Spatiotemporal Variability of Cyanobacterial Harmful Algal Blooms with Respect to Changing Environmental Conditions

Jennifer L. Graham and Keith A. Loftin
Kansas Water Science Center

2014 Water Mission Area Research Lecture Series
<table>
<thead>
<tr>
<th>USGS Colleagues</th>
<th>Academic and Other Non-USGS Colleagues</th>
<th>Collaborating Entities</th>
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<tbody>
<tr>
<td>Trudy J. Bennett</td>
<td>Ann St. Amand</td>
<td>Kansas Water Science Center</td>
</tr>
<tr>
<td>Amy M. Beussink</td>
<td>John R. Beaver</td>
<td>Ohio Water Science Center</td>
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<tr>
<td>Lee J. Bodkin</td>
<td>Nicolas A. Clercin</td>
<td>South Carolina Water Science Center</td>
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<td>Guy M. Foster</td>
<td>Theo W. Dreher</td>
<td>Texas Water Science Center</td>
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<td>Donna S. Francy</td>
<td>John A. Downing</td>
<td>USGS Cooperative Studies Program</td>
</tr>
<tr>
<td>Theodore D. Harris</td>
<td>John R. Jones</td>
<td>USGS Toxic Substances Hydrology Program</td>
</tr>
<tr>
<td>Celeste A. Journey</td>
<td>Susan B. Jones</td>
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<td>Michael T. Lee</td>
<td>Daniel V. Obrecht</td>
<td>USGS Office of Water Quality</td>
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<td>Michael T. Meyer</td>
<td>Timothy G. Otten</td>
<td>US Environmental Protection Agency</td>
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<td>Erin A. Stelzer</td>
<td>Lenore P. Tedesco</td>
<td>Iowa State University</td>
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<tr>
<td>Mandy L. Stone</td>
<td>Nicholas B. Tufillaro</td>
<td>IUPUI Center for Earth and Environmental Studies</td>
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<td>Megan B. Young</td>
<td>Michael J. Turco</td>
<td>Oregon State University</td>
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<tr>
<td>Andrew C. Ziegler</td>
<td>Frank M. Wilhelm</td>
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<td>The Wetlands Institute</td>
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Overview

• Cyanobacterial Harmful Algal Blooms
• USGS Capabilities
• Occurrence
• Spatiotemporal Patterns
• Environmental Influences
What Are Cyanobacteria?

• Cyanobacteria are true bacteria, but have chlorophyll-a like algae.

• Structurally the cyanobacteria are bacteria-like, but functionally they are algae-like.

• Because cyanobacteria function like algae in aquatic ecosystems, they typically are considered to be part of algal communities (this is why they often are called blue-green algae).

Images from Rosen and others, OFR 2010-1289
What is an Algal Bloom?

- The definition of a “bloom” is somewhat subjective.

- Common definitions include:
  - Algae have high cell densities (20,000 to 100,000 cells/mL).
  - Proliferation of algae is dominated by a single or a few species.
  - There is a visible accumulation of algae.
What Causes Algal Blooms?

Many environmental factors influence the occurrence of algal blooms. In general, an algal bloom indicates an ecosystem imbalance.
What Makes Some Algal Blooms Harmful?

Harmful algal blooms (HABs) can occur anytime water use is impaired due to excessive accumulations of algae.

- Ecologic Concerns
- Economic Concerns
- Public Health Concerns

Texas – golden algae bloom
Photo courtesy of TPWD and G. Turner

Kansas – cyanobacterial bloom
**What Cyanobacteria Produce Toxins and Taste-and-Odor Compounds?**

<table>
<thead>
<tr>
<th></th>
<th>Hepatotoxins</th>
<th>Neurotoxins</th>
<th>Dermatoxins</th>
<th>Taste/Odor</th>
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<tr>
<td></td>
<td>CYL</td>
<td>MC</td>
<td>ANA</td>
<td>SAX</td>
</tr>
<tr>
<td>Anabaena</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Aphanizomenon</td>
<td>X</td>
<td>?</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Microcystis</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oscillatoria/Planktothrix</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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</tbody>
</table>

Photos courtesy of A. St. Amand

After Graham and others, 2008, TWRI Chapter 7.5
http://water.usgs.gov/owq/FieldManual/
How Toxic Are Cyanotoxins?

- **Acute Toxicity**
  - Neurotoxic
  - Hepatotoxic
  - Dermatoxic

- **Chronic Toxicity**
  - Carcinogen
  - Tumor Promotion
  - Mutagen
  - Teratogen
  - Embryolethality
  - Neurodegenerative Diseases

After Chorus and Bartram, 1999
Are There Regulations for Cyanotoxins?

