test and validate models for phosphorus. Rainfall, and associated increases in nutrient flow, can trigger severe bloom formation. Lake Okeechobee has large blooms, but they do not persist during the cooler months. Other Florida lakes, Lake Apopka for instance, have more persistent cyanobacteria blooms.

Satellite models for estimating concentrations (chlorophyll and cells) are best developed with field radiometry (simulating the satellite spectral bands), then validated against water samples and other field observations. The strong spatial variability in many cyanobacteria blooms means that there can be larger variations within a pixel, potentially caused several-fold differences between the pixel value (the average of the entire areas) and a water sample. Satellites are more sensitive than the human eye to low chlorophyll levels and are able to detect 20,000 cells/mL *Microcystis*. As a result, cyanobacteria can be detected by satellites at concentrations that may pose a risk but would typically not otherwise be noticeable. However, satellites cannot measure toxicity because toxicity does not produce an optical signal, and not all blooms are toxic or have the same cellular production of toxin.

Satellite sensitivity and specificity need to be reconciled with field validation. Cyanobacteria have strong spatial gradients nearshore, and depth/timing can be problematic. The best algorithms are designed to be mostly insensitive to sediments or CDOM, otherwise false positives may be common. This may occur in the nearshore areas of Lake Okeechobee. We also have limited understanding of picocyanobacteria, which may produce a correct signature from satellite, but is difficult to identify with microscopy and is not well understood as far as toxicity risk. Due to all of these factors, bloom imagery may cause confusion when incorrectly interpreted by the general public.

What we think we know

- When a bloom starts and peaks using satellite data.

What we don't know

- Picocyanoplankton can have phycocyanin, however there is little known about the toxicity. Does it matter because it's so small?

Research Priorities: Bloom Prediction & Modeling

1. Collect regular nutrient (external and internal) load data into Lake Okeechobee	49%
2a. Improve blue-green algae prediction 2b. Develop good physical models of water column structure and circulation	41%
3a. Evaluate the accuracy of satellite imagery compared to discrete and *in situ* sampling 3b. Create a better explanation of satellite imagery for the lay audience	

Priorities that received majority votes are displayed by rank percentage.

Bloom Detection & Monitoring

The State of Florida has multiple ways to receive notifications regarding the occurrence and location of a cyanobacterial bloom, and blooms are detected through multiple channels. They may be encountered during routine surface water sampling programs by state and local agency field staff, county and local government communication, and through the NOAA satellite imagery for north and south Florida. The general public also submit bloom notifications via the algal bloom hotline or online reporting form available since 2016 (https://floridadep.gov/AlgalBloom).

Algal bloom reports are assessed daily during the bloom season. Sampling locations are prioritized based on the potential for human exposure and harm, representativeness of multiple reports, previous sampling history and toxin analysis, and the availability of personnel. Sampling efforts are coordinated between various agencies. Samples are collected primarily to assess public risk and for aquatic resource protection and management. Data may also be used to determine the factors that contribute to the occurrence, persistence, and severity of the bloom, as well as to predict and mitigate for future blooms.

Sample methodology includes the collection of representative water samples to best address the human health risk due to incidental ingestion of bloom water during recreational activities. The Florida Department of Health uses the precautionary principle and bases human health advisories on the presence or absence of detectable levels of cyanotoxins, not on numeric thresholds. The U.S. EPA's recommended cyanotoxin thresholds of 8 µg/L microcystins and 15 µg/L cylindrospermopsins, are based on incidental ingestion of surface water by children during normal recreational activity. Toxin concentrations of a representative water samples are more appropriate for this purpose than scum samples.

The state of Ohio has incorporated a genetic cyanobacteria screening tool for early detection in drinking water. Methods include a multiplex qPCR for screening cyanobacteria instead of conventional algae identification and enumeration via cell counts. The assay identifies and quantifies whether the genes responsible for the production of microcystins, saxitoxin, and cylindrospermopsin are present. It also quantifies the 16s gene which can be roughly correlated to the amount of total cyanobacteria that is present in the water source.

In Florida, bloom samples are collected from the environment and are analyzed for cyanotoxins, algal identification, chlorophyll *a*, and nutrients. Cyanotoxin analysis is completed using a liquid chromatography mass spectrometer (LCMS) direct inject machine, which allows for a quick turnaround time. There are over 250 microcystin congeners but only a handful can be detected by LCMS. Current analysis includes six microcystin congeners (LR, RR, YR, LA, LF, LY), anatoxin-a, and cylindrospermopsin. Saxitoxin, microcystin congeners -LW and -WR, and desmethyl-LR will be added soon. Dominant or co-dominant algal species are identified in bloom samples using light microscopy.

