STATE OF THE SCIENCE FOR

Cyanobacterial Blooms in Florida

Produced from the 2023 Blue-Green Algae State of the Science Symposium

Sea Grant FLORIDA

UF IFAS Extension UNIVERSITY of FLORIDA

FOR MORE INFORMATION

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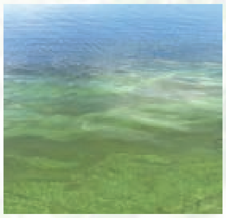
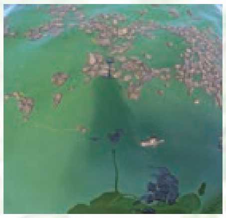
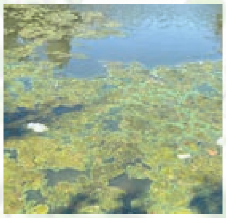
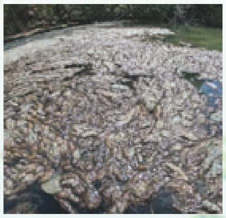








ACRONYMS USED

ALS - Amyotrophic Lateral Sclerosis
BGASOS - Blue-Green Algae State of the Science
BMAA - Beta-Methylamino-L-Alanine
C - Celsius
CDC - Centers for Disease Control
CDOM - Colored Dissolved Organic Matter
CIcyano - Cyanobacteria Specific Index
cyanoHAB - Cyanobacteria Harmful Algal Bloom
DIN - Dissolved Inorganic Nitrogen
DIP - Dissolved Inorganic Phosphorus
DVM - Diel Vertical Migration
ELISA - Enzyme-Linked Immunoassay
EPA - Environmental Protection Agency
FDA - Food and Drug Administration
FDACS - Florida Department of Agriculture and Consumer Services
FDEP - Florida Department of Environmental Protection
FDOH - Florida Department of Health
FIFRA - Federal Insecticide, Fungicide, and Rodenticide Act
FWC - Florida Fish and Wildlife Conservation Commission
HAB - Harmful Algal Bloom
HABHRCA - Harmful Algal Bloom and Hypoxia Research and Control Act
HABSOS - Harmful Algal Bloom State of the Science
IRL - Indian River Lagoon
KCoL - Kissimmee Chain of Lakes
lb - Pound
LCMS - Liquid Chromatography Mass Spectrometer
LMB - Lanthanum Modified Bentonite
LOSOM - Lake Okeechobee System Operating Manual
m - Meter
MC - Microcystin
MSI - Multispectral Imager
N - Nitrogen
NASA - National Aeronautics Space Agency
NOAA - National Oceanic and Atmospheric Administration
NO3 - Nitrate
NO4 - Orthonitrate
NPS – Nonpoint Source
OLCI - Ocean and Land Colour Imager
P - Phosphorus
PPE - Personal Protective Equipment
PPT - Parts Per Thousand
PS – Point Source
Q10 - Temperature Coefficient
OHHABs - One Health Harmful Algal Bloom System
RFP - Request for Proposal
rRNA - Ribosomal Ribonucleic Acid
SAV - Submerged Aquatic Vegetation
SFWMD - South Florida Water Management District
SJRWMD - St. Johns River Water Management District
SOP - Standard Operating Procedures
SPATT - Solid Phase Adsorption Toxin Tracking
TMDL - Total Maximum Daily Load
TN - Total Nitrogen
TP - Total Phosphorus
µg/L - Micrograms per Liter
UME - Unusual Mortality Event
USACE - United States Army Corp of Engineers

Introduction

This report summarizes the outcomes of the *2023 Florida Blue-Green Algae State of the Science Symposium* held May 15 & 16 in Maitland, Florida. The symposium was hosted by the Florida Sea Grant College Program and the University of Florida's Institute of Food and Agricultural Sciences with funding from the Florida Department of Environmental Protection (FDEP). This document serves as an update and a complement to the *2019 Harmful Algal Bloom State of the Science Symposium* (HABSOS) report which can be found here.

The symposium was conducted at the request of the Blue-Green Algae Task Force, the goals of which were to:

1. Identify what progress has been made since the inaugural symposium in 2019, determine what knowledge gaps still exist, and prioritize new research needs to inform and improve cyanoHAB management in Florida.
2. Efficiently share updates on new findings and ongoing efforts to ensure that the most current best practices are being employed statewide and that ongoing efforts are not being duplicated.

More than fifty researchers and managers from around the state and across the country attended the symposium. Participants represented 20 unique institutions encompassing academia, local, state, and federal agencies, non-profit organizations, and industry allowing for diverse and comprehensive assessment of the current state of cyanobacterial harmful algal bloom (cyanoHAB) research and management.

The purpose of the 2023 symposium was threefold:

- Facilitate information exchange among harmful algal bloom scientists and managers.
- Assess the current state of research and management for Florida's cyanoHABs.
- Identify data gaps and prioritize research and management needs for cyanoHABs in Florida.

The Blue-Green Algae State of the Science Symposium II (BGASOS II) assessed progress made since the first State of the Science Symposium in 2019. The 2019 symposium resulted in a set of consensus statements that summarized *what we know, what we think we know,* and *what we need to know* in regards to the five thematic areas: **drivers of cyanoHABs; bloom detection and monitoring; prediction and modeling; mitigation and management;** and **public health.** The data gaps *(what we need to know)* drove a list of research priorities that were grouped by similarity and ranked.

Whereas the first State of the Science Symposium focused specifically on *Microcystis* blooms in Lake Okeechobee, BGASOS II took a broader perspective looking at various cyanobacterial bloom-forming taxa across Florida within the same five thematic areas. The format for the symposium included lightning round presentations followed by facilitated discussion. In order to assess progress since 2019, each session in 2023 began with a short presentation that looked back to 2019. The 2019 consensus statements were also provided to participants as a reference.

Each session consisted of four 5-minute lightning round presentations that covered new or ongoing research or management efforts. Invited presenters were provided templates for presentations and were instructed to focus on the major project take-aways and conclusions. Presenters also identified which research priority(ies) from 2019 their project addressed as well as any new data gaps that arose from these efforts. At the conclusion of all four lightning presentations, there was a Q&A panel with all of the presenters followed by facilitated discussion. Symposium attendees identified what they learned over the last four years and research gaps. New research priorities were identified in three ways; via presentations, facilitated group discussion, and through the symposium registration process. Remaining research priorities from the 2019 symposium (those not sufficiently addressed), along with those identified during the 2023 symposium were then collated into a single set of research priorities. These were then presented back to the participants for final discussion, clarification, and modification. The final set of research priorities were then voted on via Mentimeter in order to develop a new prioritized set for 2023.

Two additional sessions were conducted to address other cyanoHABs of concern. These sessions focused specifically on pico and nano-cyanobacterial blooms in the Indian River Lagoon and benthic cyanoHABs statewide. These sessions proceeded with a formal invited presentation summarizing the current state of the science for each bloom with a focus on what is unique about these blooms as compared to other cyanobacterial blooms. They were followed by a panel discussion to identify research and management priorities for these cyanoHABs. Consensus statements, summarizing what we know, along with data gaps, and research and management priorities were developed for these additional sessions.

The consensus summaries presented here represent the current state of knowledge as identified by symposium participants during the presentations and facilitated discussion and are not intended to be a comprehensive research and management review. The lightning round presentations focused on research and management projects conducted within a four year time span and the consensus statements summarize what we have learned from these projects. However, the data are temporally and spatially specific rather than broadly applicable across all years and scenarios, and caution should be made in extrapolating long-term trends from these summaries since bloom conditions are very dynamic. The information presented in this document reflects the general consensus of symposium participants.

SESSION 1

Drivers of Bloom Initiation & Termination

2019 Consensus Statement (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, light, stability of the water column, and interactions with other biotic members of the community. In general, cyanobacteria need both nitrogen (N) and phosphorus (P); however, some cyanobacteria

groups have the ability to use atmospheric N, removing this element as a limiting factor. *Microcystis* species are unable to do this and require an external source of N.

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 N and P.

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 N and P 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. Cyanobacterial 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 cyanobacterial 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% N by mass, whereas *Microcystis* cells are approximately 7% N by mass. Thus, *Microcystis* needs excess N 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 nontoxic *Microcystis*. Even those strains that can produce toxin do not always do so. Research suggests N availability drives what strains are present and how much toxin they are producing. Toxic strains require more N, and N availability limits microcystin production such that the ratio of microcystin to *Microcystis* biomass decreases as toxic to nontoxic 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 the water column for others to utilize.

Drivers of CyanoHABs – What We've Learned Since 2019

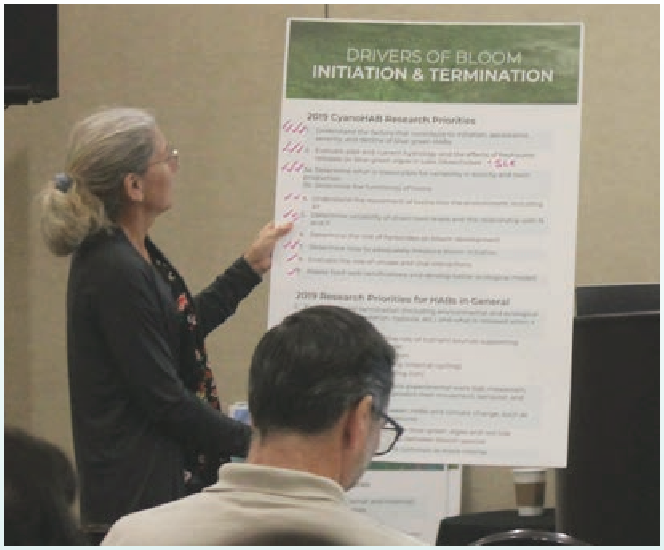
While much of the existing research and management has focused on *Microcystis*, new research methodologies show that blooms are more diverse and are composed of numerous cyanobacterial taxa. This is supported by satellite imagery that is able to detect (what is assumed to be) cyanobacteria when *Microcystis* is not present. Spatiotemporal assessments show that there are many bloom forming genera in both Lake Okeechobee and the Kissimmee Chain of Lakes (KCoL), with many more in the latter. It is important to understand which bloom-former occurs when, where, and why, recognizing that each cyanoHAB appears to have distinct drivers and that adaptive management of flow in and out of Lake Okeechobee has an effect on these drivers.

Phytoplankton assemblages in Lake Okeechobee

Recent advances in sequencing technologies have increased our ability to characterize and understand cyanobacterial community structure and how it changes spatially, temporally, and across different systems. The phytoplankton assemblages of the Lake Okeechobee system, assessed from surveys conducted since 2019, were spatially structured within five distinct lake zones. Nitrate, phosphate, and alkalinity explained the greatest proportion of variation in the spatial structure, with community-level threshold changes occurring at 182 micrograms per liter (μg/L) of nitrate. These assemblages were dominated by picocyanobacteria, representing >50% of the relative abundance in Lake Okeechobee. Picocyanobacteria are important as some produce toxins. They are also a potential food source and can exacerbate other blooms. While the ecological roles of picocyanobacteria in nutrient cycles and aquatic food webs are acknowledged, the factors governing their underlying ecological forces remain inadequately understood. Despite their importance to the microbial community picocyanobacteria do not always show up in microscopy. They are, however, detectable when analyzed via molecular genetics, thus highlighting the importance of methodology.

Beyond the picocyanobacteria, under non-bloom conditions, the dominant taxa over time and space were the non-bloom forming species *Aphanocapsa*, *Merismopedia*, and *Planktolyngbya*. However, during blooms four major cyanoHAB bloom formers were identified using 16S rRNA metabarcoding. They include: *Microcystis, Dolichospermum, Cuspidothrix,* and *Raphidiopsis*.