World Health Organization provisional guidelines for microcystin-LR

- Finished Drinking Water (Chronic Effects): 1 µg/L
- Recreational Areas (Acute Effects)
  - Low Risk: <10 µg/L
  - Moderate Risk: 10-20 µg/L
  - High Risk: 20-2,000 µg/L
  - Very High Risk: >2,000 µg/L

“Algae may make for stinky water, but it poses no health risks”

-Concord Monitor, Concord, NH July 7, 2006

http://www.who.int/water_sanitation_health/dwq/chemicals/microcystinsum.pdf
How Common Are Toxic Cyanobacterial Blooms?

After Graham and others, 2009
Cyanobacterial Harmful Algal Blooms

**Fundamental Research Goals**

- Gain mechanistic understanding of the factors influencing the occurrence, fate, and transport of cyanobacterial toxins and taste-and-odor compounds.
- Gain understanding of temporal and spatial variability in toxin and taste-and-odor occurrence.
- Develop predictive models for occurrence, fate, and transport that can be used as decision making tools.

*Elysian Lake, Minnesota*
Consistent Guidelines for Study Design and Sample Collection are Essential for Nationally Comparable Data

SIR 2008-5038 Guidelines for Design and Sampling for Cyanobacterial Toxin and Taste-and-Odor Studies in Lakes and Reservoirs (Graham and others)

http://pubs.usgs.gov/sir/2008/5038

USGS National Field Manual Chapter 7.5 Cyanobacteria in Lakes and Reservoirs: Toxin and Taste-and-Odor Sampling Guidelines (Graham and others)

http://water.usgs.gov/owq/FieldManual/Chapter7/7.5
Robust and Quantitative Analytical Methods are Essential to Adequately Characterize Cyanotoxin Occurrence, Fate, and Transport

USGS Organic Geochemistry Research Laboratory

- Enzyme-Linked Immunosorbent Assays (ELISA)
- LC/MS/MS
- Toxicity Assays

http://ks.water.usgs.gov/researchlab

Ongoing research to evaluate efficacy of:
- Autoclaving
- Boiling
- Freeze-Thaw
- Sonication
- QuikLyse

http://pubs.usgs.gov/of/2008/1341/
New Methods will Enhance Understanding and Characterization of Occurrence, Fate, and Transport

USGS Ohio Microbiology Laboratory

- Molecular qPCR DNA and RNA assays for:
  - Total cyanobacteria
  - Total *Microcystis*
  - *Microcystis*-specific microcystin genes
  - *Anabaena*-specific microcystin genes
  - *Planktothrix*-specific microcystin genes

Prepared in cooperation with the Ohio Lake Erie Commission

Relations Between DNA- and RNA-Based Molecular Methods for Cyanobacteria and Microcystin Concentration at Maumee Bay State Park Lakeside Beach, Oregon, Ohio, 2012

Stelzer and others, 2013

http://dx.doi.org/10.3133/sir20135189
Occurrence

High Microcystin Concentrations (> 1 µg/L) in the 2007 National Lake Assessment Were Most Common in the Upper Midwest

33% of lakes had detections (n=1,028)
Maximum concentration: 230 µg/L
Median: <0.10 µg/L (0.52 µg/L *)
Mean: 1.0 µg/L (3.0 µg/L *)

*Detections only

After Beaver and others, 2014
Cylindrospermopsins Were Detected by ELISA in About 5% (n=659) of Analyzed Lakes; Occurrence was Most Common in the South
Saxitoxins Were Detected by ELISA in About 8% (n=678) of Analyzed Lakes; Occurrence was Most Common in the Upper Midwest and the South.
Microcystins are Widespread and Common in the Midwest

78% of lakes had detections (n=359)
Maximum concentration: 52 µg/L

After Graham and others 2004, 2006, and 2009
Multiple Toxins and Taste-and-Odor Compounds Frequently Co-Occur in Cyanobacterial Blooms

Detectable Toxins/T&O Compounds
- Microcystin - 100% of Lakes (n=23)
- Geosmin - 83%
- MIB - 35%
- Anatoxin-a - 30%
- Saxitoxin - 17%
- Cylindrospermopsin - 9%
- Nodularin - 9%

After Graham and others, 2010
Cyanotoxins and Taste-and-Odor Compounds Co-Occur Less Frequently in Routinely Collected, Non-Bloom Samples

Graham and others, in preparation
Occurrence of Cyanotoxins and Taste-and-Odor Compounds is Not Necessarily Tightly Coupled to Cyanobacterial Abundance or Community Composition

Francy and others, in preparation
Occurrence

**Actinomycetes Bacteria Also May Produce Taste-and-Odor Compounds**

**LAKE HOUSTON, TX**

- Non-summer, water residence time < 100 days
- Summer, water residence time < 100 days
- Non-summer, water residence time > 100 days
- Summer, water residence time > 100 days