Despite the amount of sampling conducted, we know that we are not monitoring cyanobacteria nearly as well as red tide. Cyanobacteria HAB monitoring will be increased in 2020 compared to 2019 as a result of additional funding from the legislature. Sampling approaches are unique to location, so Ohio's response will be different than Florida's. Sampling methodologies also matter when detecting cyanotoxins.

In Florida, Lake Okeechobee is routinely monitored due to its propensity to experience algal blooms, including *Microsystis aeruginosa* blooms. Lake Okeechobee has three distinct zones. The pelagic zone is characterized by higher turbidity and nutrients. The nearshore zone may be clear or turbid and contains submersed plants, and the littoral zone is shallow with dense marsh vegetation, lower nutrients and clearer water.

Within the lake, 17 monitoring sites, including eight nearshore and nine pelagic, are monitored monthly for a suite of physical, chemical and bloom conditions. At six sites, samples are collected for phytoplankton community composition and microcystins determined by ELISA method. During blooms, additional samples from bloom areas are collected and analyzed for dominant species identification and microcystins. Expansion of the routine Lake Okeechobee monitoring program will increase the number of sites sampled from 17 to 32 and will include more regular algal identification and toxin analyses. Lake Okeechobee routine algal bloom monitoring is useful for providing general trends on localized bloom conditions; however, the extrapolation of these data is limited spatially since *Microcystis* blooms are heterogeneous and field sample collection may occur in an area where the bloom is not spatially or temporally present.

Instantaneous surface reflectance data via Handheld Hyperspectral Radiometer is supplementing routine water quality monitoring data and the SeaPRISM weather platform will continuously measure incident sunlight and light reflected from the water. These and other more frequent, less time-consuming determination of algal bloom conditions on Lake Okeechobee will allow for timelier management decisions.

What we think we know

- Sample collection, preparation, and analysis methods have significant effects on the levels of cyanotoxins reported.
- Cynaboacteria blooms are not always reported and sampled.
- In addition to posted signage, the public must use visual observation and historic bloom information to inform their decision about whether to recreate in a waterbody due to rapidly changing bloom conditions.
- Cyanotoxin concentrations are likely underestimated due to our limited ability to quantify the hundreds of toxins that could potentially be present.

Research Priorities: Bloom Detection & Monitoring

1. Enhance blue-green algae monitoring, including time series (longitudinal) as another data point ▪ Improve blue-green algae field identification	50%
2. Determine if and what role environmental conditions have on cyanotoxin levels	23%
3. Develop a standard method for measuring *Microcystis* (cells through molecular) (Look at other state regulations for improvements or changes)	
4a. Evaluate if and what relationship exists between biomass and toxin levels 4b. Implement vertical profiles to get an accurate assessment of biomass	
5. Evaluate the correlations between hypoxia and nutrient fluxes	
6. Develop sampling plans to meet existing recommendations and use (e.g., WHO, EPA)	
7. Implement vertical profiles to get an accurate assessment of biomass	
8. Understand sensor limitations	
9. Detect and treat taste and odor compounds	

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Bloom Mitigation & Control

There are a variety of management approaches for cyanobacterial blooms, including *Microcystis aeruginosa*. Bloom management may be proactive or reactive, indirect or direct. Proactive approaches to controlling blooms may include long-term management strategies such as mitigating nutrient inputs and/or climate change. They can also include direct, short-term options designed to prevent an algae bloom before it begins. Reactive approaches are more common and control the phytoplankton blooming rate or remove algae from surface waters.

The selected management approach(es) should consider several important factors such as the type of waterbody, the size of the waterbody, the type of bloom, water quality, and ecosystem impacts, as many control options have limitations regarding scalability and pollutants. Bloom management may also need to take an adaptive approach since species composition may shift during the duration of a bloom and management response is not consistent across species. An important consideration is that managing blooms does not necessarily equate to managing toxins.

Physical controls involve techniques which remove the algae material from the waterbody and include harvesters, rakes and surface skimmers. Other physical control strategies are designed to disrupt the cyanobacteria's ability to vertically migrate. These techniques include aeration, mechanical mixing, and sonication. Physical control can also be achieved by hydraulic or hydrologic manipulations.

Biological control includes algicidal bacteria, plant bioactive compounds, enzymes, and herbivorous fish such as grass carp and tilapia, although cyanobacteria are known to be distasteful as compared to other microalgae.

Chemical controls may be proactive such as with barley straw or blue dyes. Barley straw inhibits the growth of cyanobacteria whereas dyes reduce algae growth by inhibiting light penetration and blocking photosynthesis. Reactive chemical control methods also include the addition of coagulants or flocculants which facilitate sedimentation of cyanobacteria to the bottom. There are many EPA registered algicides and aquatic herbicides which may be used to kill an existing cyanobacteria bloom. These include a variety of chemical compounds such as copper-based algicides, peroxides, endothall, and diquat dibromide, for example. Algicides are a relatively rapid method, but the fate of the chemical and the toxin from lysed cells remain unknown, while the nutrients from the dead cells are released and recycled by other cyanobacteria, algae, or plants. Treatment effectiveness may also vary by species and bloom.