These primary bloom formers show strong spatial and temporal distinction. *Microcystis* were more prevalent in the northern region of the lake, near the mouth of the Kissimmee River, likely due to nutrient influx from the river. It prefers high light, high photic depth, low turbidity, and a high N:P ratio. *Microcystis* also prefers the highest water temperatures, around 31 degrees Celsius, as compared to the other bloom forming cyanobacteria. These conditions are often found in the wet season. *Dolichospermum* was more typically found in the southern region of the lake. *Dolichospermum* prefers high light, high photic depth, high P, low turbidity, and hot water temperatures, although not quite as hot as *Microcystis. Dolichospermum* was more highly abundant in the wet season where abundance almost doubles that of the dry season. *Cuspidothrix* (formerly *Aphanizomenon*) occurred less frequently, and prefers the cooler temperatures found in the dry season and low nutrients, both N and P. Like *Cuspidothrix*, *Raphidiopsis* most commonly occurred during the cool, dry season. *Raphidiopsis* has lower nutrient requirements than the other cyanobacteria and also prefers really shallow waters, with abundance inversely proportional to lake stage. The role of interspecies interactions is, as expected, species specific. Some bloom-forming taxa, such as *Dolichospermum* and *Microcystis* do not appear to be correlated at all, whereas *Raphidiopsis* and *Cuspidothrix* regularly co-occur. Each bloom-forming cyanoHAB also has its own unique microbiome and bacterial relationships. *Aphanizomenon, Planktothrix*, and *Sphaerospermopsis* were also found in Lake Okeechobee but at very low abundances. Other



functional groups in Lake Okeechobee include, but are not limited to green algae, desmids, diatoms, cryptophytes, chrysophytes, haptophytes, dinoflagellates, and euglenids.

The cyanobacteria that comprise the community within Lake Okeechobee are capable of producing the four most common cyanotoxins: microcystin, cylindrospermopsin, anatoxin, and saxitoxin. Actual toxins detected within Lake Okeechobee during a one year assessment included microcystin (LR & RR), anatoxin-a, and nodularin (which is not traditionally thought to be a freshwater toxin), however it is not known which genera produced the latter two toxins in the lake. Microcystin and other HAB toxins have been shown to enter into the food web into higher trophic levels.

CyanoHAB formers in the Kissimmee Chain of Lakes

The cyanobacterial communities within the KCoL were dominated by N-fixing diazotrophs, each with distinct drivers. Diversity within the KCoL was higher than that of Lake Okeechobee and there was also considerable variability of taxa within the individual lakes that comprise the KCoL. In addition to the four bloom forming genera found within Lake Okeechobee, there was a high relative abundance of *Aphanizomenon* in these lakes, as well as *Planktothrix*, and *Sphaerospermopsis*. These genera also occurred in Lake Okeechobee, but at significantly lower abundance. Picocyanobacteria were also found in the KCoL, but again, at much lower abundance. The drivers of bloom forming genera within the KCoL are not well known at this time, nor do we understand why these taxa are not as prevalent within Lake Okeechobee.

Microcystis drivers In Lake Okeechobee

Of the dominant cyanoHABs in Lake Okeechobee, *Microcystis* has been the most widely studied. Understanding the factors that contribute to the persistence of *Microcystis* blooms in Lake Okeechobee, such as the importance in recycling of nutrients as blooms reach a certain stage, and changes in metabolism can help with understanding bloom progression. For instance, *Microcystis* cell concentrations rapidly increased in Lake Okeechobee during April/May. Counterintuitively, the proportion of dead cells was also greatest during early bloom initiation stages and declined as the bloom progressed. *Microcystis* metabolic rates also peaked in the mid to later parts of the bloom. The shift in physiology and the lack of dead cells in the sediments suggests that dead cells in the water column are rapidly digested into the ecosystem (consumed or dissolved), however this is a hypothesis that needs to be confirmed.

Sediments can be used as an indicator of *Microcystis* spp. bloom initiation. Previous decadal research in Lake Okeechobee shows that mud tends to accumulate in the deeper areas of the lake. Dissolved nutrients (phosphate and ammonium) are released to pore waters and flux to overlying waters. More recent sub-seasonal scale sampling over the course of one year indicates that throughout the mud areas of Lake Okeechobee, sediments are almost entirely anaerobic and dissimilatory iron(III) reduction is the dominant microbial respiration pathway governing nutrient accumulation in pore waters. Sediment nutrient fluxes in Lake Okeechobee were highly variable seasonally, and DIN and DIP fluxes were not necessarily coupled. Phosphate fluxes were most intense over the summertime during peak anaerobic iron respiration. Sediment ammonium fluxes, however, were an order of magnitude greater than nitrate fluxes and experienced an inverse seasonal pattern relative to phosphate, with highest concentrations at the start of the bloom season (April/May). Ammonium was also more spatially variable than phosphate across the two sampling locations. This seasonal mismatch in ammonium concentrations and respiration is currently not understood. Stratification of *Microcystis* occurred between surface and bottom waters, especially where turbidity was higher, an indication that *Microcystis* was vertically migrating and out-competing other organisms at more turbid sites for either light, nutrients, or both. Nitrogen in Lake Okeechobee is more variable than previously thought, varying in space and time. As previously discussed, *Microcystis* is known to favor high N:P ratios. With respect to sediment pore water inventories and nutrient fluxes, the DIN:DIP ratio was much higher early on in the bloom season and then dropped below the Redfield ratio, becoming unfavorable when the blooms tend to die off. Although there was a slight temporal delay of a few weeks, water column DIN:DIP ratios mirror sediment pore water ratios, suggesting sediments drive the water column DIN:DIP ratios in mud-bottom areas. Finally, sediment resuspension can be a source of DIN and both a source and sink for P to the water column, depending on conditions such as the sediment iron redox conditions which can affect P scavenging when encountering water column dissolved oxygen.

CyanoHAB drivers in downstream rivers and estuaries

When evaluating the relationship between the cyanobacteria and nutrients in the lower Caloosahatchee River, an inverse relationship was found between chlorophyll concentrations and nitrogen oxides (NO_x) over the course of a one-year monitoring program. Nitrogen shaped the phytoplankton community and was mainly coming from the watershed. Phosphorus, on the other hand, came from the sediment, particularly when oxygen and pH conditions were low. In mesocosm experiments, added nutrients (nitrate, ammonium, and phosphate) were all rapidly removed from the water column within 24 hours of dosing, but this did not always translate to higher algal biomass. However, there was some evidence of seasonal nitrate limitation.

Despite *Microcystis* occurring in Lake Okeechobee, it does not occur in the St. Lucie Estuary in the absence of Lake Okeechobee discharges. Metagenomics at some sites in both the St. Lucie and Caloosahatchee estuaries have identified *Microcystis panniformis* instead of *M. aeruginosa*. *M. panniformis* does produce microcystin and there have been healthy colonies of *M. panniformis* in the winter, but the greater significance of the presence of this species is unknown.

What We Think We Know

- Climate drivers – there may not be a cyano season anymore.
- Adaptive management out of Lake Okeechobee has an effect on drivers.
- Climate change force multipliers (increased rainfall intensity, increasing temperature, etc.) impact blooms. They can also exacerbate blooms by releasing nutrients.
- Most communities are dominated by a few types of bacteria.
- There is seasonal N-limitation in Lake Okeechobee.
- Nitrogen varies in Lake Okeechobee more than we previously thought.
- No major *Microcystis* blooms in the St. Lucie Estuary without Lake Okeechobee discharge.

What We Don't Know

- Why is there more ammonium in sediments early in the season, decoupled from when one would expect to have the highest respiration rates?
- What are the factors that determine whether resuspension is a source or sink for P to the water column?
- What is the role of N in bloom formation? We need to better understand:
  - Stoichiometry,
  - The spatial and temporal distribution of N sources in Lake Okeechobee,
  - The role of new (influx) versus legacy (retained) N and the processes of nutrient recycling and N-fixation.
- What are the genera-specific drivers of cyanoHABs? What is the lag time between driver and response? What are the thresholds for those drivers?
- What taxa is producing anatoxin-a and nodularin and does methodology impact toxin detections?
- The bloom formers in the KCoL are different when compared to Lake Okeechobee. Specific research questions include:
  - Why is there such a high abundance of picocyanobacteria in Lake Okeechobee as compared to the KCoL?

- Who is there, when, and where? What does bloom succession look like from initiation to senescence?
- Why are there differences across this system? Are these just temporal differences or are there distinct drivers in these lakes?
- What toxins are they producing?
- What do the microbial associations look like (including heterotrophic bacteria and microzooplankton grazers)?
- What is the role of HAB physiology in bloom maintenance and termination?
- *M. aeruginosa* versus *M. panniformis* – does it matter?
- What is the interaction of the picocyanobacteria in Lake Okeechobee with the other species?
- What is the role of interspecific competition and interspecies interactions in community dynamics?

RESEARCH PRIORITIES	
1a. Understand the factors that contribute to initiation persistence severity and decline of blue-green HABs (including different taxa, different lakes, etc.). 1b. Driver identification including climate change effects (temperature, precipitation, runoff, etc.)	82%
2a. Stoichiometry – new versus legacy nutrients (nutrient recycling and N fixation) – need to understand the distribution of N. 2b. Understand nutrient sources.	73%
3a. Fundamental biogeochemistry and bloom dynamics 3b. Factors determining timing of variable blooms	58%
4. Sediment nutrient dynamics and sediment triggers for blooms	52%
5. Conditions that trigger toxin production (*also in monitoring) ▪ Ability to determine when HABs will begin N-fixation and toxin production. ▪ Determine variability of strain toxin levels and the relationship with N and P. ▪ Determine the function of toxins.	52%
6. Advance cyanobacteria identification and physiology.	
7. Assess the role of hydrology color and nutrients in HABs.	
8. Assess food web ramifications and develop better ecological models.	
9. Determine how to adequately measure bloom initiation.	
10. Understand the movement of toxins into the environment including air.	
11. Evaluate past and current hydrology in Florida lakes that experience blooms. ▪ Evaluate the effects of freshwater releases on Blue-green algae in Lake Okeechobee and St. Lucie Estuary	
12. Assess algae transport. ▪ Vertical migration to obtain sediment nutrients	
13. Determine the role of herbicides on bloom development.	
14. Evaluate the role of viruses and viral interactions.	

Priorities that received majority votes (e.g., selected as one of five most important by at least 50% of participants) are displayed by percent vote 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.

SESSION 2

Prediction & Modeling

2019 Consensus Statement

Cyanobacteria, including *Microcystis* spp., 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 model, 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), have tradeoffs. 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 cyanobacterial 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 cyanobacterial blooms means that there can be larger variations within a pixel, potentially causing 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 colored dissolved organic matter (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.

Prediction & Modeling – What We've Learned Since 2019

There are several new models attempting to both understand Lake Okeechobee bloom dynamics and also develop short-term and seasonal bloom predictions. Models provide an opportunity to figure out what might be triggering a bloom. These can be scenario driven, but also can be used for short- and long-term forecasts. In any case, these models require an understanding of what happened in the past in order to predict what will happen next. Both efforts also depend on the ability to improve cyanoHAB detection and ground-truth the data inputs. This includes accurately monitoring those features known to impact the growth, distribution, and toxicity of cyanobacteria. As we work to improve our modeling efforts, we will also improve our understanding of what data are needed for model accuracy.

The existence of multiple models strengthens our predictive capabilities. However, uncertainty with algal prediction models continues to be a challenge. CyanoHAB models and forecasts are based on an understanding of the intricate interaction of biological, chemical, physical, and geological processes that foster blooms, enhance their toxicity, and lead to their demise. As model accuracy is tightly linked with the multidisciplinary input features, improvements in data or external models for physical (e.g., upstream watershed inputs, water column structure and circulation, precipitation, and wind) and biogeochemical processes (e.g., sediment processes and rates, nutrient availability, colony formation, growth rates, phytoplankton abundance and biomass) are also needed. Additionally, model improvements are needed to resolve seasonal mismatches with satellite imagery which may be associated with picocyanobacteria.

Access to existing datasets such as DBHydro is critical for model success. As models are developed, data needs increase and become more specific. Key to developing modeling products is not just identifying when and where blooms are occurring, but also why, so that management or mitigation measures can be implemented to address these needs. Short- and long-term bloom forecasts require detailed data sets on blooms, combined with existing monitoring systems. Long-term datasets are important for bloom forecast development and accuracy. Algal bloom prediction models will require outputs of several models to be used as inputs. Therefore, the accuracy of these input models will be critical. Validation of models with historical data is critical to ensure they work for the application intended.Integral to successful model development is having scientists and tool developers working together from the beginning. Also key is ensuring the decision-makers who will be using the product are engaged throughout development.

A challenge for cyanoHAB models will be to translate what's been learned in Lake Okeechobee to other lakes in Florida in order to inform management there. Florida also needs to look to other areas outside of the state to see what's being done that could apply to Florida blooms. Lastly, since 2019, more audiences, including the general public, are using satellite imagery products. User interpretation of satellite imagery is generally not a problem; however, it becomes more problematic when multiple products are looking at the same problem.