After Beussink and Graham, 2011
Genetic Data Help Identify Systems with the Potential for Cyanotoxin Production

Ohio Lakes, Summer 2013

**Microcystis mcyE DNA**

**Planktothrix mcyE DNA**

Francy and others, in preparation
Seasonal Patterns in Microcystin Concentration are Unique to Individual Lakes and Peaks May Occur Anytime Throughout the Year

After Graham and others, 2006
Spatiotemporal Patterns

Vertical Migration or Wind Movement of Surface Accumulations May Rapidly Change the Spatial Distribution of Cyanobacteria

Rock Creek Lake, Iowa
2006 Beach Closure Event

Beach Area
Monday
July 31

Photo Courtesy of IA DNR

Photo Courtesy of IA DNR

Beach Area
Thursday
August 3

Boat Ramps
Friday
August 11

Photos Courtesy of IA DNR
Spatiotemporal Patterns

Vertical Migration or Wind Movement of Surface Accumulations May Rapidly Change the Spatial Distribution of Cyanobacteria

Rock Creek Lake, Iowa
2006 Beach Closure Event

WHERE DID THE CYANOBACTERIA GO?

Most likely explanation is redistribution in the water column

Photos Courtesy of IA DNR
Spatiotemporal Patterns

Satellite (and Other Aerial) Imagery Captures Spatial Variability Across an Entire Lake Surface

Absorption by phycocyanin c. 625 nm

Absorption by chlorophyll-a c. 680 nm

Cheney Reservoir, KS
July 2014 HICO Imagery
Spatiotemporal Patterns

Ground Truth Data Are Required to Develop Models to Estimate Cyanobacterial Abundance Using Satellite Imagery

Cheney Reservoir, KS
June 2014
Cyanobacteria and Associated Compounds May Vary Longitudinally in Reservoirs Due to Gradients in Water-Quality and Hydrologic Conditions

Cheney Reservoir
August 30, 2013

Geosmin (ng/L)
Microcystin (µg/L)
Cyanobacterial Biovolume (mm$^3$/mL)

Downstream

Cheney 41
Cheney 33
Cheney 27
Cheney 23
Cheney 9
Cheney 4
Genetic Data Improve Understanding of Spatiotemporal Gradients Observed in Cyanobacteria and Associated Compounds

Spatiotemporal Patterns

- 7% of BV Anabaena
- 85% of BV Anabaena
- ~100% of BV Anabaena
- 58% of BV Microcystis
- 15% of BV Microcystis
- <1% of BV Microcystis
Spatiotemporal Patterns

Cyanobacterial Toxins and Taste-and-Odor Compounds May Be Transported for Relatively Long Distances Downstream from Lakes and Reservoirs

Milford Lake release sends algae to Kansas River
MARIA SUDEKUM FISHER, Associated Press
Published 09:10 p.m., Wednesday, September 21, 2011

SEPTEMBER 8, 2011

http://pubs.usgs.gov/sir/2012/5129/
Downstream Transport and In Situ Production May Both Contribute to Observed Cyanotoxin and Taste-and-Odor Compound Concentrations

Municipal Reservoir #1, Spartanburg County, SC


After Journey and others, 2011
Globally, Microcystin Occurs in Lakes of All Trophic Status, But Occurrence and Concentration Increase with Trophic Status

Environmental Influences

After Harris and others 2014
Regional Associations Between Microcystin and Environmental Variables May Not Be Linear

After Graham and Jones, 2009
There is No Single Environmental Variable that is Consistently Associated with Microcystin Occurrence and Concentration

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Strongest Correlate</th>
<th>$r_s$</th>
<th>p-value</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilby</td>
<td>Conductance</td>
<td>-0.86</td>
<td>&lt;0.01</td>
<td>48</td>
</tr>
<tr>
<td>Forest</td>
<td>Chlorophyll &gt; 35 µm</td>
<td>0.67</td>
<td>&lt;0.01</td>
<td>49</td>
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<tr>
<td>Harrison</td>
<td>Total Nitrogen</td>
<td>0.78</td>
<td>&lt;0.01</td>
<td>49</td>
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<tr>
<td>Marceline</td>
<td>Dissolved Organic Carbon</td>
<td>0.66</td>
<td>&lt;0.01</td>
<td>49</td>
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<tr>
<td>Mozingo</td>
<td>Magnesium</td>
<td>-0.84</td>
<td>&lt;0.01</td>
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<tr>
<td>Nodaway</td>
<td>Nitrate</td>
<td>-0.46</td>
<td>&lt;0.01</td>
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<tr>
<td>Paho</td>
<td><em>Ceriodaphnia</em> abundance</td>
<td>0.81</td>
<td>&lt;0.01</td>
<td>28</td>
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<tr>
<td>Sterling</td>
<td>Sodium</td>
<td>0.60</td>
<td>0.03</td>
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</table>
Environmental Influences