More data is needed to assess the feasibility and scale-up costs of many of these control options. Long-term data are also needed on the effects of chemical formulations, proposed bacteria and proposed enzymes on the environment and non-target organisms. Proactive methods that address nutrient management or bioremediation should be part of a bloom management strategy. Not all waters and not all blooms are the same; what works in one may not work in another.

What we think we know

- Site-specific benthic characteristics will affect the efficacy and safety of mitigation and mitigation practice.
- Algal bloom mitigation must take potential ecological harm and human health risks into consideration.
- The scale of some blooms makes the application of some algal bloom mitigation techniques unfeasible.

What we don't know

- The fate of algicides.

Research Priorities: Bloom Mitigation & Control

1. Control all nutrient pollution (N & P) – including different forms of N (urea, ammonia, etc) ▪ Determine the relative importance (quantitative measures) of different nutrient inputs ▪ Convert all septic tanks near water to municipal sewage	51%
2a. Determine if your management practice will actually achieve the goal of reducing blooms in Lake Okeechobee and what the ramifications are (chemical, biological, ecological, socioeconomic) 2b. Develop blue-green algae control methods 2c. Evaluate and weigh engineering approaches versus ecological approaches	43%
3. Evaluate what hydrological conditions can impact management and future management options	
4. Determine a strategy for effective messaging to public regarding expectations, timelines, and costs	
5. Create a central database for alternative technologies	

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Public Health

Cyanobacteria blooms can occur year-round, in a variety of waters, and can be different spatially and temporally. Cyanobacteria produce cyanotoxins as secondary metabolites. There are different types of cyanotoxins including but not limited to saxitoxins, anatoxin-a, cylindrospermopsin, and microcystins, the latter of which are produced predominantly by *Microcystis*. The toxicity of these cyanotoxins differ as do their interactions with, and effects on, different organs in the human body. Not all cyanobacteria blooms produce toxins and it is not possible to tell if a bloom is toxic simply by appearance. Therefore, public health messaging in Florida follows the precautionary principle and focuses on avoiding all bloom waters.

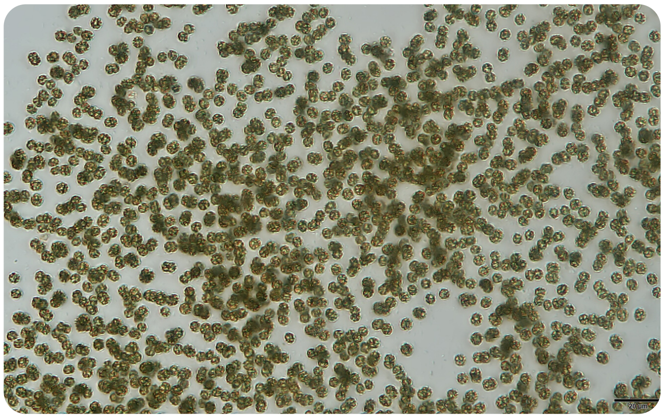

Image: *Microcystis aeruginosa*
Credit: B. Rosen, Florida Gulf Coast University

There are several cyanobacterial exposure pathways for humans and animals. The most frequent exposure pathway is through direct skin contact which may occur during recreational activities such as swimming. However, incidental ingestion is the primary exposure pathway to cyanobacterial toxins. This occurs by immersion and may occur during some recreational activities in waterbodies. These activities may also lead to inhalation of aerosols. Exposure via this pathway is increased by disruption of cells at the water surface, such as that which would occur as a result of jet-skiing or by motorboating.

Ingestion of drinking water is another exposure pathway; however, in Florida most drinking water is from groundwater where toxic cyanobacteria blooms are not an issue. But, with increased reliance on surface water for drinking in Florida the safety of drinking water is becoming more of a concern.

Finally, ingestion exposure can occur if contaminated shellfish and/or fish are consumed. Cyanotoxins tend to concentrate in the viscera of fish and shellfish, with lower levels present in the muscle. Bivalve shellfish that are eaten whole (e.g., oysters, clams, mussels) are a potential source of exposure to concentrated cyanotoxins. In Florida, freshwater shellfish are not commercially harvested, and recreational harvest is prohibited outside of approved shellfish harvest areas, which are all marine or estuarine. Still, *Microcystis* blooms can be present in estuarine harvest areas. At this time, there are no U.S. regulatory guidelines regarding cyanotoxins in shellfish; however, the Florida Department of Agriculture and Consumer Services has in the past closed estuarine shellfish harvesting areas when cyanobacteria blooms were present. The risk of exposure from ingesting illegally harvested shellfish is possible during cyanobacterial blooms. Other shellfish, such as blue crabs, may present a health risk if the hepatopancreas or roe is eaten. Cyanotoxins tend not to accumulate in edible portions of finfish to the same degree as in their viscera but eating finfish may still result in exposure to cyanotoxins, possibly above World Health Organization guidance levels under the right conditions.