Modeling bloom dynamics in Lake Okeechobee

Lake Okeechobee cyanobacterial blooms are driven by complex physical and biochemical factors. Understanding the effects of various environmental drivers on cyanoHAB dynamics is necessary for applying management actions. Numerous models have been developed that seek to understand relationships among hydrodynamics and water management operations (i.e., LOSOM), nutrient loads, and cyanoHABs within and out of Lake Okeechobee and the downstream estuaries.

Lake Okeechobee models suggest that the coupling between physics and light control diurnal bloom dynamics and spatial patterns. During the summer months dominant wind patterns result in a 2-layer circulation system where winds from the SSE drive surface flow to the NNW where bottom waters are thus predominantly driven toward south or southwest. There is also a very strong diurnal cycle where the water column is well mixed at night but vertically weakly stratified during the day due to weaker winds. This couples with the biological behavior of cyanobacteria to promote surface blooms; many cyanobacteria can perform diurnal vertical migration, floating to the surface during the day and then sinking to depth at night. Bloom seasonality in Lake Okeechobee is further defined by wind and temperature; water temperature being one of the most important predictors of blooms within the lake. During the summer, warm temperatures and the relatively weak winds work in concert to drive strong surface blooms, especially amongst those vertically migrating cyanobacterial species. For example, growth of *Microcystis* has a higher dependency on temperature (Q10, or rate of increase for each 10 degree Celsius (C) increase in temperature) relative to other taxa. However, *Microcystis* loses buoyancy when temperatures decrease.

Warm water temperatures and high P and N favor frequent and persistent cyanoHABs. Models indicate that reductions in both phosphorus and nitrogen coming into Lake Okeechobee would be more effective at reducing blooms (determined by chlorophyll-*a* concentrations >40 μg/L) in the lake than targeting a single nutrient, as it is currently done. However, the optimal level of N and P reduction has not yet been determined. Most freshwater lakes are P-limited, but algal blooms in Lake Okeechobee appeared to be much more synchronized with inorganic nitrogen forms (nitrate, specifically).

Modeling bloom dynamics out of Lake Okeechobee

Physical models indicate that water column structure and circulation with the Caloosahatchee and St. Lucie are quite complicated and the connecting canals (C-43 and C-44, respectively) can either act as conduits or incubators for cyanoHABs, depending on flows out of Lake Okeechobee. During periods of high lake discharges, water moves through the canals/rivers in a few days transporting algal cells out of the system. However, during times of low flows, blooms can be produced, and nutrients recycled, within the rivers themselves.

Nutrient (P and possibly N) imports from the upstream watershed affect loadings into the lake, as well as exports out of the lake. Nutrient exports from the lake to the tributaries are very sensitive to resuspension parameters and load imports. Sediment resuspension is wind-driven across the shallow lake and dominated by strong storms including hurricanes. There appears to be more PO_4 relative to dissolved inorganic nitrogen in lake exports. Thus, during large discharge events, residual P loading from the lake may be transported out of the Caloosahatchee River Estuary and feed coastal cyanoHABs. However, the salinity tolerance of these freshwater cyanobacteria will affect their spatial range within both the St. Lucie and Caloosahatchee river estuaries.

Model simulation of Lake Okeechobee P dynamics based on reservoir operations can be used to estimate P exports to the St. Lucie and Caloosahatchee rivers and also to determine an optimized lake operation for P load reduction. Currently, the impact of lake discharge optimization for N loads is under investigation, but given the greater sensitivity of algal blooms to nitrate it is likely that optimizing releases with nitrate in mind could have optimistic outcomes for algal bloom reduction in the canals and estuaries.

Forecasting blooms in Lake Okeechobee

Satellite imagery delivers information on bloom intensity, distribution, and frequency and can be used for daily monitoring, initiating short- and long-term forecasts, and compiling multi-decadal time series. Satellite ocean color sensors can see cyanobacteria as it appears on the surface, but they can't see the water column, so blooms at depth can not be captured. Conditions at the surface provide an indication that there is activity, and based on this activity, the ability to predict what will happen next. There are tools available to create benchmarks which can be used retrospectively to assess when a bloom is occurring. However, from a management perspective, a consistent definition for the start of a bloom, or even what constitutes a bloom is lacking.

Detection of algal groups using satellite imagery is improving. NOAA's cyanobacteria index (CI-cyano) algorithm detects phycocyanin from Sentinel-3; phycocyanin detection via satellite when *Microcystis* is not present suggests it is detecting other taxa. Because toxins are not detectable via remote sensing, *in situ* monitoring of potentially toxic species is key. Developing a relationship between satellite imagery and water samples is a current research emphasis.

Next generation technologies, such as artificial intelligence and the high-computing power of Google's cloud platforms, are being used to improve model accuracy and short-term predictive capabilities for Lake Okeechobee. This is done by leveraging the increased computing power of distributed servers, combining DBHydro field-sampling data with NOAA satellite imagery. To date, models developed for cyanoHAB prediction using this approach have examined parameters such as wind speed and direction, dissolved inorganic nitrogen, inorganic P, and temperature. Existing models have not yet met the goal of achieving a balanced accuracy of less than 80% at a 2-3 day timeframe. Future plans include integrating hyperspectral imagery through ClimateEarth to improve the accuracy of satellite imagery.

In the final stages of development, NOAA's short-term 5-day forecast for Lake Okeechobee relies on satellite imagery to provide an initial cell concentration field, and then a spatially explicit hydrodynamic-particle tracking-water quality model of the Lake Okeechobee ecosystem is used to move the cells around based on winds and circulation. Retrospective analysis is complete and hydrodynamic automation testing is ongoing. Additionally, more rigorous validation of the forecast is underway with the U.S. Army Corps of Engineers (USACE).

While short-term forecasts determine the location, size and trajectory of current blooms, a long-term seasonal forecast predicts the severity for the bloom season. Development of a seasonal forecast is important for anticipating or managing expectations. Every year bloom dynamics can be different; the starting time, the persistence, and the senescence. Retrospective analysis of past blooms can be used to make future bloom predictions as correlations could potentially allow for a mechanistic forecast. Using existing *in situ* data, modeling can be used to reproduce parameters such as water level, air temperature, water temperature, and circulation. Satellite data can be used to validate circulation data in addition to providing chlorophyll estimates via a cyanobacteria index. Using this approach, time series are available from 2002 to the present.

A long-term evaluation of environmental factors shows that, when evaluating 10 day periods, major bloom events (2005, 2016, and 2018) stand out, but milder blooms are detectable in between. Hurricanes and water levels have been proposed as factors in driving blooms. This long-term dataset suggests they were factors driving large blooms in 2005, but less so in other years. Thus, understanding bloom dynamics in relation to factors such as water levels, relative mixing from the winds, and nutrient loading is critical for forecast development.

What We Don't Know

- Phytoplankton biological rates/behaviors (diel vertical migration, colony formation, grazing rate)
- Phytoplankton abundances & biomass (groups)
- Phytoplankton nutrient assimilation rates
- Sediment time-series data (processes/rates)
- Which conditions are best/most useful for bloom prediction to help allocate resources
  - What are the (other) important predictors to include in a bloom forecast?
- Upstream and watershed inputs
  - Discharges, nutrients, phytoplankton
  - Caloosahatchee River, St. Lucie River, and Kissimmee River
- Measuring and predicting toxins – how do we explain these models to better communicate risk for the public?
- How effective is lake discharge optimization for N loads and algal biomass?
- What is the optimal N & P reduction from the watershed?
- Nutrient budgets for the Caloosahatchee and the St. Lucie rivers and estuaries, including groundwater and local runoff.

RESEARCH PRIORITIES	
1. Develop operational forecasts of blooms for short- and long-term. ▪ Multiple model ensemble	82%
2. Collect regular nutrient load (internal and external) data. ▪ Need to develop nutrient budgets that include nutrient sinks other than traditional phytoplankton.	64%
3a. Improve the comparability of satellite imagery with discrete and *in situ* sampling. 3b. Create a better explanation of satellite imagery for the lay audience. **3a and 3b were not grouped by relatedness prior to vote.*	64% 24%
4. Improve predictive modeling of cyanoHABs at multiple temporal and spatial scales. ▪ Quantify uncertainties due to model process, parameters, and observations. ▪ Develop good physical models of water column structure and circulation. ▪ Develop taxa specific functional traits.	61%
5. Integrate models (scenario forecasting) for improved management decision-making.	58%
6. Examine the relationships between antecedent water quality and bloom predictions.	
7a. Incorporate sediment nutrient dynamics into 3D models (empirical diffusive, groundwater flux, and resuspension fluxes). 7b. Incorporate full sediment diagenetic modeling into 3D models (coupled sediment module). 7c. Monitor sediment dynamics from remote sensing.	
8. Use a cloud-based computing platform to employ artificial intelligence and machine learning to develop algal bloom prediction and forecast models.	
9. Create a strategic process to determine what tools should be integrated (satellite imagery, remote sensing, machine learning models) and at what scale.	
10. Develop models that can separate point source and nonpoint sources of pollution.	
11. Create a better explanation of models for the management end-user community.	

Priorities that received majority votes (e.g., selected as one of five most important by at least 50% of participants) are displayed by percent vote 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.

SESSION 3

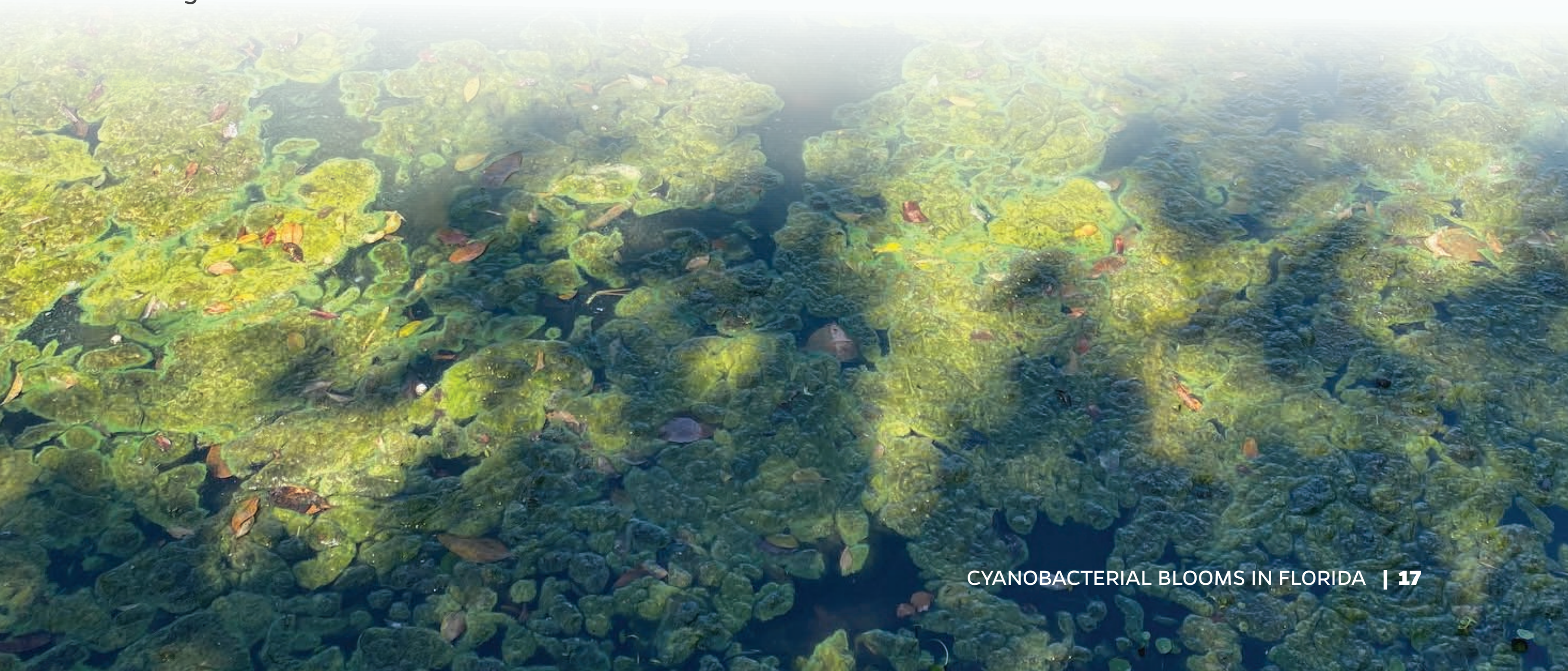
Detection & Monitoring

2019 Consensus Statement

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 (FDOH) 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 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 *Microcystis 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've Learned Since 2019

The State of Florida's CyanoHAB surveillance and response program exists to protect public health by limiting the public's exposure to unsafe water conditions. This program identifies waters where cyanobacterial bloom conditions exist. Water samples are collected and analyzed for cyanotoxin producing species or toxin presence. Results are posted as quickly as possible, so health agencies can disseminate to the public in order to limit public exposure to toxins. Results are also posted on the publicly accessible Protecting Florida Together algal bloom dashboard (https://floridadep.gov/AlgalBloom). In addition to sampling specifically for chlorophyll-a and toxins, additional water quality information such as chlorophyll and nutrient content is collected in order to build a dataset that can be used by researchers to better understand bloom dynamics, such as why, where, and when they are occurring.

