Improving the Lake Erie HAB Tracker:
A Forecasting & Decision Support Tool
for Harmful Algal Blooms

By

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Abstract

This Master's Project sought to improve the performance, data display and utility of the Lake Erie HAB Tracker model for predicting the location and movement of harmful algal blooms (HABs) in western Lake Erie. These improvements will benefit stakeholders by allowing public water systems to prepare for HAB events and by allowing anglers and boaters to avoid affected locations. Specifically, this research addressed three topics: 1) *Microcystis* colony rising/sinking (buoyant) velocity, a parameter in the HAB Tracker model, was measured using an improved method. Statistical relationships were obtained between buoyant velocity and environmental variables, showing lower buoyancy associated with greater light exposure, smaller colony size and deficient nutrient levels. 2) Model skill was assessed in comparison to satellite-derived HAB distributions using a neighborhood-based spatial smoothing method. We found that model skill was improved after spatial smoothing using a 3-km neighborhood. 3) We conducted a series of focus group interviews with Lake Erie fishing charter captains and recreational anglers to evaluate perceptions of HABs and the HAB Tracker. Our results indicated that the majority of anglers seek to avoid fishing in HABs, but that beliefs vary regarding the impact of HABs on fish and human health. We determined that anglers may find the HAB Tracker to be useful, but we recommend specific changes to improve the presentation of information on the HAB Tracker web site to make it more accessible. We also recommend improved content and methods of communication to better reflect angler concerns and interests.

Acknowledgements

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Chapter 1: Introduction

1.1 Harmful Algal Blooms in Lake Erie

1.1.1 Background

Lake Erie is the smallest of the Great Lakes by volume (484 km^3), and the shallowest (GLIN, 2017). The Lake Erie shoreline borders two countries (the United States and Canada), four U.S. states (Michigan, Ohio, Pennsylvania, and New York) and the Canadian province of Ontario. It is also the warmest and the most biologically productive. Although Lake Erie is more naturally productive than the other Great Lakes, eutrophication has progressed since settlement of the region (Han et al., 2012).

In the 1960s and 1970s, algal blooms proliferated in the Western Basin of Lake Erie, severely degrading water quality. These blooms were the result of increased cultural phosphorus loading, and were successfully decreased largely by limiting municipal and industrial point sources (Makarewicz and Bertram, 1993). In the 1970s, successful policy initiatives, such as the Clean Water Act and Great Lakes Water Quality Agreement, were enacted to reduce total phosphorous levels in Lake Erie allowing the water quality of the lake to improve (Clean Water Act, 1972; GLWQA, 1972).

Since the mid-1990s, Lake Erie has experienced a resurgence of algal blooms, particularly in the western basin (Brittain et al., 2000; Stumpf et al., 2012; Michalak et al., 2013). Surprisingly, total phosphorous loads have remained relatively stable since the 1980s, although levels of biologically available phosphorous or dissolved reactive phosphorous (DRP) have increased since the 1990s (Richards et al., 2010; Richards, 2006). Recent bloom events have been linked to this increase in DRP, and attributed to phosphorous loading from agricultural non-point sources primarily from the Maumee River (Michalak et al., 2013).

Recent open-lake blooms are predominantly composed of *Microcystis,* a cyanobacterium that can produce a group of toxins called microcystins. These blooms are termed harmful algal blooms (HABs), because of the toxins they can produce. *Microcystis* forms blooms in many nutrient-rich waterbodies world-wide (Harke et al., 2016). The invasion of *Dreissenid* mussels to Lake Erie in the 1990s has contributed further to the recent proliferation of HABs. *Dreissenids* employ selective filter feeding behavior by which they avoid toxic *Microcystis* and favor the consumption of non-toxic phytoplankton, eliminating these other organisms as resource competitors of *Microcystis* (Vanderploeg et al., 2001).

The increasing size and frequency of HABs are of concern to communities surrounding Lake Erie, because the microcystins produced by the blooms are hepatotoxins, a substance that can cause damage to liver tissue. Human health is at risk when water contaminated with microcystins is ingested or exposed to the skin, for example during recreational activities in Lake Erie. In several cases, the recreational use of contaminated water has been linked to human illness with symptoms including fever, headache, stomach cramps, vomiting and weakness (Carmichael and Boyer, 2016). Recreational activities, such as swimming, can also lead to allergic responses including irritation to the skin, eye, and throat (W.H.O., 1999). However, skin contact with microcystin poses a smaller threat to human health than ingestion, because absorption of the toxin through the skin is unlikely.

Exposure to microcystin through the consumption of drinking water presents greater health risks. People who have consumed contaminated drinking water have experienced a headache, sore throat, nausea and vomiting (Carmichael, 2001). In severe cases, chronic microcystin exposure can result in liver injury or acute liver failure (Li et al., 2007; EPA, 2015). When people ingest food that may be contaminated with microcystin, such as algae tablets, fish, or duck, they may also be at risk (Gilroy et al., 2000)).

The presence of microcystin also poses risks for wildlife and the environment. Microcystin can decrease the abundance and richness of macro-invertebrate communities (White et al., 2005), poison pets, livestock, and wild animals (Oberholster et al., 2009), and also contribute to fish kills during bloom seasons (Whitton, 2012). Researchers have determined that microcystin negatively impacts the health of fish (Chorus and Bartram, 1999). In a laboratory setting where tilapia and trout were exposed to microcystin, damage occurred to the gills of the fish (Garcia, 1989). Laboratory studies also indicated that dissolved microcystin might be harmful to fish embryos (Oberemm et al., 1997). The most definitive effect of microcystin on fish was a gradual degeneration of the liver in salmon smolts placed in open water contaminated with the microcystin in the coastal waters of British Columbia and Washington State, USA. This damage resulted in significant economic losses for the fishing industry of 170 tons of production worth approximately $245,000 (Treasurer et al., 2003).

Continued HAB occurrences are likely to cause substantial economic losses for the fishing industry. Anglers spend approximately $2 billion annually in Ohio to fish Lake Erie (Great Lakes Commission, March 2014). Lake Erie is known as the walleye capitol of the world, and is renowned for its exceptional fishing opportunities. Losses to this industry as a result of HABs could be as much as $2.4 million (Binghman et al., 2015). In a 2014 survey of Lake Erie recreational anglers, 96% of 533 respondents indicated that they were aware of HABs and 65% reported that their fishing behavior changed as a result of HABs on Lake Erie (Lake Erie Protection Fund, 2014). The Ohio charter fishing industry was valued at approximately $67 million in 2013 (Lake Erie Protection Fund, 2014). For the past several years, the size of the charter fishing industry on Lake Erie has declined (Lucente et al., 2010). Captains attributed this decline to increasing operator costs, declining fish numbers, and the impact of non-native invasive species on the lake system. The presence of HABs within Lake Erie is likely to exacerbate problems facing the Lake Erie fishing industry.