Dose exposures for potential human health impacts need to account for toxin concentration and frequency of exposure. EPA's cyanotoxin thresholds for microcystins and cylindrospermopsin are based on incidental ingestion by children during a normal recreational activity. The goal is to advise the public to avoid recreating during blooms and to keep pets away. These thresholds are based on toxin concentrations in the water, not in scum. The state of Florida's human health advisories are based on presence or absence of detectable levels of cyanotoxins, not on a numeric threshold.

In addition to exposure through aquatic systems, cyanotoxins as contaminants of the soil are a concern. We know that some agricultural crops uptake microcystin, and that these toxins inhibit plant growth which lowers crop yields. Pathways for plant exposure include the use of dried toxic cells as fertilizer or the use of surface water contaminated with cyanotoxins for agricultural irrigation. Exposed soils present the possibility of human exposure as does consumption of the contaminated crop produced.

Human exposure impacts may be short- or long-term. In Florida, most data are from self-reported exposures and illnesses, and the most common symptoms reported are skin rashes and eye, nose and throat irritation. There are some confounding factors from other secondary metabolites or bloom byproducts. For example, decomposing cyanobacteria can emit hydrogen sulfide. This gas can also cause some of these reported symptoms, especially eye, nose, and throat irritation. As a result, it is difficult to distinguish impacts of other bloom byproducts from the acute impact of cyanotoxins.

There is much that is unknown about the longer-term impacts of cyanotoxins. Researchers are looking for those connections, and they are hypothesizing what those links may be. Even though links have been suggested, we do not have conclusive research demonstrating causal relationships between exposure and effects. One such example is beta-Methylamino-L-alanine (BMAA), which has been suggested to cause amyotrophic lateral sclerosis (ALS) and other neurological diseases. This is a controversial topic and is a concern of the general public; however, data are still insufficient to establish clear dose-effect relationships that could be used to establish human health-based exposure thresholds. At present there is a lack of consensus regarding its ubiquitous occurrence, uncertainty on concentrations reported, problems with replication of study findings, and analytical methodology variable.

Challenges evaluating human health impacts from cyanobacterial blooms are numerous. They include a limited understanding of exposure dose through some exposure pathways, symptoms that are not specific to HAB exposures, no FDA approved clinical laboratory tests for exposure, health care professionals lacking expertise in HAB-related illnesses, the migration of people in and out of affected areas, scarcity of air monitoring data, and the expense and time of conducting long-term, human health studies. Current human health research priority areas for the state include prevention, treatment, addressing health disparities, and improving screening detection and accuracy.

What we don't know

- Longer term impacts of cyanotoxins.
- How does the particular toxin get to a person? What is the exposure, what is the duration, what is the frequency?
- How does the toxin get through that exposure pathway to cause a harmful health effect?
- Floridians actual exposure to cyanotoxins due to our limited ability to detect and quantify many cyanotoxins.

Research Priorities: Public Health

1. Identify all toxins, risk, and levels of toxicity, including microcystin, BMAA, stress ▪ Determine longevity of diverse cyanotoxins in biota relevant for human health consumption ▪ Understand the persistence of microcystins in sediments and the water column, their ability to be remobilized, and how that effects drinking water ▪ Determine human exposure pathways through the food chain (e.g., beef, seafood, crops, and milk) ▪ Assess synergistic effects of toxins with other toxic chemicals	66%
2. Develop more clear diagnostic criteria for health care providers	
3. Evaluate the correlations between hypoxia and nutrient fluxes	
4. Need clinically approved matrix-specific assays for cyanotoxins in biological samples	
5. Establish more effective guidelines for drinking water treatment for all contaminants (i.e., saxitoxin)	
6. Determine the best way to measure toxins in the food web	

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Communications Summary

Harmful algal blooms are complex, making communicating with the public particularly challenging.

Specific challenges include a lack of knowledge and general misconceptions about HABs. These are magnified by the transient nature of people in and out of Florida in addition to the public's broad access to information sources, not all of which are correct or reputable. Because there are mental and social impacts associated with HABs, when the public receives conflicting messages regarding the state of HAB science, they may become frustrated and ultimately mistrust the science and the scientists conducting HAB research.