Enhanced monitoring efforts and technologies have also improved our ability to respond to these events, but the data gaps remain the same. It is still difficult, with a reasonable level of accuracy, to predict the timing and toxicity of blooms, despite knowing where they are likely to occur. We also still struggle to understand the mechanisms that drive cyanotoxin production in a bloom, which is essential for protecting public health. Detection and monitoring is a collaborative effort. Sample collection, preparation, and analysis methods have significant effects on what is detected and reported. Small modifications may greatly enhance the synergies from the work we are currently doing.

Management success

Coordination and transparency among and between state agencies and local health departments has improved significantly since 2019. In 2021, FDEP and FDOH produced a document that describes agency roles and responsibilities, including sample collection, analysis, data transfer, and outreach. In addition, educational materials are posted on the Protecting Florida Together website, including a journey map which outlines the transparency document in a lay audience fashion. There are also new signs available that can be placed at state-owned properties which are designed to alert users to the possible occurrence of a cyanobacterial bloom and also provide guidance for reducing exposure risk.

Enhanced monitoring

The state continues to conduct response-based monitoring, and since 2019, cyanobacterial blooms, with a Lake Okeechobee bias, are being reported more frequently. This monitoring has been enhanced in a number of ways leading to an improved understanding of cyanotoxins as well as those factors that contribute to cyanobacterial bloom formation, maintenance, and decline. Since 2019, the state has added additional microcystin congeners to their suite of toxin analyses (-LW, -WR, desmethyl LR, -HilR, and -HtyR), as well as nodularin and saxitoxins to the suite of toxins they are analyzing for. The use of satellite imagery to conduct reconnaissance and provoke sampling efforts has also increased. This response-driven sampling allows for toxin analysis prior to the public reporting these blooms, thus allowing for faster data dissemination.

The state, through FDEP, has provided funding to both the South Florida (SFWMD) and the St. Johns River (SJRWMD) Water Management Districts to establish a routine HAB monitoring program at fixed stations. The SFWMD monitors bimonthly at 28 stations (May-Oct.) and monthly at eight stations (Nov.-April) on Lake

Okeechobee. Prior to 2020, sampling by the SJRWMD was collected ad-hoc in response to HAB observations. Samples are now collected monthly during the dry season and twice monthly during the wet, peak bloom season at ten fixed stations throughout the St. Johns River watershed. These stations are largely in areas where blooms occurred historically and are important for either recreational or drinking water uses. Response-driven samples are still collected in addition to the routinely monitored sites. Samples are analyzed by FDEP for cyanotoxins (microcystin, cylindrospermopsin, anatoxin-a, and saxitoxin) and a qualitative scan to determine dominant taxa.

The SJRWMD lab analyzes samples for water quality parameters. Across these routine monitoring programs, some methodologies follow state Standard Operating Procedures (SOPs) whereas other water quality parameters are collected using district-specific methodologies. These differences need to be accounted for and recognized as they do impact the data and data interpretation.

Along the St. Johns River, considerable variability has been observed in both size and duration of blooms across water bodies. Cyanobacteria, most commonly *Microcystis*, are dominant in about a third of the samples but other genera of potentially toxic cyanobacteria with different drivers and ecologies were also observed. While typical wet season blooms are seen at most sites, Lake Jesup experiences the most consistent blooms which can be initiated in both the wet and dry seasons, depending on the year. Microcystin and cylindrospermopsin are observed in about 15-20% of samples across northern St. Johns River sites, with most at concentrations less than 1 μg/L which is well below the 8 μg/L action limit recommended by the EPA for recreational waters. There does not appear to be a link between bloom size and toxin concentration, indicating that factors other than biomass alone are driving toxin production.

As a result of the increased sampling efforts, the state is currently data rich and in a much better position to respond than it was four years ago. Data is used to inform management decisions and to identify understudied water bodies that are experiencing cyanoHABs and may require additional attention. For example, the SJRWMD routine monitoring program allowed the district to exchange data information with water managers when a cyanoHAB was detected in Lake Washington, a potable water reservoir for the City of Melbourne. Satellite imagery was used to supplement field monitoring data. Collectively these data sources help the district leverage funds to identify and mitigate the nutrient sources driving blooms. The state also has a better understanding of the time and resources needed in order to process samples, and when and where to expect cyanoHABs to occur. However, opportunities for improvements still exist. The turnaround time between toxin analysis and management decision-making are out of sync. Furthermore, blooms are occurring outside of routine monitoring sites and peak blooms seasons so there is an opportunity to continue to expand the routine monitoring footprint.

In addition to routine and response-based monitoring, a sampling status monitoring network has been added where cyanotoxin data is collected throughout the state using a random selection approach that is not dependent on a bloom. This approach assists with mitigation efforts by allowing the state to get ahead of blooms and implement innovative mitigation techniques on blooms before they get out of hand. The state of Florida has invested more than $20 million dollars on innovative technology grants in order to develop products that can mitigate cyanoHABs.

Faster and improved detection methods

Advances in genomics have led to greater understanding of cyanotoxins, and improvements in microscopy have led to more effective detection of cyanoHABs. New methods such as counting algal colonies in the water column can be a rapid and cost-effective method for predicting bloom formation. Algal colony counts correlate with *Microcystis* concentrations and can be applied to both colonial (e.g., *Microcystis*) and filamentous (e.g., *Dolichospermum*) cyanobacteria. Additionally, a new tool, Spectral Mixture Analysis for Surveillance of Harmful Algal Blooms (SMASH), combines in-laboratory microscopy with hyperspectral imaging to develop a map that classifies what genera of cyanobacteria are present and where. SMASH has not yet been applied in Florida, but highlights how new tools and technologies may enhance existing monitoring capabilities and perhaps inform where those efforts should be focused.

What We Think We Know

- Some toxins are better known and monitored than others. Some lakes may require more comprehensive toxin analysis.
- In addition to posted signage, the public must use visual observation and their knowledge of historic blooms in the area to inform their decision about whether to recreate in a waterbody due to rapidly changing bloom conditions.
- Need to further educate the public so that they understand how to act on signage.
- Cyanotoxin concentrations are likely underestimated because we are not able to monitor for the hundreds of toxins that could potentially be present.

What We Don’t Know

- How to predict the timing and toxicity of a bloom?

RESEARCH PRIORITIES		
1.	Need more comprehensive strategic routine monitoring (during non-bloom conditions), in addition to event HAB response sampling. ▪ Ambient monitoring ▪ Pre- and post-project monitoring	82%
2.	Monitoring should include both taxonomic and nutrient assessment (different forms, stoichiometry, and bioavailability). ▪ Need to collect additional field samples to analyze under microscope.	53%
3.	Need long-term quantitative monitoring of complete phytoplankton assemblages alongside routine water quality monitoring	50%
4.	Harmonize sampling methodologies between agencies/groups (prevent highly variable downstream data). These should be harmonized for blooms, monitoring, and aerosols. ▪ Develop standard method for measuring *Microcystis*.	
5.	Improve taxonomic descriptions of bloom-forming algae using a polyphasic approach with accompanying high-resolution photodocumentation all made easily accessible to researchers and the public through online database.	
6.	Need better *in situ* monitoring/detection of cyanotoxins including those beyond MC	
7.	Need to develop more rapid sampling using tools capable of *in situ* detection on hourly timescales.	
8.	Need continuous monitoring of water quality and algae with field deployed sensors and camera systems to address the temporal patchiness of blooms that is largely missed by typical monthly sampling.	
9a. 9b.	Monitor sediment conditions as related to HAB triggers. Monitor sediment nutrient fluxes (high frequency).	
10.	Understand sources of the major limiting nutrients.	
11.	Assess what determines occurrence of toxicity (*also in drivers). ▪ Evaluate if and what relationship exists between biomass and toxin levels. ▪ Implement vertical profiles to get an accurate assessment of biomass.	
12.	Need to educate the public regarding posted signage and visual signs of cyanoHABs to inform their decision about whether to recreate in a waterbody due to rapidly changing bloom conditions.	
13.	Evaluate the correlations between hypoxia and nutrient fluxes.	
14.	Development of a comprehensive (administrative) framework to address nutrient management, hydrology, internal recycling, etc.	
15.	Detect and treat taste and odor compounds.	
16.	Understand sensor limitations.	

Priorities that received majority votes (e.g., selected as one of five most important by at least 50% of participants) are displayed by percent vote 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.

SESSION 4

Mitigation & Management

2019 Consensus Statement

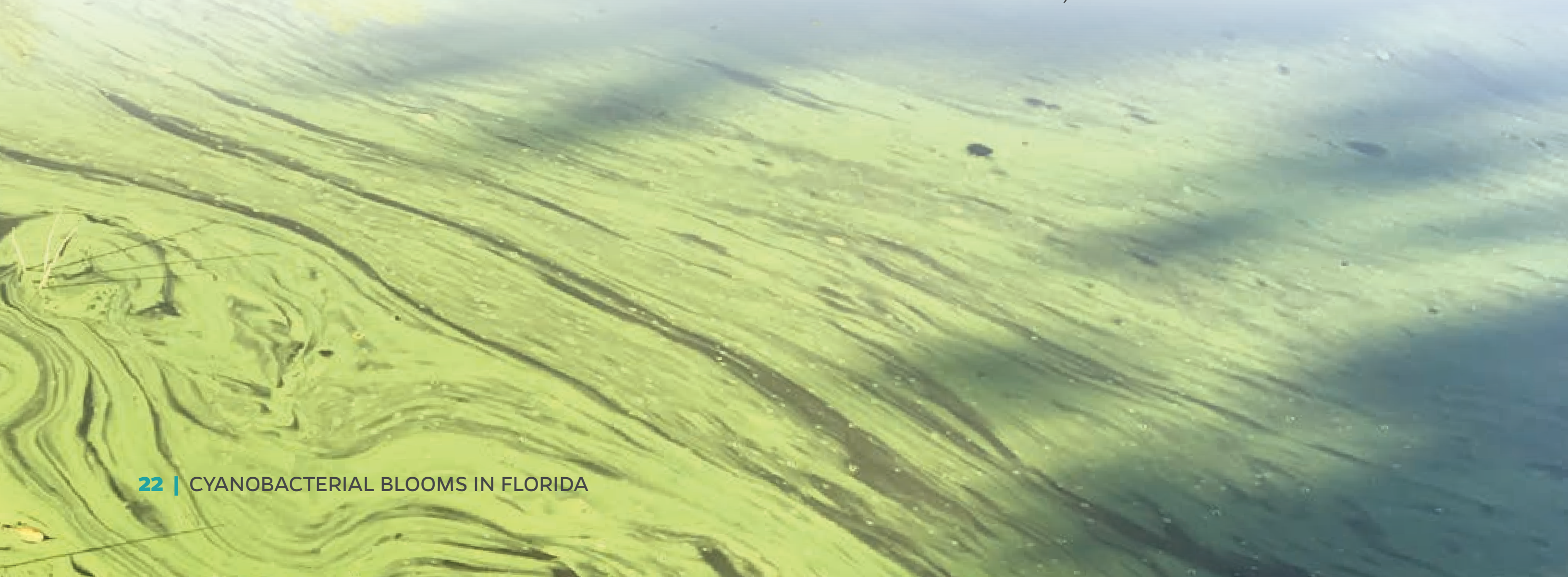
There are a variety of management approaches for cyanobacterial blooms, including *Microcystis aeruginosa*. Bloom management may be proactive or reactive, indirect, or direct. Proactive approaches to controlling blooms may include long-term management strategies such as mitigating nutrient inputs and/or climate change. They can also include direct, short-term options designed to prevent an algal 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 Environmental Protection Agency (EPA) registered algicides and aquatic herbicides which may be used to kill an existing cyanobacterial bloom. These include a variety of chemical compounds such as copper based algaecides, 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 nontarget 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've Learned Since 2019

Treating cyanoHABs requires being able to identify those that are going to be problematic, whether it produces toxin and creates a health risk. Determining the feasibility of mitigation and/or management measures in different systems, such as scale-up and costs, is also important. Ultimately, it is imperative that any cyanoHAB mitigation tools be not only safe but also demonstrate their capacity for efficacy and cost-effectiveness. This involves exploring the chemical, ecological, biological, and socioeconomic ramifications of such practices. Despite new advances in this field, there is no silver bullet for cyanoHAB management and mitigation. For this reason, engagement with the public is also important. Implementation of any cyanoHAB mitigation project requires a clearly defined goal and the criteria for effectiveness should be pre-determined. Both short- and long-term monitoring should be part of the process to evaluate efficacy. As new algal control methods are developed and deemed effective, a central database to catalog and assess the effectiveness of alternative technologies would aid in identifying successful approaches. Ideally, this database should operationalize the site-specific parameters for each technology, recognizing that these technologies cannot be tested in every waterbody.