Additional economic losses may be incurred through future incidents of drinking water contamination. Over eleven million people rely upon Lake Erie as a source of drinking water (US EPA, 2016). In 2014, the drinking water system for the city of Toledo was contaminated with microcystin. As a result, a “do not drink” order was issued, creating a water shortage among those dependent upon Toledo’s water supply, including private citizens and industry. Over $200,000 was spent per month for extra carbon treatment at public water systems to recover the drinking water system in Toledo (Ohio EPA, 2014). In a 2015 report funded by the International Joint Commission, it was estimated that the 2014 HAB event resulted in a $64 million loss in benefits. Future economic losses due to HABs are projected to impact recreation, tourism, commerce, real estate, agriculture, and local municipalities within the surrounding region. Costs to recover threatened and endangered species and remediate water quality damages, such as those caused by HABs, may be significant (Dodds et al., 2008).

1.1.2 Factors Affecting the Buoyancy and Growth of *Microcystis*

In waters where cyanobacteria occur, there are several environmental factors as well as physiological features of the organisms that affect the scale and severity of algal blooms. *Microcystis* is a prokaryotic cyanobacterium. Cyanobacteria are found in aquatic environments throughout the globe, and produce the phycobiliproteins, phycocyanin and phycoerythrin. When cyanobacterial cells are present in high concentration, the phycocyanin creates a bluish color, which accounts for the more common name, blue-green algae. Light intensity, temperature, the nitrogen to phosphorus ratio (TN/TP, DIN/DIP, etc.), photoperiod, and buoyancy control (Huisman et al. 1999a; Wang et al., 2009) can be driving factors of the blooms. In temperate regions, the typical annual cycle of *Microcystis* includes the growth of blooms during the summer, population decrease in the autumn, overwintering on the bottom of the water body, and reintroduction into the water column in the spring. This seasonal cycle could not happen without constant buoyancy regulation within *Microcystis* colonies.

Buoyancy plays a crucial role in the vertical distribution of *Microcystis* in water bodies. Blooms of *Microcystis* in temperate regions occur within the photic zone during the summer, but vertical migrations throughout the whole water column also occur. Buoyancy of Microcystis colonies depends on factors causing changes in the volume fraction of gas vesicles within cells (Thomas and Walsby, 1985b), as well as the amount of proteins and carbohydrates produced (Kromkamp and Mur, 1984). Gas vesicles are filled with gases including H_2, N_2, and O_2. Their primary function is to respond to changing environmental conditions in the water column and enable the buoyancy of *Microcystis* colonies (Walsby, 1972). In *Microcystis* cells, carbohydrates are important products of photosynthesis, and they provide a counteracting effect on the buoyancy provided by gas vesicles by increasing the specific gravity of the cells (Thomas and Walsby, 1985a). *Microcystis* need sunlight and abundant nutrients for photosynthetic processes. For this reason, light and nutrient levels are believed to influence the interactions between carbohydrates, gas vesicles, and the buoyant behavior of *Microcystis* colonies, although this relationship has not been shown for *Microcystis* in Lake Erie.

A better understanding of the vertical distribution of *Microcystis* can help to improve the estimation of bloom biomass from satellite observations in order to detect blooms and to improve predictions of their transport. According to toxicology studies on *Microcystis*, the highest toxin concentrations occur in surface scums in the water bodies (Puddick et al., 2016; Brian, 2012; Wicks and Thiel, 1990). The formation of the scum and transport of *Microcystis* are controlled by the balance between vertical mixing of the water column and the buoyancy of the colonies (Wang et al., 2009; Vincent et al., 2004).

1.2 HAB Tracker forecast model

In 2008, NOAA began using high resolution satellite imagery from the Medium Resolution Imaging Spectrometer (MERIS) and the Moderate-resolution Imaging Spectroradiometer (MODIS) to further their research on cyanobacterial blooms in Lake Erie (Wynne and Stumpf, 2010). Building upon these monitoring data, a forecast of bloom distribution and movement was developed in 2009 using a Lagrangian particle forecast model (Wynne and Stumpf, 2011). In subsequent years, the forecast was disseminated, along with other information on the bloom status, in the format of a web-based bulletin called the Lake Erie HAB Bulletin (Wynne and Stumpf, 2013), which was produced approximately twice weekly during the HAB season, or when a cloud-free satellite image was available. The Lake Erie HAB Bulletin compiles the latest information on the status of the bloom, including an estimate of the current distribution of the HAB according to the latest satellite image, a three-day forecast of HAB transport, as well as the wind speed and current movements.

In an effort to provide additional finer resolution HAB forecasts, the HAB Bulletin modeling methods were further developed into the Lake Erie HAB Tracker model, which was introduced in 2014. The HAB Tracker provides a nowcast and five-day forecast of concentration and physical transport of cyanobacteria in Lake Erie. The short-term forecasts can be utilized by stakeholders, such as municipal water managers, anglers, recreational boaters, and beach managers, to make to mitigate or avoid adverse impacts of HABs. The HAB Tracker is an experimental model, which has been further developed each season to improve model accuracy and accessibility. In 2016, the HAB Tracker model updates included a three-dimensional forecast simulating the vertical distribution of *Microcystis* using a Lagrangian particle model forced using daily updates of currents and turbulent diffusivity from the Finite Volume Community Ocean Model (FVCOM) (Rowe et al, 2016).

To evaluate and improve the model skill, it is necessary to assess the accuracy of the model through hindcast skill assessment. The hindcast compares the model's predictions to satellite images of bloom events occurring on the same day to evaluate prediction accuracy. In a hindcast method used by Wynne et al (2013), output of the model was compared to observed data in terms of the bloom centroid (geographical weighted mean) as well as the number of pixel points that are marked as likely having cyanobacteria concentration. This method traced the movement of the HAB, but was limited to the use of cloudless remote-sensing images. Subsequently, Rowe et al. (2016) developed a method to assess the HAB Tracker model using the Pierce Skill Score, which compared the model and the observation pixel by pixel. This method was more tolerant of partially cloud-covered images, but may underestimate the usefulness of the model when the shape of the HAB does not exactly match the observation, even though the HAB is approximately in the right place. Therefore, further work is needed to develop additional model evaluation approaches that are more representative of the actual utility of the forecast to users.