Frequently identified topics that cause confusion include the use of bloom terms, such as red tide, blue-green algae, and cyanobacteria which the public does not readily understand; mixed messages regarding human health concerns, particularly as it relates to BMAA; aerosol exposure and seafood safety; the causes of various blooms; bloom interrelatedness; and bloom response and control measures.

Outreach can mitigate HAB impacts by fostering awareness of potential threats, imparting accurate information regarding seafood, drinking water, and recreational safety, and encouraging participation in HAB prediction and response efforts.

In order to be effective communicators, scientists need to:

- develop a better social science understanding of what HAB information the public really wants and needs;
- identify appropriate communication formats so that messages are clear;
- understand the values held by individuals or communities, as these will influence how information is interpreted and whether that information will be accepted or rejected;
- determine how and where individuals are obtaining information, and why those outlets are preferred; and
- develop outreach inclusive of different cultural and multilingual audiences.

A goal of the *Florida Harmful Algal Bloom State of the Science Symposium* was to use the consensus statements developed for each session to facilitate better public outreach and communication from the scientific community.

Objectives for HAB communication include:

- Maintaining and disseminating information that is accurate, timely, and targeted to the appropriate audience;
- Developing information in forms that are easily accessible and understandable to a variety of age and interest groups;
- Avoiding controversial terms and focusing on issues, impacts and solutions with which the target audience can relate; and
- Ensuring individuals, groups, and communities understand each HAB message, trust its source, and respond appropriately.

Specific communication opportunities identified during the symposium include:

- increased awareness regarding the effects of anthropogenic activities on HABs;
- ensuring data and forecasting tools disseminated to the public are easily understandable;
- expanded outreach of HAB toxins and risk factors;
- mitigation measures including bloom avoidance;
- HAB toxin information for medical practitioners and veterinarians; and finally,
- realistic messaging regarding public expectations as it relates to bloom control, including timelines and costs.

In Memoriam

Karl Havens

1957-2019

Dr. Karl Havens was the Director of the Florida Sea Grant College Program and Professor in the Department of Fisheries and Aquatic Sciences at the UF/IFAS School of Forest Resources and Conservation. Before joining UF as professor and chair of the department of fisheries and aquatic sciences, he served as chief environmental scientist at the South Florida Water Management District from 1993-2004, where he became one of Florida' s most respected voices on the science behind the management of Lake Okeechobee and the Everglades. Karl had 35 years of experience in aquatic research, education, and outreach and was the recipient of the Edward Deevey, Jr. Award from the Florida Lake Management Society.

Most recently, Karl delivered a plenary talk on nutrients, algae blooms and climate change at the 2019 Greater Everglades Ecosystem Restoration conference. He was to have been announced as a member of Florida Governor Ron DeSantis's blue-green algae task force, was leading the UF/IFAS Harmful Algal Bloom task force, and was an active and enthusiastic member of this Symposium's steering committee. Karl's contributions to the field, as well as his leadership and mentorship will be greatly missed.

References

Aikins, S. and E. Kikuchi. 2001. Water current velocity as an environmental factor regulating the distribution of amphipod species in Gamo Lagoon, Japan. Limnology 2:185–191.

Alliance for Coastal Technologies. 2017. Sensors for monitoring of harmful algae, cyanobacteria and their toxins. Workshop Proceedings, January - February 2017.

Alliance for Coastal Technologies. 2018. Practical uses for drones to address management problems in coastal zones. Workshop Proceedings, September 2018.

Anderson, D. 2019. Control of marine harmful algal blooms: assessing the state of current technology. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Atkinson, A.J., O.G. Apul, O. Schneider, S. Garcia-Segura and P. Westerhof. 2019. Nanobubble technologies offer opportunities to improve water treatment. Acc. Chem. Res. 2019, 52, 5, 1196-1205.

Backer, L.C. 2019. *Karenia brevis* Red tides: Update on human health effects and what's next. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Bormans, M., Z. Amzil, E. Mineaud, L. Brient, V. Savar, E. Robert and E. Lance. 2019.Demonstrated transfer of cyanobacteria and cyanotoxins along a freshwater-marine continuum in France. Harmful algae, 87, p.101639.

Chaffin, J.D. 2019. Working towards a forecast of Lake Erie cyanobacterial bloom toxicity. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Chaffin, J.D., D.D. Kane, K. Stanislawczyk and E.M. Parker. 2018. Accuracy of data buoys for measurement of cyanobacteria, chlorophyll, and turbidity in a large lake (Lake Erie, North America): implications for estimation of cyanobacterial bloom parameters from water quality sonde measurements. Environmental Science and Pollution Research 25:25175–25189.