Innovative technology

The State of Florida has initiated a grant program that funds innovative technologies for freshwater cyanoHAB control. The program prioritizes projects that focus on prevention, prediction, and monitoring, as well as those that offer mitigation and cleanup solutions. The application process for these grants is available through the Protecting Florida Together website. Technology projects must be innovative and scalable from lab to field. The timing of project execution needs to consider the application process and permit acquisition in relation to the bloom schedule. The process of obtaining permits and regulatory approval for algal control projects can be time-consuming and challenging. Application of innovative technologies depends on location and ownership (i.e., state, municipality, or private) of the water body.

Chemical control

Chemical control of algal blooms is an ongoing area of research. This approach involves the application of chemicals that inhibit the growth of, or are lethal to, cyanoHAB organisms. Researchers and agencies are continuously exploring novel methods and technologies to effectively combat harmful algal blooms, this includes the potential development of algal group-specific control agents. However, any algaecide used should be registered by both the EPA (under FIFRA) and the Florida Department of Agriculture and Consumer Service (FDACS).

Several projects have been conducted to evaluate the efficacy of various algaecides, herbicides, and flocculants in mitigating cyanobacterial blooms in different Florida water bodies. These efforts are leading to an increased understanding regarding the fate and broader feasibility of a suite of products. Notable chemical agents include copper- and peroxide-based algaecides, and lanthanum modified bentonite (LMB) clay. Research with algaecides suggests that not all products are the same and that chemical formulation, including inactive ingredients, matters. Effectiveness may vary depending on the concentrations of chemicals, sensitivity of algal species, and other environmental factors. Optimum concentrations are different if target algal species or bloom intensity are different. For example, hydrogen peroxide, granulated peroxide products, and chelated coppers were found to be most effective against *Microcystis aeruginosa*, while only certain peroxide-based algaecides were effective against *Microcystis wesenbergii* because of its thick mucilaginous sheath. Additionally, the effectiveness of certain peroxide products were enhanced when used in combination with other products. The application of either an herbicide (brand withheld) or L-lysine with hydrogen peroxide both demonstrated a synergistic effect in controlling *Microcystis*. Hydrogen peroxide induced the succession of phytoplankton communities from bloom forming to non-bloom forming cyanobacteria. The stability and decomposition rates of different peroxide-based algaecides were impacted by salinity and organic matter in the water, however.

The release of cyanotoxins upon application of chemical treatments need to be considered. At low concentrations, chelated coppers decreased the concentration of cells with minimal release of microcystins. Whereas, peroxide-based products lyse the cells, releasing the toxins upon death. Transcriptome analysis of *Microcystis* showed that treatment with hydrogen peroxide stressed *Microcystis* but it did not induce microcystin gene expression. The application of hydrogen peroxide on *Microcystis* did increase extracellular microcystin for a few days after which it disappeared, most likely due to microbial degradation and the dispersion of toxins into the surrounding water. LMB clay (although not registered as an algaecide but is used for phosphorus binding) and pyrolized materials such as *Sargassum*, can be effective in sorbing microcystins from the water column, indicating an opportunity for treatment combinations if used with an algaecide that lyses the cells. Long-term data are needed on the effects and decay rate of microcystins and other cyanotoxins.

Application strategies for the use of chemical control methods must account for multiple considerations. These include the size of the water body, the presence or absence of flows, water quality, temperature and salinity, target species and concentration, algaecide formulation, dose, timing, application methods, and the frequency of use. As an example, a project to prevent HABs on Lake Minneola, a roughly 2,000 acre mesotrophic lake in the Ocklawaha Chain and a popular recreation area and drinking water source, included the use of treatments with floating granule release of a peroxide-based algaecide. Six preventative treatments and eight spot treatments resulted in no formation of HABs during the project; however, phytoplankton surveys did not detect a shift in the phytoplankton communities away from bloom forming species. It should be noted that this project also lacked a control lake for comparison. In Lake Okeechobee, sequential treatments of a granular peroxide product were necessary to sustain product efficacy indicating that product half-life should also be considered when developing a treatment regime. In mesocosm experiments, the application of hydrogen peroxide was not an instant approach. Results took weeks to a month before they were realized.

Physical control

Electrochemical methods for advanced oxidation, such as nanobubbles have been used. Both pure air and ozone nanobubble machines have been evaluated. Some level of success has been seen with ozone nanobubbles, but the location of these systems is key. For example, this technology does not work well in areas with high organic material. Of additional importance, these systems only work while they are running, otherwise algae will rapidly return.

In some lakes, HABs can be harvested via floating or land-based systems. As a harvest technique, nutrients are removed which also reduces the likelihood of further cyanoHAB development. Algae harvesting on Lake Jesup, a hypereutrophic lake connected to the St. Johns River in Seminole County, used a floating barge-based processor with a dissolved air flotation process. The average chlorophyll-*a* concentration of the bloom was 132 μg/l and the system removed approximately 85% of the biomass. Algae harvesting can be very cost-effective, depending upon incoming water quality and the coagulant selected. For example, the costs of the Lake Jesup project fluctuated depending on the suspended solids and P concentrations of the inflowing water. The fate of the collected materials also must be considered. The resultant biomass collected from Lake Jesup was a waste product that required transportation and disposal at a wastewater

treatment plant, impacting the project's overall cost-effectiveness. Estimates from the Lake Jesup project equated to approximately $427 per pound of P removed.

If the waste product can be valorized, this will inherently improve the project's cost-effectiveness. Future efforts are needed to convert harvested wastes into commodities, so that the sale can offset the harvest cost. An example of this is in the SJRWMD rough fish harvesting program which removes P at less than $100/lb because fish are sold and the proceeds offset the cost of harvesting them. Not included in these benefits is that these fish stir up the bottom, so reducing bioturbation is also likely helpful.

Prevention

Mitigation and management approaches discourage cells from moving up in the water column and slow the bloom, but eventually blooms recover. For example, when nanobubbles are turned off the bloom returns, and sometimes there's a shift in species. With the application of chemical controls that decay quickly, algae outside the kill zone can quickly move in and fill the space. Thus, the most direct way to mitigate cyanobacterial blooms is to reduce the availability of nutrients. One way to accomplish this is to look at the global P cycles and identify places to capture and recover P, like wastewater treatment plants.

Since the upstream watershed contributes most of the excess nutrients, upstream watershed management plans are necessary to improve water quality and mitigate cyanoHABs in lakes, receiving canals and estuaries. More research is needed to address and control all forms of nutrient pollution, including different forms of N (urea, ammonia, etc.). We also need to consider that some technologies simply transfer point-sources of pollution to nonpoint pollution (e.g., reclaimed water and biosolids).

What We Think We Know

- We know what doesn't work generally but not necessarily what will work in every water body.
- Site-specific benthic, water quality, and hydrologic characteristics will affect the efficacy and safety of mitigation and management practice.
- Algal bloom mitigation must take potential ecological harm and human health risks into consideration.
- Water body size and bloom scale may make the application of certain algal bloom mitigation techniques unfeasible.

What We Don't Know

- How to evaluate cost-effectiveness of bloom mitigation and determine cost:benefit?
- What do you do with harvested biomass?
  - Is biomass a waste product or can it be a commodity?
- What is the fate of algaecides (and economic sustainability of these products)?
- What is the effect of various mitigation technologies on cells and toxins?
- What is the acceptance of different technologies across different stakeholder groups?
- What do we know about the recovery (target vs non-target taxa)?
- What is the efficacy of these treatments outside of the kill zone? Are we actually improving conditions?
- What are the long-term effects of chemical formulations, proposed bacteria, and proposed enzymes on the environment and non-target organisms?

RESEARCH PRIORITIES	
1. Holistically improve nutrient source management to reduce nutrient pollution (N&P). ▪ Focus on nutrient cycling & bioavailability. ▪ Improve understanding of nutrient sources (PS vs NPS) and sinks (planktonic and benthic algae as sinks). ▪ Managing phosphorus content of reclaimed water and biosolids. ▪ Phosphorus recovery at Water Reclamation Facilities.	94%
2. Develop scalable HAB mitigation tools that are economically feasible.	76%
3. Develop new technologies for mitigating sediments as related to HABs (nutrients mitigation).	61%
4. Need to field test potential control and/or mitigation strategies.	61%
5. Evaluate what hydrologic conditions can impact management and future management options.	55%
6. Determine a strategy for effective messaging to the public regarding expecta-tions, timelines, and costs.	
7. Develop commercial commodities that can be produced from cyanoHABs.	
8. Determine safe and effective mitigation.	
9. Need to include sampling of macroalgae (such as *Dapis pleuosa*) not just the water column.	
10. Conduct a field experiment to evaluate the effectiveness of hydrogen peroxide-based treatments of algal blooms under no-flow and flowing conditions from Lake Okeechobee.	
11. Develop blue-green algae control methods.	
12. Develop treatments that focus on cyanobacteria or N-fixation or toxin gene sequences.	

MANAGEMENT PRIORITIES	
1. Integrate modeling with mitigation practices to prescribe the best management action (technology, where and when).	79%
2a. Determine if your management practice will actually achieve the goal of reducing blooms and what the ramifications are. ▪ Integrate management practices implemented at local scale with nutrient modeling at watershed scale. and HAB predictive model at lake level – optimize management practice at watershed scale. 2b. Evaluate and weigh engineering approaches versus ecological approaches.	70%
3a. Better integrate the management of water quality and hydrology towards the goal of HAB management within the TMDL and MFL programs.	70%
4. Streamline process on the effectiveness of BMAP programs beyond project tabulation. ▪ Review lake responses to implemented management actions (if TMDLs were met does WQ correspond).	57%
5. Growth and land use management policies.	55%
6. Incorporate internal phosphorus recycling into Basin Management Action Plans.	
7. Focus on managing internal sediment nutrient loading (best decision - to reduce external loading, remove/dredge existing sediments, etc.).	
8. Create a central database for alternative technologies.	
9. Management optimization.	

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SESSION 5

Public Health

2019 Consensus Statement

Cyanobacterial 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 cyanobacterial 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.

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 cyanotoxins. 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 cyanobacterial 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 cyanobacterial 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 variables.

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've Learned Since 2019

Understanding human and animal cyanotoxin exposures and illnesses can help to prevent future illnesses. However while codes exist for reporting toxin exposure, it is not mandatory to report to the FDOH. Additionally, a number of surveillance and epidemiological studies are underway to assess human and domestic animal short- and long-term exposure to cyanotoxins, but results are still years away for some of these longer-term efforts. In the absence of clear results, recent efforts have focused on outreach and education to the public health community.

Since 2019, many partnerships have been formed designed to standardize information for key stakeholders, including human and veterinary health care providers and the public. Partnerships provide multiple sampling data sources to trigger automatic public notification on ProtectingFloridaTogether.gov. Current outreach efforts are working to increase awareness of emergency response personnel to the possibility of cyanotoxin exposure, and educating the public of cyanobacterial events, including through a partnership with Florida's Poison Control Centers. In-person veterinary education and online educational tools for veterinarians and pet owners have been developed. Similarly, an article written for primary healthcare providers was produced to increase awareness of cyanoHAB risks and symptoms as well as treatment and testing related to exposure. Additionally, a guidance document for occupational exposure to HABs and personal protection equipment (PPE) has been developed.

Efforts have also focused on enhancing the resources necessary to support long-term longitudinal cohort studies. Since 2019, methods have been developed to test for the presence and level of toxins in human tissue and a biorepository of blood and urine samples during bloom and non bloom conditions has been established.