The HAB Tracker is typically updated daily from July to October, and can be accessed through the National Ocean and Atmospheric Administration's Great Lakes Environmental Research Laboratory (NOAA-GLERL) Great Lakes HABs and Hypoxia website: https://www.glerl.noaa.gov//res/HABs_and_Hypoxia/habTracker.html. The HAB Tracker model was developed as a joint effort of NOAA-GLERL and University of Michigan Cooperative Institute for Limnology and Ecosystems Research (CILER). Development of the HAB Tracker model was funded Great Lakes Restoration Initiative through the US Environmental Protection Agency and NOAA.

1.3 Research Approach

This research investigated three means by which to improve the HAB forecast model:

1) Establish a relationship of *Microcystis* buoyancy as a function of colony size, light exposure and nutrient conditions by direct measurement of *Microcystis* colony buoyant velocities.

2) Evaluate the Fractions Skill Score (FSS) method as a means to improve quantification of the HAB Tracker model's prediction accuracy in the presence of spatial mismatch between simulated and observed HAB location.

3) Assessing the utility of the HAB Tracker model for Lake Erie anglers, while exploring the information and tools that anglers use for decision-making in the presence of HABs through a series of focus-group studies.

Chapter 2: *Microcystis* Buoyancy

2.1 Background

Understanding the factors that control vertical distribution of *Microcystis* is important for improving satellite-derived estimates of bloom biomass and for predicting the transport of blooms. The Lake Erie HAB Tracker model includes a random-walk vertical mixing model that considers water turbulence and buoyancy. To improve the existing HAB Tracker model, it is crucial to learn more about the factors that influence the vertical migration of *Microcystis* in western Lake Erie. This vertical migration within the water column is caused mainly by changes in the specific gravity of *Microcystis* colonies, and resulting changes in buoyant velocity.

Microcystis buoyancy is significantly affected by external factors including physical factors such as light intensity and chemical factors such as nutrient availability (Thomas and Walsby, 1985b; Kromkamp and Mur, 1984). *Microcystis* colonies present in surface water were less buoyant during the day and more buoyant at night (Ibelings et al. 1991; Medrano et al. 2013), because of the accumulation of carbohydrate during the day due to photosynthesis and loss of carbohydrate at night due to respiration (Oliver and Walsby, 1984). Nutrient availability also influences *Microcystis* buoyancy by affecting the health of *Microcystis* cells (Kromkamp and Mur, 1984; Thomas and Walsby, 1985a). While present in a nutrient-deficient environment, *Microcystis* cells are observed in irregular shapes with limited ability to produce gas vesicles, the major driver of positive buoyancy, or carbohydrates, the major source of negative buoyancy (Walsby, 1972; Thomas and Walsby, 1985a). Carbon (C), nitrogen (N) and phosphorus (P) are the most useful elements for indicating the nutrient status of phytoplankton. The nutrient deficiency levels of different environments are indicated by stoichiometry of different seston C, P, N molar ratios (Hecky et al., 1993). Comparisons between dissolved and particulate nutrient measurements and these ratios can indicate whether the cells are in a nutrient deficient condition or if the cells are healthy. For example, total dissolved phosphorus (TDP) is an indicator of nutrient abundance in lake water, and the particulate phosphorus (PP) may be assumed to represent the nutrient levels of *Microcystis* itself, if *Microcystis* is the main form of particulate matter in the sample under bloom conditions.

Physical and chemical external factors affect the buoyancy of *Microcystis* by influencing the size and density of colonies (Nakamura et al., 1993). According to Stoke's law, when the force by gravity (the difference between weight and buoyancy) of a particle balances with the fluid drag force, the particle reaches its terminal velocity, *V*:

$$V = \frac{2}{9}\frac{(\rho_p - \rho_f)}{\mu} g R^2 \tag{2.1}$$

In equation (2.1) above, g is the gravitational acceleration constant (9.8 m s^{-2}), μ is the dynamic viscosity of the fluid (kg m^{-1} s), ρ_p and ρ_f are the mass density (kg m^{-3}) of the particle and the fluid, respectively, and R is particle radius. If particle motion is described by Stoke's law, we would expect a log-log plot of velocity versus particle diameter to produce a straight line for a given condition with a slope of two in a quiescent fluid (water); if, on the other hand, particle motion is controlled by turbulence, we would expect to see no relationship between velocity and particle diameter.

In the study by Nakamura et al. (1993), the relationship between *Microcystis* velocity and colony size was obtained in samples collected from a lake in Japan. In 1993, Nakamura et al. used a microscopic video camera and recorder, while a photographic method (Tambo and Watanabe, 1967, 1979; Reynolds, 1973) and multi-exposure photographic method (Li and Ganczarczyck, 1987) were previously employed to analyze characteristics of vertical movement. In 2015, Kevin Kijanka (a Summer Fellow at NOAA-GLERL) measured buoyant velocities of *Microcystis* colonies in Lake Erie using a videographic method similar in many respects to that of Nakamura et al. (1993). Both results show a consistent fit with the linear relationship in a log-log plot between *Microcystis* velocity and diameter (Figure 2.1). Other than colony diameter, density of gas vesicles within cells, density of the colony, and the shapes of *Microcystis* colonies are also factors that might affect this relationship (Thomas and Walsby, 1985b; Kromkamp and Mur, 1984; Nakamura et al., 1993).