Chaffin, J.D., T.B. Bridgeman, S.A. Heckathorn and S Mishra. 2011. Assessment of *Microcystis* growth rate potential and nutrient status across a trophic gradient in western Lake Erie. J Great Lakes Res 37:92–100.

Clark, J.M., B.A. Schaeffer, J.A. Darling, E.A. Urquhart, J.M. Johnston, A.R. Ignatius, M.H. Myer, K.A. Loftin, P.J. Werdell and R.P. Stumpf. 2017. Satellite monitoring of cyanobacterial harmful algal bloom frequency in recreational waters and drinking water sources. Ecological Indicators, 80, 84-95.

Conley, D.J., H.W. Paerl, R.W. Howarth, D.F. Boesch, S.P. Seitzinger, K.E. Havens, C. Lancelot and G.E. Likens, 2009. Controlling eutrophication: nitrogen and phosphorus. Science 323: 1014–1015.

Deng, J., H.W. Paerl, B. Qin, Y. Zhang, G. Zhu, E. Jeppesen, Y. Cai, Y. and H. Xu. 2018. Climatically-modulated decline in wind speed may strongly affect eutrophication in shallow lakes. Science of the Total Environment, 645, pp.1361-1370.

East, T., P. Jones and Z. Welsh. 2019. Linking satellite imagery with water quality to detect algal blooms in Lake Okeechobee. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Elser, J.J., M.E.S. Bracken, E.E. Cleland, D.S. Gruner, W.S. Harpole, H. Hillebrand, J.T. Bgai, E.W. Seabloom, J.B. Shurin & J.E. Smith, 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecology Letters 10: 1124–1134.

Flewelling, L.J. 2019. Beyond Red tide: An overview of marine harmful algal blooms in Florida. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Florida Oceans and Coastal Council. 2009. The effects of climate change on Florida's ocean and coastal resources. A special report to the Florida Energy & Climate Commission and the people of Florida.

Glibert, P.M., J.M. Burkholder, T.M. Kana, J. Alexander, H. Skelton and C. Shilling. 2009. Grazing by *Karenia brevis* on *Synechococcus* enhances its growth rate and may help to sustain blooms. Aquat. Microb. Ecol. 55, 17–30.

Havens, K.E., R.T. James, T.L. East & V.H. Smith, 2003. N:P ratios, light limitation, and cyanobacterial dominance in a subtropical lake impacted by nonpoint source nutrient pollution. Environmental Pollution 122: 379–390.

Heil, C.A. 2019. Florida red tide: Initiation, development & termination: Knowledge, data gaps and areas of uncertainty. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Heil, C.A., L.K. Dixon, E. Hall, M. Garrett, L. Matthew, J.M. Lenes, J.M. O'Neil, B.M. Walsh, D.A. Bronk, L. Killberg-Thoreson, G.L. Hitchcock, K.A. Meyer, M.R. Mulholland, L. Procise, G.J. Kirkpatrick, J.J. Walsh and R.W. Weisberg. 2014. Blooms of Karenia brevis on the West Florida Shelf: Nutrient sources and potential management strategies based on a multi-year regional study. In Nutrient dynamics of *Karenia brevis* red tide blooms in the eastern Gulf of Mexico, Harmful Algae September 2014 38:127-140.

Heil, C.A., G.A. Vargo, D. Spence, M.B. Neely, R. Merkt, K. Lester and J.J. Walsh. 2001. Nutrient stoichiometry of a *Gymnodinium breve* Davis (Gymnodiniales: Dinophyceae) bloom: what limits blooms in oligotrophic environments? In: Hallegraeff, G., Blackburn, S.I., Bolch, C.J., Lewis, R.J. (Eds.), Harmful Algal Blooms 2000. Intergovernmental Oceanographic Commission of UNESCO 2001, Paris, pp. 165–168.

Hu, C., F.E. Muller-Karger, C.J. Taylor, K.L. Carder, C. Kelble, E. Johns, and C.A. Heil. 2005. Red tide detection and tracing using MODIS fluorescence data: A regional example in SW Florida coastal waters. Remote Sensing of Environment, 97 (3), pp.311-321.

Jeong, H.J., J.Y. Park, J.H. Nho, M.O. Park, J.H. Ha, K.A. Seong, C. Jeng, C.N. Seong, K.Y. Lee and W.H. Yih, 2005. Feeding by red-tide dinoflagellates on the cyanobacterium *Synechococcus*. Aquat. Microb. Ecol. 41, 131–143.

Kirkpatrick, B. 2019. HAB detection and monitoring. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Kosten, S., V. L.M. Huszar, E. Becares, L.S. Costa, E. van Donk, L.A. Hansson, E. Jeppesenk, C. Kruk, G. Lacerot, N. Mazzeo, L. De Meester, B. Moss, M. Lurling, T. Noges, S. Romo and M. Scheffer. 2012. Warmer climates boost cyanobacterial dominance in shallow lakes. Global Change Biology 18: 118–126.