Animals as sentinels for reducing human exposure

Exposure to cyanotoxins can occur through ingestion, inhalation, or skin contact, and acute health effects are well documented. Due to behavioral differences, pets and livestock have an increased exposure risk compared to humans. Animals can be exposed when drinking water that contains toxins, by ingesting scum, foam, and other contaminated materials in or near water, and also by swimming through blooms and then licking their fur. Because of how they use the water, animals ingest a large portion of the toxins that are in the water, leading to increased clinical signs. As a result, animals provide an important early trigger for public notification of cyanoHABs.

Better characterization of veterinary cyanobacterial toxicosis, including risk factors, clinical presentation, and testing can inform human health. One of the problems in veterinary medicine is the need for a 48 hour history. Because cyanotoxins do not present differently from other toxins, veterinarians need to understand an animal's history in order to narrow down toxin type. Sample collection from animals at the time of presentation also aids in future testing. Microcystin can be found in urine for several months after exposure. Without a history, it is difficult to establish cause and effect when assessing a new disease.

By looking to Florida's mosquito control surveillance program as a successful model, progress has been made towards developing a surveillance program for cyanotoxins in domestic animals to prevent exposure in humans. As part of the surveillance program, an animal case model was selected, case definitions have been created, in addition to database triggers for public notification and communications. Having case definitions provides data consistency. Since 2019, partnerships have been established with various state agencies to improve reporting and public awareness, with a goal of increasing reports of human and animal related cyanoHAB exposures. This is being done through map systems which help link people to resources. Educational materials and continuing education classes have been developed for veterinarians and pet owners. Additional efforts have included working with laboratories to create a panel of labs for veterinarians so they have a group of toxins to be able to test for.

Seeking to understand long-term exposure risk

Despite numerous occurrences of cyanoHABs in Florida, and an acknowledgement of acute public health impacts, the long-term health effects from exposure remain unresolved. This is an emerging science, and requires multiple disciplines, and progress is underway on several short- and long-term research studies in Florida. Collectively, these studies will investigate exposure to cyanotoxins among Florida residents, workers, and visitors across various locations. Active samples collected include nasal swabs, blood, urine, and tissue collection. Microbiome data and respiratory function are also being measured, as is environmental data for comparison across bloom and non-bloom conditions. The efficacy of a novel passive device is also being assessed to evaluate aerosolized cyanotoxins. These studies will investigate various exposure pathways, including inhalation, ingestion, and dermal absorption.

One of the major challenges in human exposure studies is recruiting and retaining participants over the long term, especially during non-bloom times when community interest may wane. Some individuals do not want to be part of a study because they don't want to know the result, don't know what the results will be used for, or fear results may negatively impact them. This underscores the importance of social science for both understanding behaviors and motivations, and building relationships and trust. Additionally, the COVID pandemic and the absence of significant bloom events in recent years has forced some researchers to reevaluate project goals and explore alternative study designs and methods.

What We Think We Know

- Under experimental conditions, passive devices can detect toxins.

What We Don't Know

- What is the best biomarker for the long-term impact of cyanotoxins?
  - Is there a long-term effect?
- How does a particular toxin get to a person?
  - What is the exposure, what is the duration, what is the frequency?
  - Are there unknown exposure pathways (e.g., through the placenta wall, blood brain pathway, and breast milk)?
- What is the mechanism for aerosolization from water to air?
  - What are the decay rates?
  - What meteorological conditions lead to aerosolization?
- Due to our limited ability to detect and quantify many cyanotoxins, what is Floridians' actual exposure to cyanotoxins?
- What are the background toxin levels during non-bloom periods?
- How effective are personal protective equipment (beyond masks) and decontamination procedures for occupational health exposures?

RESEARCH PRIORITIES	
1. Understand short and long-term health effects from exposure to cyanotoxins. ▪ Veterinary diagnostics	84%
2. Develop more clear diagnostic criteria for health care professions & vet professionals.	72%
3. Characterizing human exposure to cyanotoxins. ▪ Vulnerable/compromised populations (kids, pregnant women, respiratory impaired, socio-economic communities, etc.)	66%
4. Developing report back mechanisms of exposure and health effects to the community.	
5. Validate methods to detect presence and meaning of cyanotoxins in human tissues.	
6. Use social science regarding messaging to allow the public to use good judgment. ▪ for pet owners ▪ for people concerned about inhalation ▪ about non-toxic compounds, such as BMAA or in the exaggerated threat to aerosols	
7a. Evaluate physical, mental and social health risks for the public and those implementing control strategies. 7b. Determine psycho-social impact on individuals living near blooms.	
8a. Need aerosolized toxin measurements for public health monitoring and policy. 8b. Develop airborne toxin exposure risk assessment.	
9. Establish more effective guidelines for drinking water treatment for all contaminants.	
10. Determine the best way to measure toxins in the food web.	
11. Identify all toxins, risks, and levels of toxicity. ▪ Synergistic effects across toxins.	
12. Determine what control strategies individuals are using on their own without guidance and what the potential health impacts of those strategies are. ▪ Develop guidance recommendations based on these needs.	
13. Develop Point of care testing for health care providers.	
14. Need clinically approved matrix-specific assays for cyanotoxins in biological samples.	

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Pico- & Nano-Cyanobacterial Blooms

IN THE INDIAN RIVER LAGOON

Algal blooms, and associated fish kills, have been reported in the Indian River Lagoon (IRL) since the late 19th century. Blooms are part of a productive natural system, especially one that is characterized by long residence times and limited exchange with the ocean. Historically, ephemeral inlets appeared along the barrier islands, but today, the lagoon is arguably more hydrologically stable, with oceanic exchange determined by the location of five permanent inlets.

Since 2011 however, the northern and central segments of the lagoon, including the Mosquito Lagoon and Banana River Lagoon, have experienced blooms that were more intense, more widespread, and longer-lasting than those recorded in the previous 25 years. During the ten-year period between 2011 and 2020, intense blooms occurred in 2011, 2012, 2016, 2019, and 2020; a large fish kill accompanied the 2016 bloom and a smaller fish kill occurred in 2020. The fish kills were associated with drops in concentrations of dissolved oxygen as the bloom terminated. Modeling based on data from Landsat satellites, estimated chlorophyll-*a* concentrations to be greater than 100 μg/L during the peaks of blooms in 2016, 2019, and 2020.

In addition to increased biomass, the composition of blooms shifted. Historically, blooms in the northern IRL were dominated by dinoflagellates and diatoms, and the biomass of these blooms peaked at less than 600 μg carbon/L. Since 2011, the northern IRL has experienced brown tides and blooms of nanoeukaryotes, as well as picocyanobacterial “green tides” and mixed blooms. Nanoplanktonic eukaryotes and cyanobacteria generated biomass greater than 2,000 μg carbon/L in 2018 and 2021. After 2012, the pelagophyte *Aureoumbra lagunensis* (i.e., brown tide) joined the list of dominant taxa, with peak biomass greater than 10,000 μg carbon/L in 2016 and 2019. The prevalence of picocyanobacteria is not constrained to the northern IRL, however. They, along with the cyanobacteria *Synechococcus*, have been documented in the southern reaches of the IRL since 2017 but at lower densities.

The drivers of these blooms are still being investigated, but understanding bloom dynamics is complicated by the fact that many of these small phytoplankton are unidentified. It is likely that a combination of long-term loads of nutrients to the system and unusual stochastic events contributed to the observed changes. Events include severe winters in 2009 and 2010 followed by unusually warm summers, declines in drift algae, large rain events driven by long-term climatic cycles and stochastic storms, and

an overall shift in the N:P ratio. There is additional evidence that picocyanobacterial densities are correlated with lower salinities (<24 ppt), often caused by storms (e.g., Hurricane Nicole). There is also evidence to suggest less bottom-up control as picocyanobacteria and nanoeukaryotes are able to utilize organic compounds in the form of amino acids. Finally, there appears to be less top-down control of these smaller bloom forming organisms. Laboratory experiments indicate that as cell concentrations increase grazing pressure declines.

The intensity of the blooms and the resultant reductions in light penetration have changed the ecology of the lagoon, specifically with regards to seagrass. Seagrass grows to a depth of approximately 0.9 m, and the predominant seagrass species in the lagoon requires a minimum of approximately 20% of incident light to survive. Since 2011, the frequency and duration of periods when incident light at 0.9 m drops below 20% has increased, as evidenced by data from Banana River Lagoon and Northern Indian River Lagoon. Mapping showed a precipitous decline in seagrass acreage and, in combination with data on percent cover from transects, indicated upwards of a 90% loss in biomass of seagrass.

Seagrass is the primary structural habitat in the lagoon and these prolonged declines in coverage and biomass have led to ecological changes affecting seagrass-dependent species. Manatees rely on seagrass as a primary food source. Transitions in their diet from seagrass to drift algae increased the incidence of a clostridial bacterium that produced a toxin, resulting in an unusual mortality event (UME) in 2013. A dolphin UME, which has not been resolved, also began in 2013. In 2021, another manatee UME began, and it was characterized by loss of adipose tissue indicative of a long-term lack of food. There may be other impacts that have yet to be characterized. For example, approximately 70% of the sport fish in the lagoon rely on seagrass as a key habitat. Furthermore, the potential effects of toxins produced by picocyanobacteria remains unclear. Microcystins have been detected in the environment during picocyanobacterial blooms, but the relationship between toxin concentration and cell biomass is unresolved.

Management of blooms in the IRL is focused on trying to achieve the total maximum daily load (TMDL) via reductions in loads that are identified in the IRL's Basin Management Action Plans. St. Johns River Water Management District's water quality modeling indicates that a 70–75% reduction in loads of nutrients was required to see a substantial reduction in concentrations of chlorophyll-*a* during the 2011 bloom; we currently have achieved approximately 50% of the planned reductions, and there are some challenges associated with the process. First, current TMDLs were established to restore water quality that supports the growth of seagrass, but there is a concern that the link between requirements for incident light and growth have been decoupled due to limitations on recruitment of seagrass. Second, lists of projects that will reduce loading exist, but availability of funding remains an issue. Lastly, reducing loads of nutrients is a strategy for managing blooms in the long term. Innovative technologies to mitigate blooms in the short term are being tested in Brevard County, but the efficacy of these technologies is yet to be determined.

Data gaps:

- Species level identification
- Drivers and dynamics of contemporary bloom-forming species
- Efficiency and effectiveness of bottom-up and top-down controls
- Timing and trigger of picocyanobacterial toxicity
- Ecological effects of blooms

Research and management priorities:

- Manage the ecosystem degradation before it is too late.
- Manage nutrient inputs, including internal cycling, to get us back to a historic N:P ratio and/or historic NO_3^-:NO_4^+ which favor diatoms and dinoflagellates.
- Document the stoichiometry of nutrients and implement source tracking.
- Identify species and document interactions among species.
- Enhance routine and event-driven monitoring
- Use the tools available to identify species appropriately.
- Cultivate problematic organisms in the laboratory for use in experiments.

Marine & Freshwater Benthic Cyanobacterial Blooms

IN FLORIDA

Benthic cyanobacterial blooms are characterized as growing attached on the bottom in the littoral zone. They exist across the freshwater to marine continuum and are a widespread issue for Florida. Benthic cyanobacteria produce oxygen bubbles, which become entrained in the algal mass, causing it to detach from the bottom, rise to the surface, and accumulate in floating mats, primarily within zones of stagnation and along the littoral zone. Temperature, wave activity, overgrowth, and senescence may also cause detachment. People and animals are at greatest risk for exposure when activities, such as playing in the water, results in detachment from the bottom or when recreation occurs near floating mats. Socioeconomic consequences of floating mats, which are most visible, include compromised aesthetic quality and limited recreational opportunities. In addition, these blooms can have ecosystem impacts. Decomposition of detached mats pulls oxygen from the water column, potentially creating hypoxic zones; both seagrass and manatee impacts due to benthic cyanobacteria have been documented.

Until recently, most benthic cyanoHABs (freshwater and marine) have incorrectly been identified as *Lyngbya* or *Lyngbya*-like. Benthic cyanoHABs are often multi-generic and multi-specific, making identification complex and challenging. However, correct identification aids risk assessment and communication among managers and scientists. Identification of benthic cyanoHABs can be done using genetic and morphological techniques. Genetics can be used to initially aid in determining genera and species differences; once you know what to look for, morphology can be used to identify many of Florida's primary organisms. Both freshwater and marine benthic cyanobacterial blooms can contain toxins as well as other pathogenic microorganisms including bacteria, fungus, or planktonic microeukaryotes (i.e., the eukaryotic HAB species). Many of these secondary compounds constrained within the benthic mats are still unknown. Thus, accurate identification is important for safe and effective monitoring, mitigation, and public health response.