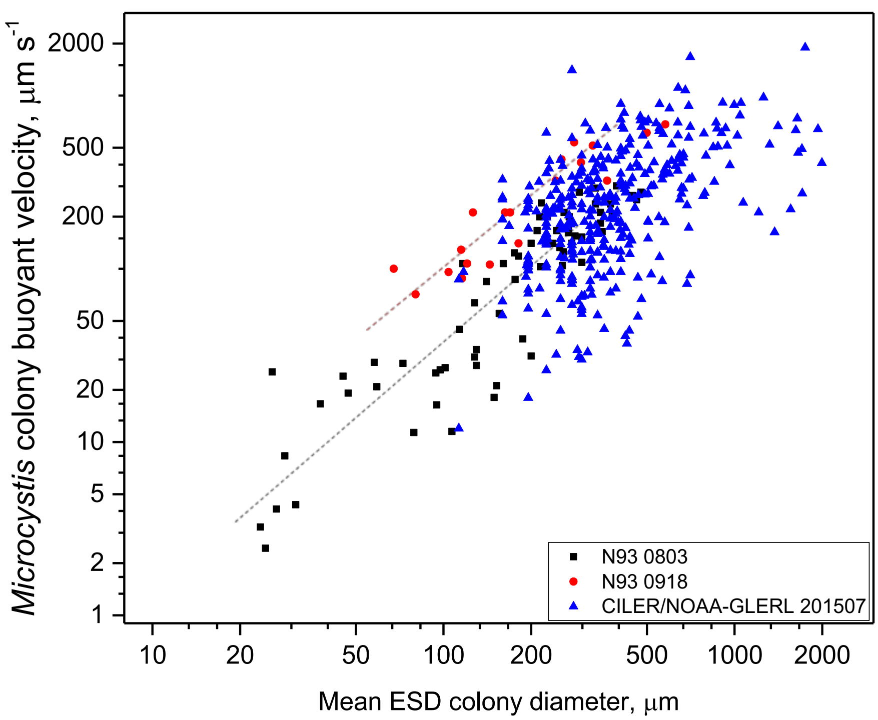

Figure 2.1 Relationship between *Microcystis* colony buoyancy and mean colony equivalent spherical diameter (ESD). Figure reproduced from Rowe et al. (2016). The velocity data were collected from Lake Erie sample in July 2015 and data points digitized from Nakamura et al. (1993, Figure 3. N93 0803 and N93 0918 represent the data collected on Aug 3rd and Sep 19th in 1993).

2.2 Research Objectives & Hypotheses

To improve the ability of the HAB Tracker model to predict the vertical distribution of *Microcystis* in western Lake Erie, this research aimed to:

1) Refine methods to measure buoyant velocities for *Microcystis* colonies over a range of sizes.
2) Develop a predictive relationship of *Microcystis* buoyancy as a function of light exposure and colony size.
3) Determine effects of nutrient on *Microcystis* buoyancy and growth rate.

Based on these objectives, the following hypotheses were tested:

1) If prolonged exposure to light during the day has a negative effect on *Microcystis* buoyancy, then buoyant velocity values of *Microcystis* colonies will be lower in the late afternoon for a given colony diameter and, conversely, higher in the early morning;
2) Buoyant velocities will decrease in response to nitrogen and phosphorus deficiency in Lake Erie. Nutrient deficiency will be indicated by an unbalanced N/P cell quota in the form of particulate C: P, C: N and N: P values nutrient deficient ranges indicated by Hecky et al. (1993).

To test these hypotheses, novel videographic methods were used in this study to determine effects of light intensity and colony size on the buoyant velocities of *Microcystis* colonies collected from western Lake Erie. We incubated whole water samples in an outdoor incubator maintained at ambient lake temperatures. Light levels were varied to represent day and night conditions for a surface scum or turbulent mixed layer distributions. After an overnight adaptation to ambient light and temperature conditions, we measured buoyant velocities of water taken from the bottles in the morning and late afternoon.

2.3 Methods

2.3.1 Water Sample Collection and Processing

Water samples containing *Microcystis* were collected weekly from July to October 2016 from Lake Erie by University of Michigan CILER and NOAA-GLERL at eight different monitoring stations distributed throughout the western basin (Figure 2.2). Five of the stations were nearshore (WE 02, 06, 08, 09, 12), while the other three (WE 04,13,15) were offshore. We used water collected at a site where *Microcystis* was most abundant on a given date; therefore, site location varied from experiment to experiment.

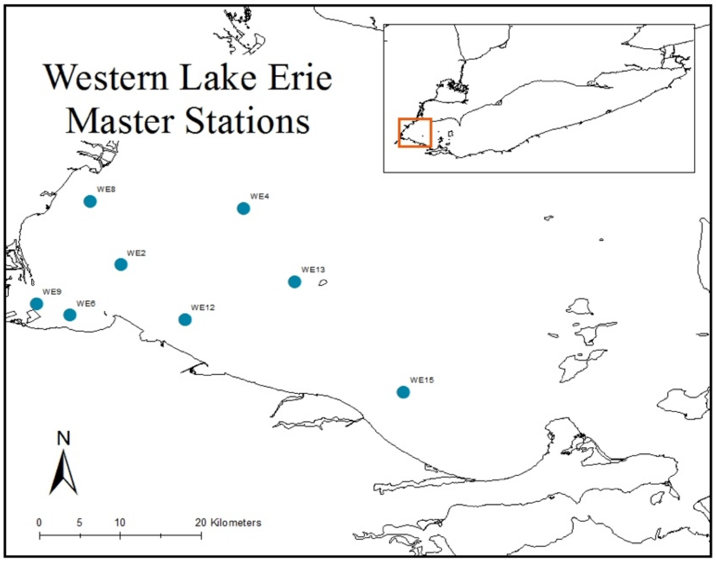

Figure 2.2 Western Lake Erie Monitoring Stations (NOAA-GLERL & CILER)

Microcystis samples were collected with 5-L Niskin bottles from three discrete depths in the water column: surface scum (if present), 1m below the surface, as well as 1m above the lake bottom in the late morning or early afternoon and poured into 4-L polyethylene bottles for transport to the laboratory in an insulated cooler. Upon arrival in the laboratory around 1600 hrs., equal-part mixtures of scum (if present), surface, and bottom samples were combined and placed in 2.3-L clear and shaded bottles in a temperature controlled outdoor tank open to ambient light climate as described below. Also upon arrival, water samples were filtered for nutrient analyses (dissolved and particulate carbon, nitrogen and phosphorus). Analytical methods were described by Vanderploeg et al. (2017).

Microcystis concentration in the sample bottles was quantified as chlorophyll concentration, and was measured using FluoroProbe (BBE Moldaenke), a fluorometer with algae class differentiation. Additionally, to test cellular health conditions, growth rates of *Microcystis* colonies (*r*) were calculated using initial and final particulate organic carbon (POC) measured in sample bottles: $r = 1/t*ln(C_t/C_o)$, where *r* is the growth rate, *t* is elapsed time in days, C_0 and C_t are the POC concentrations at time 0 and *t*. The initial POC was measured at 0900 hrs. on the next day after sample arrival, and final POC was measured 24 hours after the initial measurements, which makes $t = 1$ *day* and $r = ln(C_t/C_o)$.

2.3.2 Buoyancy Experimental Setup

An outdoor incubator tank was used to simulate Lake Erie temperature and incident light exposure conditions. The insulated incubator tank (120cm long × 61cm wide × 60 cm height) was filled with tap water. A temperature control system (Cole Parmer, Polystat) was used to maintain the temperature in the tank to match the in-situ water temperature when samples were collected from the lake. Light received by the samples in the tank was quantified as Photosynthetically Active Radiation (PAR). PAR was measured by two sensors, one down-welling PAR sensor (LI-COR, LI-190R Quantum Sensor) beside the tank and one spherical PAR sensor (LI-COR, LI-192 Underwater Quantum Sensor) mounted under water in the tank.