Lewis Jr, W.M. and W.A. Wurtsbaugh. 2008. Control of lacustrine phytoplankton by nutrients: erosion of the phosphorus paradigm. International Review of Hydrobiology, 93(4-5), pp.446-465.

Lewis, W.M., W.A. Wurtsbaugh, and H.W. Paerl. 2011. Rationale for control of anthropogenic nitrogen and phosphorus in inland waters. Environ. Sci. Technol. 45, 10030–10035.

Liu, Y. and R.H. Weisberg. 2012. Seasonal variability on the west Florida shelf. Prog. Oceanogr. 104, 80–98.

Magana, H.A., C. Contreras and T.A. Villareal. 2003. A historical assessment of *Karenia brevis* in the western Gulf of Mexico. Harmful Algae 2, 163–171.

Marvin, K.T., and R.R. Proctor Jr. 1964. Preliminary results of the systematic screening of 4,306 compounds as ''red-tide'' toxicants. US Fish Wildl. Serv. Data Report No. 2, 84 p.

Marvin, K.T. and R.R. Proctor Jr. 1967. Laboratory evaluation of red-tide control agents. Fish. Bull. 66, 163–164.

Miller, M.A., Kudela, R.M., Mekebri, A., Crane, D., Oates, S.C., Tinker, M.T., Staedler, M., Miller, W.A., Toy-Choutka, S., Dominik, C. and Hardin, D., 2010. Evidence for a novel marine harmful algal bloom: cyanotoxin (microcystin) transfer from land to sea otters. PLoS One, 5(9), p.e12576.

Moisander, P.H., E. McClinton III, & H. Paerl. 2002. Salinity effects on growth, photosynthetic parameters, and nitrogenase activity in estuarine planktonic cyanobacteria. Microbial Ecology,43(4), 432-442.

Moisander, P.H., M. Ochiai, and A. Lincoff. 2009. Nutrient limitation of *Microcystis aeruginosa* in northern California Klamath River reservoirs. Harmful Algae, 8(6), pp.889-897.

Novoveská, L. and A. Robertson. 2019. Brevetoxin-producing spherical cells present in *Karenia brevis* bloom: Evidence of morphological plasticity?. Journal of Marine Science and Engineering, 7(2), p.24.

Oelsner, G.P. and E.G. Stets. 2019. Recent trends in nutrient and sediment loading to coastal areas of the conterminous U.S.: Insights and global context. Science of the Total Environment 654, 1225–1240.

Otten, T.G. and H.W. Paerl. 2015. Health effects of toxic cyanobacteria in U.S. drinking and recreational waters: our current understanding and proposed direction. Curr. Environ. Health Rep. 2, 75–84.

Özkundakci, D., D.P. Hamilton, and M.M. Gibbs. 2011. Hypolimnetic phosphorus and nitrogen dynamics in a small, eutrophic lake with a seasonally anoxic hypolimnion. Hydrobiologia, 661(1), pp.5-20.

Paerl, H.W., J.T. Scott, M.J. McCarthy, S.E. Newell, W.S. Gardner, K.E. Havens, D.K. Hoffman, S.W. Wilhelm, and W.A. Wurtsbaugh. 2016a. It takes two to tango: When and where dual nutrient (N & P) reductions are needed to protect lakes and downstream ecosystems. Environmental Science & Technology, 50(20), pp.10805-10813.

Paerl, H. W., W.S. Gardner, K.E. Havens, A.R. Joyner, M.J. McCarthy, S.E. Newell, B. Qin & J.T. Scott, 2016b. Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. Harmful Algae 54: 213–222.

Paerl, H.W. T.G. Otten and R. Kudela. 2018. Mitigating the expansion of HABs across the freshwater – to – marine continuum. Environ Sci & Tech, 52, 5519-5529.

Paerl, H. 2019. HABs along the freshwater – to – marine continuum: Emerging and evolving issues. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Park, T.G., Lim, W.A., Park, Y.T., Lee, C.K., Jeong, H.J., 2013. Economic impact, management and mitigation of red tides in Korea. Harmful Algae, 30 (1), pp131–143.

Pierce, R.H., M.S. Henry, C.J. Higham, P. Blum, M.R. Sengco, and D.M. Anderson. 2004. Removal of harmful algal cells (*Karenia brevis*) and toxins from seawater culture by clay flocculation. Harmful Algae, 3(2), pp.141-148.