Freshwater benthic cyanoHABs can exist in a variety of natural and artificial environments including lakes, canals, streams, springs, rivers, and stormwater treatment ponds. The key bloom-forming freshwater genera are *Anabaena, Microcoleus,* and *Oscillatoria.* Other bloom forming freshwater organisms detected in Florida include *Microseira wollei, Heterscytonema,* and the more recent genus *Iningainema*. Freshwater benthic cyanobacteria are known toxin producers. Anatoxins, microcystins, nodularins, cylindrospermopsins, and saxitoxins have been detected within Florida or the greater United States, as have some uncharacterized toxins.

Marine benthic cyanoHABs can occur in brackish and marine environments and have been detected along shorelines and marinas and within natural habitats including mangroves, seagrasses, corals, and sandy dunes. Deepwater cyanobacterial mats have also been reported. The lifecycle of benthic cyanobacterial blooms follow a simple pathway, however, specific bloom dynamics are still unknown, specifically in regards to nutrient cycling. In the dry season there is limited cyanobacterial growth, due to lower temperatures and little nutrient influx. As the season progresses, there is a concomitant increase in cyanobacterial growth. Increased growth can cause ecological disturbance including water turbidity, light competition and smothering of benthic habitats. As the mats detach from the bottom, they can also pull seagrass blades out of the sediment. Upon detachment, cyanobacterial mats will start to decompose resulting in low dissolved oxygen, noxious odors, and the release of toxins. Benthic cyanobacteria can continue to reproduce up until the point of decomposition.

While there are still many unknowns and unidentified organisms, recent progress has been made in taxonomic identification of marine benthic cyanoHABs. Many of the key marine benthic cyanobacteria can be classified based on their habitat. For mangrove environments, the primary genera are *Vermifilum*, *Ophiophycus*, and *Leptochromothrix*. Primary seagrass-associated genera include *Dapis, Okeania,* and *Sirenicapillaria*; all of which are capable of nitrogen fixation. Additional key marine benthic genera that have been identified include *Neolyngbya*, *Nunduva*, *Capilliphycus*, *Affixifilum*, *Hormothamnion, Spirulina, Caldora, Rivularia,* and *Moorena*. The three dominant genera for coral-associated benthic cyanobacteria are *Symploca*, *Roseofilum*, and *Geitlerinema*. Cyanotoxins associated with marine benthic mats include anatoxins, saxitoxins, microcystins, and lyngbyatoxins.

Consistent monitoring protocols are important because how and where sampling occurs can produce different information. For example, toxin analysis of a water column sample will yield significantly lower toxin concentrations than analysis of benthic mats or time-integrative SPATT (Solid Phase Adsorption Toxin Tracking) samples.

The monitoring protocol for freshwater benthic cyanoHABs is generally a four step process.

1. Coverage and visual assessment of the bloom
2. Collection of bloom mat material for species and toxin identification
3. Water column sample collection
4. SPATT deployment to detect *in situ* toxins through time

Monitoring of marine benthic cyanoHABs is similar to that of freshwater but can be complicated by scale, access, and depth. Sampling procedures may also be habitat dependent.

1. Coverage and visual assessment of the bloom
2. Collection of bloom mat material for species and toxin identification
3. Cleaning of mat material to remove microfauna
4. Water column sample collection
5. SPATT deployment to detect *in situ* toxins through time

Effective management of benthic cyanoHABs will require a greater understanding of these blooms. A roadmap for response has been outlined and starts with knowing what species are present, what toxins are being produced, and by which organisms. A robust spatio-temporal monitoring program needs to be developed to help determine the drivers of benthic cyanobacterial blooms. Consistent monitoring of the benthos is also important for

accurately assessing the overall health of a system. Nutrient impairment may not always manifest itself through phytoplankton, but through the benthos. Water column sampling alone may not be telling the whole story. Currently, most spatial sampling efforts only provide a snapshot in time (e.g., aerial seagrass surveys, fisheries monitoring bycatch data, Eyes on Seagrass).

Mitigation and treatment efforts for benthic cyanoHABs are currently limited. There are challenges with getting chemical interventions at depth. Benthic cyanoHABs also respond differently to chemical treatments than planktonic species, in some cases increasing their growth. Mechanical harvesting is more preferential and is currently being investigated as a public health option to remove the mats along the wrack line. Harvesting is also being considered as a strategy to get rid of internal biomass and nutrients. Removal efforts need to be followed by submerged aquatic vegetation (SAV) planting, or else the benthic mats will return.

Data gaps

- Drivers of bloom initiation
- What are the nutrient sources (i.e., water column or the benthos)?
- What happens to the components of the bloom as the bloom deteriorates?
- Biologically relevant rate evaluations
- Toxins and secondary compounds
- What is the relationship between planktonic and benthic blooms?
- Impacts on marine and freshwater flora & fauna (mangroves, seagrass, marine mammals, mullet, blue crab, etc.)

Research and management priorities:

- Species and toxin identification
- Improve how the research and management community talks about these blooms (accuracy and specificity of species and toxins).
- Drivers of ecosystem change and benthic cyanobacterial growth (nutrients and temperature, internal vs external)
- Improve public outreach (bloom awareness & associated risks, avoid recreational contact and irrigation use).
- Laboratory cultivations
- Define management responsibilities between FDEP and FWC.
- Manage (public) expectations of ecosystem restoration and management efforts.
- Continue current nutrient reduction strategies.
- Create standardized water sampling and monitoring protocols.
- Create a Florida Benthic HAB working group (freshwater &/or marine).
- Understand the relationship with benthic cyanobacteria and other blooms.

Best Practices for CyanoHABs

One goal of the symposium was to ensure that 1) current best practices are being applied across discrete research and management projects; and 2) ongoing statewide efforts are not being duplicated. To address these concerns, participants were assigned into one of five breakout groups according to the symposium's primary session themes. For each breakout group, session participants were tasked with identifying best practices for methodologies, effectively communicating across academic and management silos, and reducing duplication and preventing redundancies in research. They were also prompted to identify any social science (e.g., economic, sociology, political science, communication, etc.) research gaps and priorities. Many of the recommendations were consistent across multiple breakout groups and these are summarized below. Session specific recommendations are presented beginning on page 38.

Best practices for methodologies

Overall, a universal streamlining of methodologies and parameters is not realistic, as the research and management question should drive the data. However, the most important best practices for data collection are 1) the assurance of quality data, and 2) the availability of metadata. Data are only useful if they can be trusted and if one understands what they mean. Where appropriate, the community should standardize data and metadata requirements, while allowing for technological advances and data evolution.

Best practices for sharing and preventing duplication

Overall, increased dialogue across research and management groups and across federal and state agencies is needed. Traditional mechanisms of information sharing are encouraged (i.e., participation in national and international conferences, publications – especially in open science and open source outlets, white papers, and inter-agency working groups). Focused symposia and workshops, such as the BGASOS, are essential for staying informed of what the larger cyanoHAB community is working on, to help share successes, challenges and failures, and to have open and candid discussions in a safe environment. Funding agencies need to play a larger role in preventing duplicative grant opportunities and redundant research. As such, there needs to be a mechanism for them to talk amongst themselves. Federal entities need to assess what is happening at the state level, and vice versa. Researchers and managers need to be brought together early and often in the funding process.

There is broad interest in the concept of a community of practice and a central repository (curated by state funders FDEP and/or FDOH) for the cyanobacterial research and management community. This space would act as a connected data network as well as a location for finding and reporting currently funded research projects (e.g., funding agency, grantee, and project information). The format (website, dashboard,

and/or data repository) would promote accessibility and be open-sourced.

Social science research needs

A common theme across the groups is the need to improve communication to the state's various target audiences. Social science research is needed to determine how audiences make decisions, how to frame these concepts to engage various stakeholders, and assist in the development of audience-specific motivators for behavior change.

Economic impact assessments are also a common theme. We need a greater understanding of the cost of cyanobacterial blooms to the state of Florida and improve how we communicate the costs to the public and get or maintain support for cyanoHAB research and management projects.

Definition of a bloom

Although not a component of the breakout groups, a repeated theme identified within many of the lightning round sessions was the issue that there is no universal definition of a bloom for cyanoHABs in Florida. To address this concern, and to move the conversation forward, participants were tasked with writing down their own perceived definition of a bloom. Across all submissions three major categories emerged: quantitative definitions, qualitative definitions, and definitions from the human and ecosystem health perspective (Appendix I). While a consensus definition was not the purpose of this activity, further refinement would help with effective communication between scientists, environmental agencies, policymakers, and the public. Further, research and management projects would benefit from pre-identifying what definition of a bloom their project is adopting. This would allow for more transparent goals, objectives, and an improved ability to evaluate success.

Best practices for drivers

There is currently no methodological standardization for those parameters most important to assessing drivers of bloom initiation, however, there is agreement that there needs to be some level of standardization on what parameters should be sampled as well as how that data are collected. The Florida DEP standard operating procedures could be used to identify which methods are best. At a minimum, environmental data need to state the location and time/date that the data were collected, what sampling methodologies were used, and what the detection limits are. Other measurements that are important for determining drivers of bloom dynamics include: sediment nutrient fluxes, ground water nutrient fluxes and nutrient loads, macro- and micro-nutrients in sediments, surface, and groundwater sources, various nutrient species, nutrient cycling and dynamics, and ambient environmental conditions (e.g., temperature), light attenuation parameters, and residence time. Information about the bloom community composition was also deemed important. These metrics include measurements of abundance (i.e., cell counts, chlorophyll, biomass, density, and percent cover via quadrat and remote sensing), taxonomic composition (single species or community), toxin type and concentration. In addition to standardizing the data metrics, there is no consistent methodology for identifying what the actual drivers of blooms are. Though consistency in data collection is identified, it is also acknowledged that there may be opportunities to relax data requirements for shared portals, as not all data needs to meet State standard water quality qualifiers for it to be useful in research projects.

Improved communication across research and management groups is necessary and should include less traditional mechanisms such as town halls and communities of practice to share information and establish common goals. The concept of sharing should be expanded to include the development of a shared-equipment process, thereby extending not just expertise but resources, as well. To facilitate, teams could be developed to share access to expensive specialized equipment that may otherwise be a barrier to research and opportunity.

More consistent and long-term funding is needed to minimize duplication across the research realm. Continuity in funding would allow research teams to continue progress and prevent the likelihood of another group taking on the same research question once a funding cycle has come to an end. Long-term funding would also benefit communications, as there would be more time for publication and dissemination, thereby improving data and research sharing across groups.

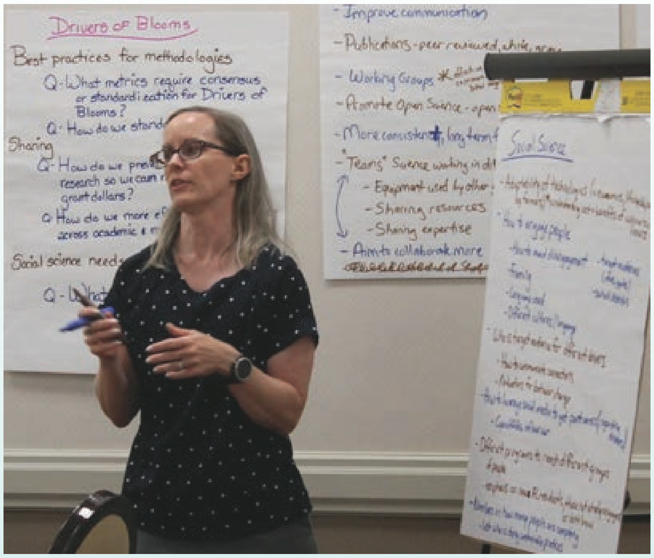
Many drivers of cyanoHABs are influenced by management activities including Best Management Practices and Basin Management Action Plans. A more thorough understanding of these programs and the adoptability of technologies, including participants and compliance numbers, incentive effectiveness, and cost:benefit analyses would help determine their effectiveness and guide future management strategies.

Best practices for prediction and modeling

Benchmark data are necessary for doing bloom prediction and modeling, but in order to standardize these metrics it is essential to first define what questions the model is trying to answer. There should be consensus on what the field data and models are, but at a minimum, benchmark data need to be of high integrity and of appropriate quality to allow for model validation and inter-comparison of models. When using externally collected monitoring data, metadata becomes imperative. A consideration for benchmark data is the disparity in temporal and spatial scale between modeling and field-based monitoring data. Each approach offers different but complementary information. Creating data indices reduces mismatch but risks losing important information. Thus, in addition to benchmark data, methods for comparing models should also be developed and shared. Providing open source codes or guidance documents as a deliverable should be added to future funding opportunities.