We incubated 2.0-L *Microcystis* lake water samples in two 2.3-L borosilicate media bottles. One sample bottle was clear allowing for incident light exposure, which represented the surface water conditions. The other bottle was wrapped with 0.9 neutral density (ND) filter (*LEE Filters 48" x 25' CL211 Gel Roll, 12.5%)*, creating an actual 11.8% PAR transmittance measured by inserting the downwelling PAR sensor into the bottle (Figure 2.3) for mixed layer light condition.

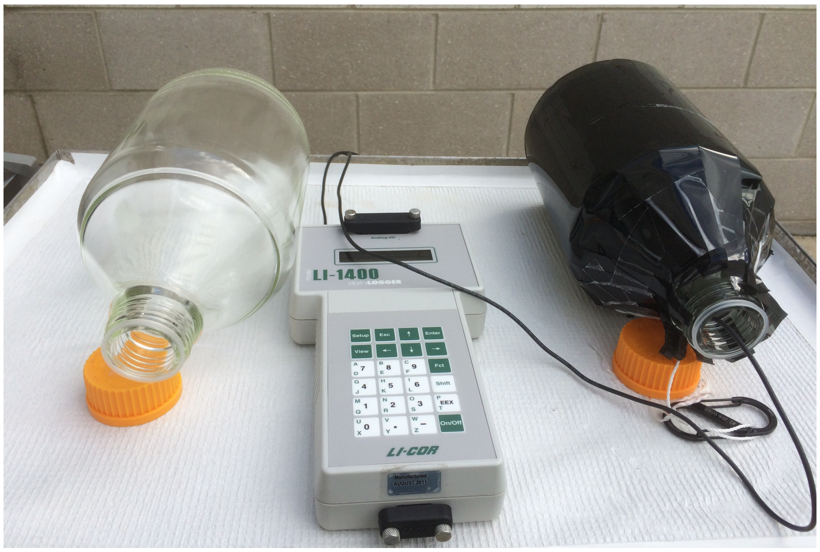

Figure 2.3 Measuring PAR transmittance of clear and shaded borosilicate media bottles. The one on the left is a regular bottle, the one on the right is wrapped with 0.9 ND filter.

The neutral-density filter was used to simulate light exposure representative of phytoplankton in a turbulent surface mixed layer in comparison with light conditions representative of surface scum conditions. The mean mixed layer irradiance as a percentage of surface irradiance ($\%I_{zm}$) was calculated as a function of euphotic zone depth and surface mixed layer depth based on methods used by Fahnenstiel et al. (2000). The typical light attenuation coefficient for photosynthetically active radiation (K_{par}) in western Lake Erie is 0.5 to 1.5 m^{-1} (Odonnel et al., 2010), and the mixed layer depth of sampling stations in Lake Erie ranges from 4 m to 8 m (Figure 2.4; Table 6.1.1, Appendix I). A neutral-density filter was applied to one of the sample bottles in this study to obtain 12% of surface irradiance, representing a relatively low level of light exposure for phytoplankton in a western Lake Erie surface mixed layer.

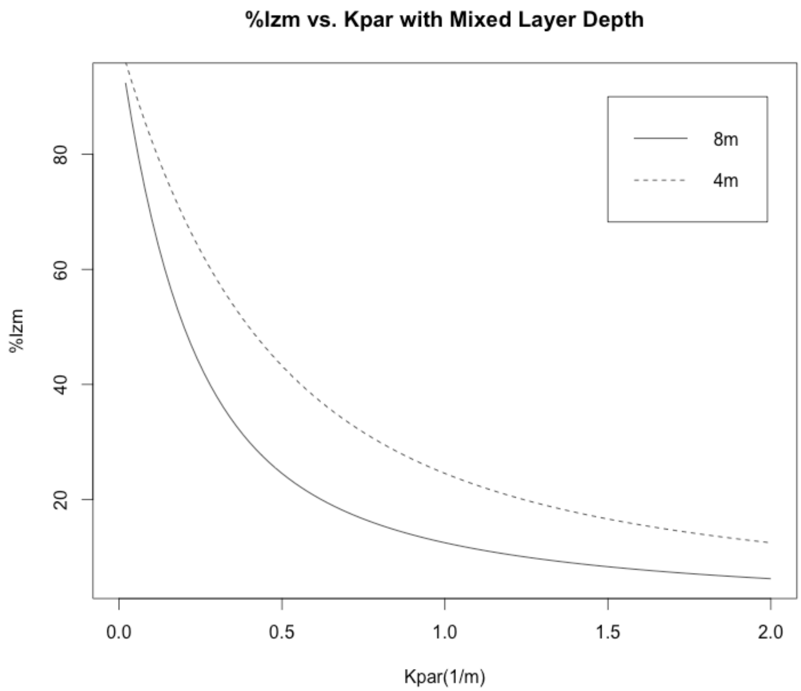

Figure 2.4 Mean mixed-layer irradiance as a percentage of surface irradiance, $\%I_{zm}$, with mixed layer depth (z_m) ranging from 4 m to 8 m (Table 6.1.1, Appendix I), and light attenuation coefficient ranging from 0 to 2.0 m^{-1} (Fahnenstiel et al. 2000, Eq. 2)

As a result, there were four different light treatments – morning clear, morning dark, afternoon clear and afternoon dark under experimental conditions. Clear and dark indicate the light difference between surface and mixed layer. Morning samples were stored in sample bottles from 1600 hrs. the day of sample arrival till the next morning around 0930 hrs., and dark samples were stored starting at the same time till around 1600 hrs. in the next day afternoon. The PAR was averaged from preceding 6 hours of the measurement time to represent the light exposure levels in the morning and in the afternoon.

2.3.3 *Microcystis* Velocity Measurements

A videographic recording system was used to measure the velocity of *Microcystis* colonies in our study (Figure 2.5). This video recording system consisted of two main components - a camera system and a software system.