Raymond, H. 2019. Ohio EPA HAB response and lessons learned. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Reich, A. 2019. Public health response to algal blooms in Florida. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Riekenberg, J., S. Bargu, and R. Twilley. 2015. Phytoplankton community shifts and harmful algae presence in a diversion influenced estuary. Estuaries and coasts, 38(6), pp.2213-2226.

Robson, B.J. and D.P. Hamilton. 2003. Summer flow event induces a cyanobacterial bloom in a seasonal Western Australian estuary. Mar. Freshw. Res. 54, 139–151.

Rosen, B.H. 2019. Cyanobacteria ecological strategies: Initiation, development & termination of a bloom. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Rosen, B.H., T.W. Davis, C.J. Gobler, B.J. Kramer, and K.A. Loftin. 2017. Cyanobacteria of the 2016 Lake Okeechobee and Okeechobee Waterway harmful algal bloom USGS Open-File Report 2017-1054.

Rounsefell, G.A. and W.R. Nelson. 1966. Red tide research summarized to 1964 including an annotated bibliography. Spec Sci Rep No. 535. US Fish and Wildlife Service, Washington, DC.

Sengco, M.R. and D.M. Anderson. 2004. Controlling harmful algal blooms through clay flocculation. J. Eukaryot. Microbiol. 51, 169–172.

Steidinger, K.A., 2009. Historical perspective on *Karenia brevis* red tide research in the Gulf of Mexico. Harmful Algae 8, 549 –561.

Stumpf, R. 2019. Remote sensing and forecasting *Karenia brevis* and cyanobacteria. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Swanson, C. 2019. Florica's CyanoHAB monitoring and response. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Tonk, L., K. Bosch, P.M. Visser and J. Huisman. 2007. Salt tolerance of the harmful cyanobacterium *Microcystis aeruginosa*. Aquat. Microb. Ecol. 46 (2), 117–123.

Vargo, G., C.A. Heila, K.A. Fanning, L.K. Dixon, M.B. Neely, K. Lester, D. Ault, S. Murasko, J. Havens, J. Walsh and S. Bella 2008. Nutrient availability in support of *Karenia brevis* blooms on the central West Florida Shelf: what keeps *Karenia* blooming? Cont. Shelf Res. 28, 73–98.

Weisberg, R.H. 2019. Red Tide: What we know, don't know and what to do about it. Florida Harmful Algal Bloom State of the Science Symposium, August 2019. https://www.flseagrant.org/algae-blooms/harmful-algal-bloom-state-of-the-science-symposium/

Weisberg, R.H., Y. Liu, C. Lembke, C. Hu, K. Hubbard, and M. Garrett. 2019. The Coastal ocean circulation influence on the 2018 West Florida Shelf *K. brevis* red tide bloom, J. Geophys. Res. - Oceans, 124.

Weisberg, R.H., L. Zheng, Y. Liu, A. Corcoran, C. Lembke, C. Hu, J. Lenes, and J.J. Walsh. 2016. Karenia brevis blooms on the west Florida shelf: A comparative study of the robust 2012 bloom and the nearly null 2013 event, Cont. Shelf Res., 120, 106-121.

Weisberg, R.H., L.Y. Zheng and Y. Liu. 2016. West Florida shelf upwelling: origins and pathways, J. Geophys. Res. - Oceans, 121, 5672-5681.

Weisberg, R.H., L. Zheng, Y. Liu, C. Lembke, J.M. Lenes and J.J. Walsh. 2014. Why a red tide was not observed on the West Florida Continental Shelf in 2010, Harmful Algae, 38, 119-126.

Yu, Z., X. Song, X. Cao and Y. Liu. 2017. Mitigation of harmful algal blooms using modified clays: Theory, mechanisms, and applications. Harmful algae, 69, pp.48-64.

Zhu, M., H. W. Paerl, G. Zhu, T. Wu, W. Li, K. Shi, L. Zhao, Y. Zhang, B. Qin & A. M. Caruso, 2014. The role of tropical cyclones in stimulating cyanobacterial (*Microcystis* spp.) blooms in hypertrophic Lake Taihu. China. Harmful Algae 39:

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Acknowledgements

Funding agencies

Special thanks to:

- Chris Ellis, Holly Abeels, Savanna Barry, Angela Collins and Maia McGuire
- USGS Coastal and Marine Science Center
- All of our invited speakers and reviewers

Florida Sea Grant is committed to enhancing the practical use and conservation of coastal and marine resources to create a sustainable economy and environment.

This publication was supported by the National Sea Grant College Program of the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA), Grant No. NA 18OAR4170085 . The views expressed are those of the authors and do not necessarily reflect the view of these organizations. Additional copies are available by contacting Florida Sea Grant, University of Florida, PO Box 110409, Gainesville, FL, 32611-0409, (352) 392.2801, **www.flseagrant.org**.

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