Duplication across modeling efforts is prevalent. Funders should coordinate early between modeling groups, with end-users and data providers to ensure all parties know who is doing what. This coordination will retain creativity while preventing funding agencies from funding similar projects, thereby maximizing limited resources. Coordination efforts will also benefit multi-model ensembles, where groups can learn from others to ensure they are tackling similar problems in different ways. It was further recognized that sharing of failures is just as important as the sharing of successes, as there is no point funding something that was already tried and unsuccessful. Opportunities for sharing should be both passive and active (in-person) and may be through meetings such as the BGASOS, the USACE Freshwater HAB Research & Development Workshop, or by the South Florida Ecosystem Task Force, or the HAB Hypoxia Research and Control Act (HABHRCA) Interagency Working Group. The group recommended that NASA should become more engaged with the Interagency Working Group.

It was recognized that framing the model is as much a social science problem as it is a natural science problem. Modelers and social scientists should have open dialogue with the community early in the development process and throughout the duration of the project. Participatory modeling is needed to 1) ensure the modelers understand the purpose of the forecast and its intended use before they start developing the product, 2) the various stakeholders understand the purpose as well as the limitations of the forecast, 3) the model is accessible to the end-user communities and is available in a platform or format that they can use and understand, and 4) modelers understand how forecasts are being used by different end-users, including what biases come into play and what messages are being inferred. Key messages and formats may be needed for different audiences.



Best practices for detection and monitoring

Standardized metrics are needed for economic impact assessments, but standardized methodologies and parameters are unrealistic for detection and monitoring of cyanobacterial blooms because data collection and analyses will be dependent on the question being answered and the purpose of the monitoring program. However, there is an opportunity to develop an acceptable list of methods for common metrics and there are some parameters that, at a minimum, should universally be collected. Best practices could be developed for:

- Water collection
- Toxin detection
- Nutrient composition
- Cell concentrations
- Species identification
- Timing and spatial sampling strategies.

This would allow for some level of comparability across labs and research groups, keeping in mind the evolution of technology. Quality monitoring data are most important, and in order to have confidence in the data, metadata (how and why) are necessary. It was recognized that a best practice of data collection should be to collect one level more than what would be useful as data can always be lumped but not be parsed out if unavailable. For example, nutrients should be measured at the species level rather than measuring only TN or TP. There is an opportunity to improve algal species identification and toxin assessment with greater collaboration and sharing of new data and imagery.

Funding of basic, long-term monitoring and detection should be made more appealing by directing resources to general monitoring programs that can be supported by regional laboratories and universities. Academic pursuits need to be more aligned with regulatory needs; targeted RFPs can eliminate redundancies while soliciting explicit applied research projects that generate the direct data needed. There is an opportunity for the management community to assist those in academia to scale-up their research for use in larger, management-scale scenarios following a design and build approach. Liaisons between academia, state, and federal agencies can help foster partnerships and communicate needs across silos.

Social justice was an important consideration for detection and monitoring. Mainly, are all communities being served equally? A specific goal of monitoring cyanoHABs is to communicate risks to the public and provide individuals with information to minimize potential health impacts. We need to know if this is being done effectively. Are we communicating at the right level without being alarmist or over-inflating the risk, and are we effectively communicating uncertainties? Communication challenges increase during extreme events when blooms lead to significant economic consequences.

Best practices for management and mitigation

A best practice for management and mitigation is to more effectively use the data to drive management decisions. However, this necessitates that the available data are comparable across groups. Sampling protocols should follow FDEP SOPs, and there should be standards for continuous data and long-term storage. Instrumentation should be calibrated consistently (frequency based on instrumentation), intercalibration workshops should be conducted, and a process for inter-laboratory sample exchanges should be developed to ensure decisions are being made with sound and accurate data. Field and laboratory SOPs need to be developed for benthic cyanoHABs.

Both management and mitigation projects require a framework for evaluating a positive outcome. We also need a clearer understanding of the specific management goals, and we need to establish a management paradigm that can be measured and implemented. For example, is the management goal to get back to a prior state or to achieve clean water? If so, how do we define clean water and what do we do to get there?

Meta analysis is needed to evaluate what has worked and what hasn't, look to prior management interventions and develop lessons learned to inform management moving forward. Specific and consistent benchmarks, including clear guidance that follows the law, need to be created to assess new technologies for mitigation. This guidance should consider scalability, tech readiness, and cost effectiveness.

In addition to academia and managers, the management and mitigation sector also needs to engage with private industry and consultants in the engineering field, and future efforts need to support collaborations across disciplines. It is also important to determine whether the goals of the managers and researchers align with community needs. Management and mitigation efforts should not lose sight of who the customer is and how best to serve them. Social science research can help make connections with the local communities and determine community priorities, while developing communication strategies for project return on investment and tempering expectations. Natural resource economists can also help determine the acceptable level of investment risk for these management and mitigation projects and create mutual gain from these projects that help serve the public.

Best practices for public health

Research on public health impacts of cyanoHABs in Florida is a developing field and as such, it is too early to assign constraints on data methodologies and protocols or define best practices. The field is still trying to determine: 1) can it be detected; 2) if it can be detected then what are we detecting; and 3) what does that detection mean for the general public and for the data? As analytical methods are developed and published there is an opportunity to develop future guidelines and standardization, but the field is still in the exploratory stages.

The field of public health currently treats the symptoms of HAB exposure rather than the toxins. Future improvements would shift to behavioral management which would include case definitions for health care and veterinary medicine diagnostic criteria. Advancements in outreach and education to the health care and veterinary medicine community could improve diagnosis, history-taking, and reporting ultimately improving public health response. Guidance documents should be developed to include current standards for presence/absence criteria, as well as personal protective equipment for occupational sectors and the general public. Targeted trainings could also assist in these efforts, as would the inclusion of HAB symptoms into health care providers and veterinary medicine diagnostic software.

A specific concern for public health researchers is in regards to the recruitment of study subjects in the same region and competition for participants between research studies. Coordinated communication efforts, such as a community of practice or website (described above) would help minimize this potential. Within the public health sphere, the CDC One Health HABs (OHHABs) group can help foster communication nationally and would be an opportunity to connect with other Oceans and Human Health Programs.

Communicating about public health impacts is a priority and an opportunity for this field. Target audiences include both the general public and the medical community. Research is needed to help determine how best to reach these audiences, who is a trusted source of information, and message testing recognizing that many people may have a stigma around harmful algal blooms. Mental health effects are also a concern for HABs, especially for long-term exposure.

Concluding Thoughts

The BGASOS II served as a progressive symposium, assessing advancements made over the four years since the inaugural state of the science symposium. This report acknowledges the substantial scientific advancement that has been made in Florida, including progress on three-quarters of the research projects identified during the 2019 symposium. This report summarizes the current state of the science, identifies new knowledge gaps and research priorities, as well as best practices for cyanoHAB research and management efforts. Importantly, it also highlights how strategic coordination and communication between the research and management community are integral to the understanding and management of cyanoHABs in Florida.

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Appendix I

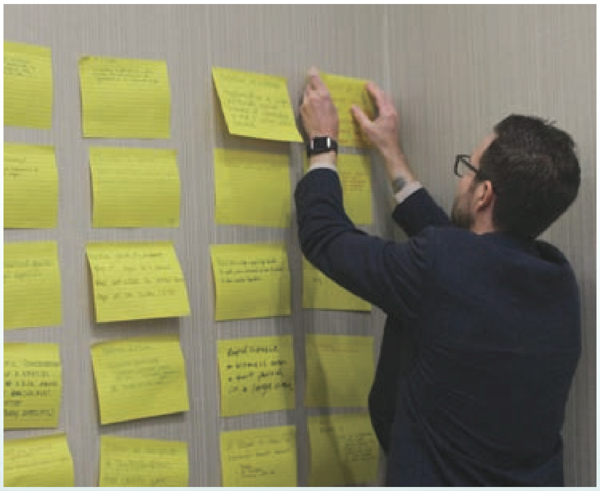
Quantitative definitions

- An algal proliferation (benthic/planktonic) that has reached critical mass (10^4) cells and poses physical/chemical stress on water quality
- A rapid and large increase in algal biomass as measured by some method (chlorophyll, cell concentrations, optical, etc)
- >40 μg/L chlorophyll with rapid growth and dominance of one or more species of algae
- A specific concentration of cells of a species that is X percentile above baseline (or average) concentration (water body specific)
- Increase in biomass above traditional, ambient, and/or long-term levels or concentrations
- Excessive growth of a group of algae to a biomass level outside the normal biomass range of the system (>2 SD)
- Chlorophyll (or biomass) increased noticeably above typical (noticeably may be a metric)
- Microscopically: > 100 natural units per mL
- High concentration of chl-a (e.g., 40 μg/L)
- Cell counts of any "blooming" species of interest some percentage threshold (set to be species specific based on potential harm) above that system's baseline at that time point (relative to historic record)
- Visual observation that exceeds specified spatial and density thresholds
- Satellite imagery (NOAA HAB index) threshold exceedances
- chl-a concentrations >40 μg/L or detection of cyanobacteria in concentrations above specific thresholds
- Bloom begins when the rate of change of population is maximum and positive.
- D cell count/dt = max and d2/dt cell count = 0. Second derivative is zero (note: graphical definition included)
- A higher than "normal" concentration of algae. "Normal" necessitates baseline data, development of thresholds based on past observations (including biomass, health risk, etc.). "Concentration" can reflect an estimate of abundance (chlorophyll, cell #s, areal coverage) that varies across taxa in terms of methods utilized.
- Change in biomass per day ≥0.5 biomass
- A proliferation of biomass in a defined area beyond site-specific threshold which may coincide with negative impacts to humans or ecosystems
- Dominant species with exponential growth
- Numerically definition of a bloom should follow WHO or EPA guidelines
- A bloom exists when the dominant feature of the water column or benthic habitat per unit area consists of algae

Qualitative definitions

- Enhanced growth of algal species
- When there is an over-production of algal cells
- Thick accumulation /growth of algae that can cause discoloration of water or mass growth on services, surface scums.
- Excessive & persistent, often visible, accumulation(s) of cyanobacteria or nuisance algae
- An overgrowth of phytoplankton that causes water discoloration/visibility issue
- Point at which an alga or group of alga dominate the aquatic or marine environment and have the potential to cause ecosystem degradation
- Rapid increase in biomass over a short period in a large area
- A bloom is when a harmful event occurs: toxin, N fixation, shading other vegetation

- A proliferation of algae beyond normal abundance
- Algae or phytoplankton in the water growing densely enough to change the color of the water or form aggregates
- A group of photosynthetic organisms found in the water that may be beneficial to the ecosystem or may cause harm to the ecosystem
- Excess quantity of algae in a waterbody that has the potential to cause environmental degradation (dissolved oxygen, fish kills). May or may not produce toxins.
- A bloom is an excessive level (growth) of a species. It conspicuously is the dominant taxon in the habitat, be it units of water or in the benthos. It would be desirable to quantify this term, but one size does not fit all.
- When growth occurs rapidly and unchecked or uncontrolled by naturally occurring competition or other controls.
- Clear, visible accumulation of biomass can be commonly referred to as a bloom without further estimate of abundance



- A higher than normal amount of algae (species and audience dependent)
- Visual observation of algae presence
- Bloom = a visible growth of algae in a waterbody
- A bloom is in the eye of the beholder. The definition is intrinsic to the beholder. The organisms themselves don't care - they are on a continuous growth curve. Therefore, let's make the definition intrinsic to the beholder. When it can be "seen" above normal background conditions, it's a bloom

Public and ecosystem health definitions

- Bloom = when the concentration of chlorophyll-*a* is greater than a threshold that causes a health concern. Harmful bloom = when the concentration of toxin is greater than a threshold that poses a health risk. The key is that it has to be defined by human health and ecological health perspectives.
- First public complaint
- A level of algae/cyanobacteria noticeable by the public
- Toxins at risk level
- I would consider the anthropogenic cause and the adverse health or environmental impact
- The presence of algal biomass in excess of typical algal community conditions which promotes poor water quality conditions and/or increased health risks
- Agglomeration of largely and toxically sufficient biomass of cyanobacteria so that it causes public concerns
- When it becomes an issue
- A marked increase in algal abundance to a level that causes negative ecological or human health effects

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