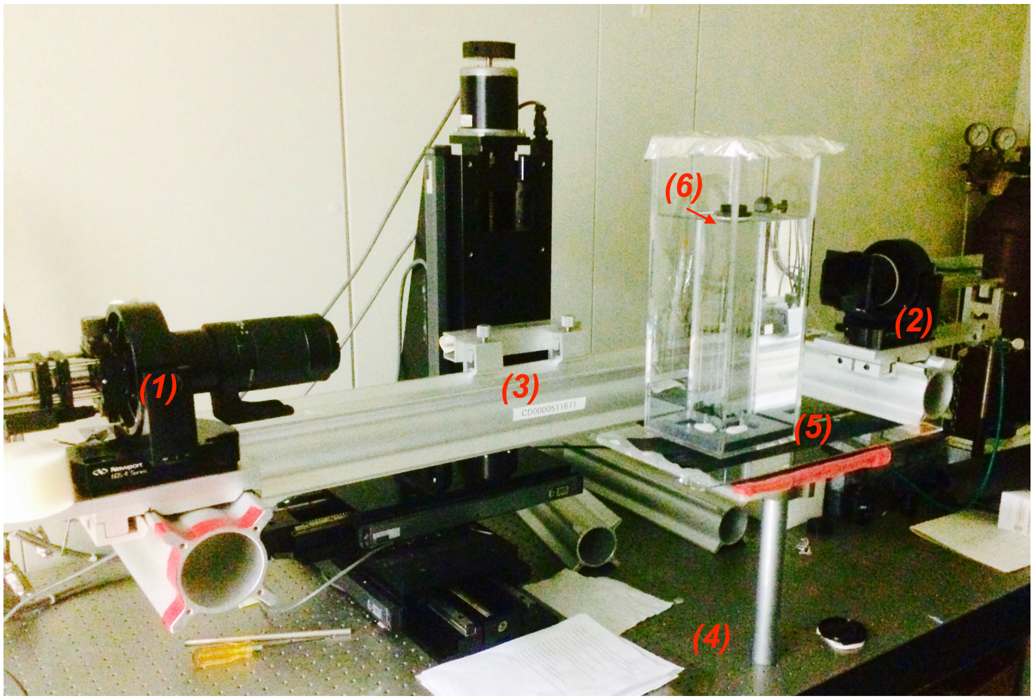

Figure 2.5 The recording system used for measuring the terminal velocity of *Microcystis* colonies rising through a quiescent column of Lake Erie water. (1) light source/red laser (410-700nm); (2) Digital video camera; (3) 3D positioning frame; (4) stationary table; (5) thermal water jacket; (6) quartz cuvette containing samples of *Microcystis* in lake water.

The camera system used in this study was housed inside of a temperature-controlled room. It utilized the Shadowgraph optics system (Rasenat, et al. 1989; Trainoff and Cannell, 2002; Strickler and Hwang, 1999), a red laser (400-710 nm, Stocker Yale Canada Inc., LASIRIS^{TM}) as the light source, and a digital video camera (Basler acA1300 – 60g mNIR) for image recording. The system was mounted on a 3D positioning frame controlled by a joystick. The joystick was set near the video monitor outside of the lab for easy focusing and recording. This camera was pointed toward a stationary table, which held a quartz prism cuvette (10 mm × 10 mm inside dimension × 305 mm tall, Clear Fused Quartz Square Tubing, Friedrich & Dimmock, Inc.) containing water samples with *Microcystis* colonies. The cuvette was housed inside of a larger, outer container that acted as the thermal water jacket (140 mm × 140 mm inside dimension × 400 mm tall). In comparison to the experiments conducted in 2015 at NOAA-GLERL by Kevin Kijanka, the new system with remote positioning system, Shadowgraph optics and higher resolution lens in the laser enabled measurements of smaller colonies with greater accuracy than in the 2015 experiments.

The camera was connected to a computer through an Ethernet cable allowing for digital recording by the software system. Videos of *Microcystis* movement were captured by Templo (Contemplas, GmbH, Germany), which is a software designed for capture of images for motion analysis. Afterwards, the buoyant velocities were analyzed and obtained using Vicon Motus (Contemplas, GmbH, Germany), the software for motion analysis. Images of mm graduations on a ruler were collected for calibration each time the cuvette was filled.

Studies have shown that *Microcystis* colonies may vary from buoyant to sinking (Ibelings et al. 1991; Medrano et al. 2013). To measure the percentages of floating and sinking colonies in our study, the number of floating and sinking colonies was counted separately in a settling chamber (Hawksley, 3 mm depth) under microscopy (Walsby and Booker, 1980), and then divided by the total number of colonies in the settling chamber. The other way to obtain the percentages was to calculate directly from the velocity measurements under the videographic recording system. For instance, number of sinking colonies was counted from velocity measurements and divided by the total number of measured colonies. The results from these two methods were then compared.

2.3.4 Method Verification

The goal of the method was to measure the terminal velocity of individual colonies rising or sinking through a quiescent fluid; thus, errors could be introduced from temperature-driven convection, bulk flow caused by turbulence, or particle-particle interactions (Ramaswamy, 2001; Ruiz et al. 2004). By maintaining uniform temperature in the incubator tank and the laboratory temperature-controlled room, temperature-driven convections were minimized. According to Ruiz et al. (2004), measurements of Stoke's velocities in uniform turbulence were conducted by controlling particle concentrations to achieve an average distance between particles of 100 times the diameter. In this way, interactions between particles were avoided. In our study, we used filtered lake water with different dilution ratios to avoid the interactions, and our goal was to make sure there was only one or two colonies present in one frame of 1cm $\times$ 1cm, which was approximately a 100-diameter separation for a 100 μm colony. Dilution was effective in avoiding development of a bulk flow pattern in the cuvette caused by the rising colonies.

To test whether fluid turbulence was causing errors in velocity measurement, we introduced polystyrene DVB microspheres (Duke Scientific Corp., Particle-Size Standards; 102 $\pm$ 2.0 μm, 5.4% CV, 15 mL and 49.5 $\pm$ 1.0 μm, 3.2%, 15 mL) within the water samples as an internal standard reference. With a known diameter and density, the terminal velocity of microspheres can be calculated invoking Stoke's Law. While measuring velocities of *Microcystis* colonies, microsphere velocities were measured in the same video frames. Afterwards, microsphere velocities measured in the experiments were compared to the theoretical value. The results of microsphere velocity were used to verify that the *Microcystis* velocity measurements were not affected appreciably by turbulence or bulk flow, and that size and distance measurements in the calibrated images were accurate.

2.3.5 Colony Size Measurements

The equivalent spherical diameter (ESD) was used to represent the colony size. ESD of an irregularly shaped object is the diameter of a sphere of equivalent volume. In this case, the ESD was calculated by converting the projected area of a *Microcystis* colony image to a diameter of a circle of equivalent area. During velocity measurements, the colonies were numbered in images from Templo, then these images from Vicon Motus were imported in ImagePro Insight (Media Cybernetics) along with the calibration images to obtain the colony sizes using ESD method. The size data were then paired with velocity data using the reference number of the particle image.