Thresholds and Probabilities May Better Define Relations Between Environmental Variables and Microcystin Occurrence and Concentration and Provide Insight into Potential Management Scenarios

After Harris and others 2014
Environmental Influences

Thresholds and Probabilities May Provide Insight into Potential Management Scenarios

After Harris and others 2014
Environmental Influences

Seasonal Patterns and Environmental Influences May Be Relatively Consistent Between Years in Some Lakes

Cheney Reservoir, KS 2001-2012

- Geosmin
- Microcystin
- Cyanobacteria

Median Normalized Values

Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec
Environmental Influences

Continuous Water-Quality Monitors Can Be Used to Develop Models to Compute Microcystin and Geosmin Concentrations in Real Time

- Recorded and transmitted hourly

- Data available online:
  - http://nrtwq.usgs.gov/ks

- Develop relations to estimate concentrations of variables that cannot be measured in real time
Environmental Influences

The Logistic Regression Model for Probability of Microcystin Concentrations > 0.1 µg/L in Cheney Reservoir Includes a Seasonal Component and Chlorophyll as Explanatory Variables

Model Form:

\[ PMC = \frac{e^{-1.305 - 1.99 \sin(2\pi D / 365) - 1.34 \cos(2\pi D / 365) + 0.0511 TCHN}}{1 + e^{-1.305 - 1.99 \sin(2\pi D / 365) - 1.34 \cos(2\pi D / 365) + 0.0511 TCHN}} \]

where:
- PMC is computed probability of microcystin, in > 0.1 µg/L
- D is day of year, in the range of integers 1 through 365
- TCHN is total chlorophyll, in micrograms per liter as chlorophyll

http://nrtwq.usgs.gov/ks

Environmental Influences

Anomalous Events, Such as Large Summer Inflows, May Disrupt Typical Seasonal Patterns

Cheney Reservoir
January-December 2013

- Geosmin (ng/L)
- Microcystin (μg/L)
- Reservoir Storage (acre-feet)

USGS science for a changing world
Environmental Influences

Isotope Data Can Help Understand Sources of Nutrients Being Utilized By Cyanobacterial Communities

NO₃ uptake will typically plot here- POM about 4‰ lighter than NO₃.

POM samples have heavier δ¹⁵N in comparison to NO₃.
Genetic Data Can Help Understand Biological Drivers of Cyanobacterial Community Dynamics

Initial Assessment of Potential Cyanobacterial Predators in Cheney Reservoir, KS

<table>
<thead>
<tr>
<th>Genera</th>
<th>Rank Abundance</th>
<th>Genera</th>
<th>Rank Abundance</th>
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<tbody>
<tr>
<td>Predatory bacteria</td>
<td></td>
<td>Chyrid fungi</td>
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<tr>
<td><em>Flavobacterium</em></td>
<td>23</td>
<td><em>Batrachoxytrium</em></td>
<td>386</td>
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<tr>
<td><em>Saprospira</em></td>
<td>167</td>
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<tr>
<td><em>Cytophaga</em></td>
<td>184</td>
<td><em>Protozoans</em></td>
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<tr>
<td><em>Sorangium</em></td>
<td>200</td>
<td><em>Naegleri</em></td>
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<td><em>Bdellovibrio</em></td>
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<td><em>Dictyostelium</em></td>
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<td><em>Mycococcus</em></td>
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<td><em>Acanthamoeba</em></td>
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<td><em>Bacteriovorax</em></td>
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<td><em>Entamoeba</em></td>
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<td><em>Stigmatella</em></td>
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<td>1295</td>
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<td><strong>Metazoans</strong></td>
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<td>Unclassified Myoviridae</td>
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<td><em>Daphnia</em></td>
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<td>T4-like Myoviridae</td>
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<td><em>Nematostella</em></td>
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<td><em>Harpegnathos</em></td>
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<td>Unclassified Siphoviridae</td>
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<td><em>Columba</em></td>
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<td><em>Acythosiphon</em></td>
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<tr>
<td>Unclassified dsDNA Phages</td>
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</table>
Conclusions

• Cyanobacterial blooms and associated toxins and taste-and-odor compounds commonly occur throughout the United States.

• Several relatively new approaches are available to help describe the spatiotemporal variability and environmental factors driving the occurrence of cyanobacterial blooms and associated compounds.

• Much more study is needed to develop reliable means of predicting and responding to cyanobacterial blooms to ensure public health protection.
Additional Information:

http://ks.water.usgs.gov/cyanobacteria/

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