2.4 Results

2.4.1 Method Verification

The mean velocities of both sized microspheres (49.5 µm and 102 µm) on each sampling day verified that the *Microcystis* velocity measurements were accurate. Figure 2.6 shows the mean velocities of the polystyrene DVB microspheres together with the theoretical values calculated by Stoke's Law. Theoretical values of these two microsphere diameters fell within the 95% confident interval on the mean of the experimentally-measured velocities.

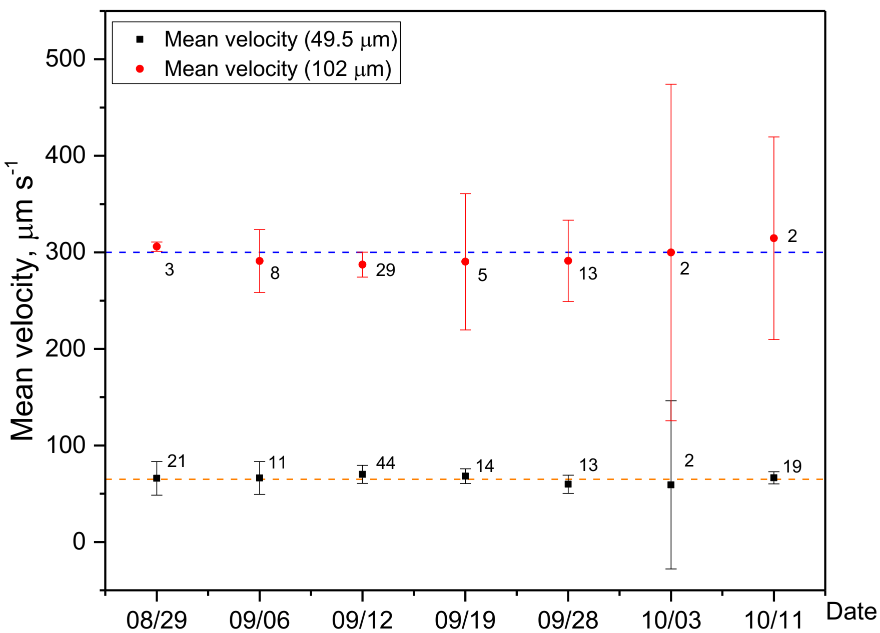

Figure 2.6 Mean velocity of microspheres for each size on each sampling day throughout the bloom season. Error bars indicate the 95% confidence interval on the mean. Dashed lines show the theoretical Stoke's velocity values for microspheres of two sizes (49.5 µm, 102 µm). Numbers next to mean values represent the number of data points measured respectively.

2.4.2 Buoyant vs. Sinking Colonies

The percentages of floating and sinking colonies indicated that floating colonies were generally more common than sinking colonies, and the occurrences of sinking colonies were mostly associated with greater light exposure and early bloom season. Figure 2.7 shows the sinking percentages in the settling chamber counted using microscopy under varying light exposure conditions. Figure 2.8 shows the percentage of buoyant and sinking colonies, while Figure 2.9 shows the sinking percentages under different light exposure conditions, as measured by videography. Among all 729 velocity measurements obtained by the videographic recording system, 92 of them were sinking. Comparing Figure 2.7 & 2.9, afternoon samples showed the highest sinking percentages in general. The condition of afternoon and clear sample bottle, which represented the longest and strongest light exposure, had the highest sinking percentage. Additionally, there was a decreasing trend of sinking colonies over the season, which was consistent between the two methods.

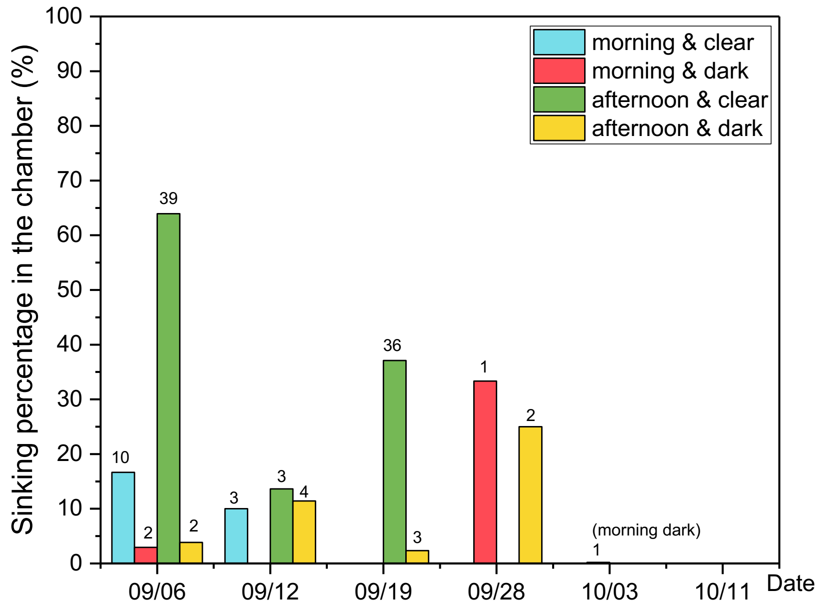

Figure 2.7 Percentage of sinking colonies in the settling chamber under microscopy. Numbers on the bars represent the actual count of sinking colonies.

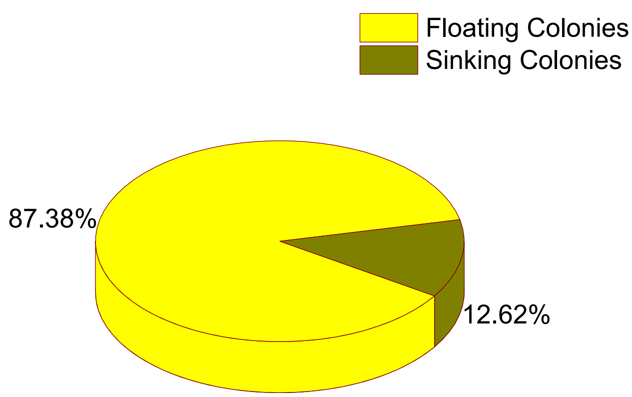

Figure 2.8 Percentage of buoyant and sinking colonies from videographic velocity results.

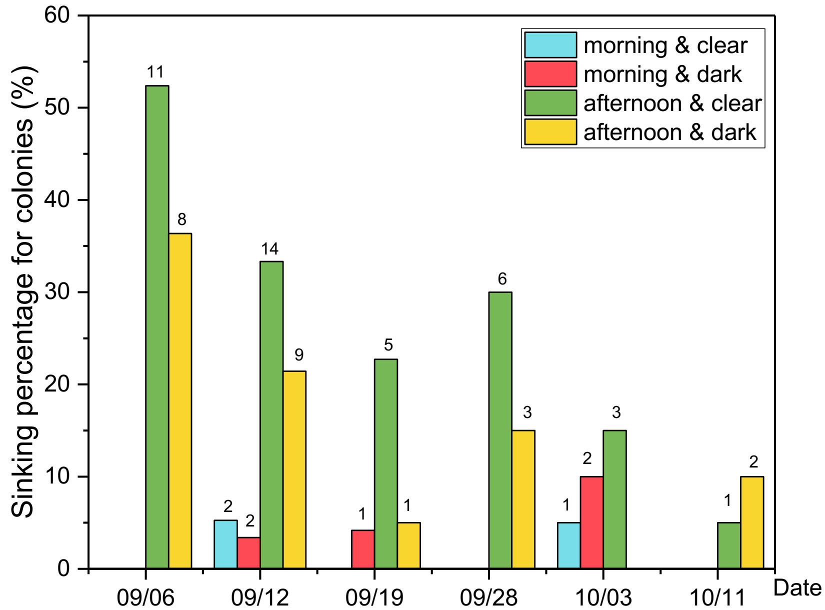

Figure 2.9 Percentage of sinking colonies based on videographic velocity measurements. Numbers on the bars represent the actual counts of sinking colonies.

2.4.3 *Microcystis* Velocity vs. Colony Size

Measured *Microcystis* velocity and colony size were significantly and positively correlated, indicated by the slope that was significantly different from zero on a log-log plot. Figure 2.10(a) shows the relationship between buoyant velocity and colony mean ESD for floating colonies, and Figure 2.10(b) shows that of sinking colonies. To display the relationship on a log-log plot, we converted the negative velocities of sinking colonies to their absolute values. Table 2.1 shows the linear regression statistics for Figure 2.10 (a) and (b).

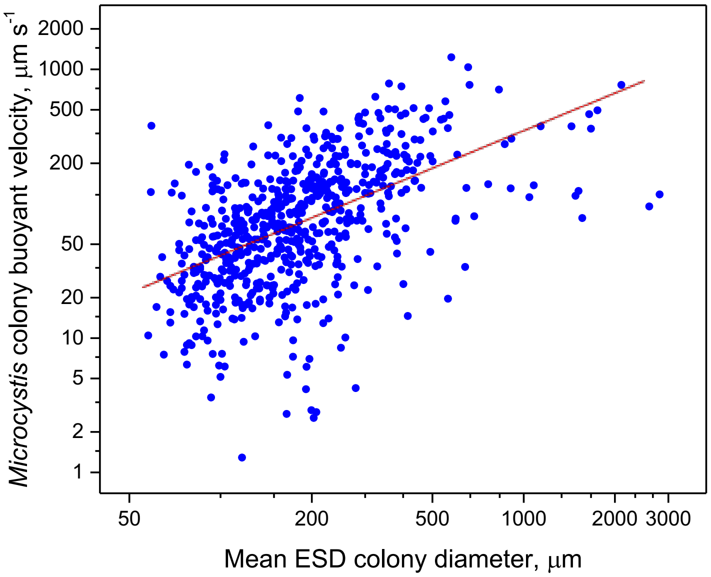

Figure 2.10(a) Regression of log velocity vs. log ESD mean diameter for buoyant colonies.

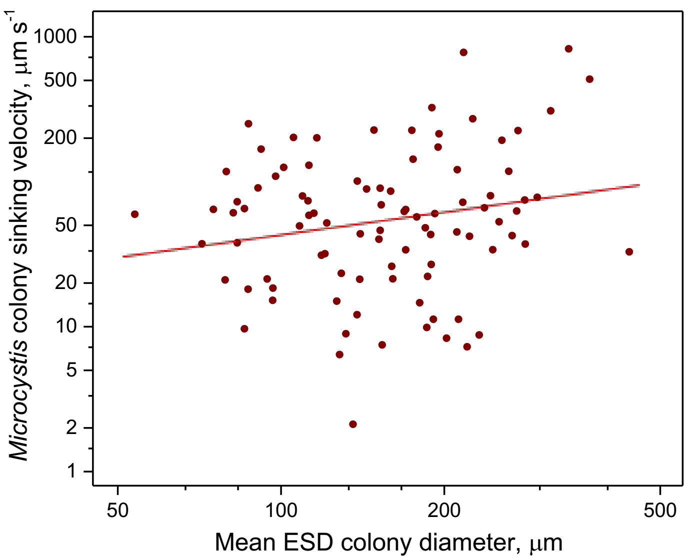

Figure 2.10(b) Regression of log velocity vs. log ESD mean diameter for sinking colonies (shown as positive values).

Table 2.1 Linear regression statistics for Figure 2.10 (a) & (b). 95% CI represents the 95 percent confidence interval for both sides of mean slope and intercept respectively.

y = ax + b, y=$\log_{10}$(velocity), x=$\log_{10}$(ESD)				
Colony Group	Slope	95% CI	Intercept	95% CI
Buoyant	0.92	0.06	-0.23	0.13
Sinking	0.45	0.27	0.74	0.60

2.4.4 *Microcystis* Velocities vs. Light Exposure

Mean velocity of *Microcystis* and light exposure measured as PAR for two separate colony size classes were significantly and negatively correlated, indicated by the slopes that were significantly different from zero in both size classes in Figure 2.11 (statistics shown in Table 2.2) and the negative correlation of mean buoyant velocity and PAR on each sampling day shown in Figure 2.12. To include the effects of colony size on *Microcystis* velocity, each week's data were divided into two groups – the colonies larger than 150 μm and those smaller than 150 μm. We chose 150 μm as the threshold value because it was the median value of each week's colony size measurements. Figure 2.13 shows that large colonies were getting more buoyant later in the season. As also indicated in Figure 2.12 and Figure 2.13, generally, colonies in the morning were generally more buoyant than afternoon colonies, and colonies in clear bottles (surface light exposure conditions) were less buoyant than those in dark bottles (mixed layer light exposure conditions). As a result, afternoon dark light condition almost always corresponded with the lowest buoyant velocity (except for Oct 3rd). Figure 2.14 and Figure 2.15 show the averaged PAR and mean velocity under different light conditions on each sampling day throughout the bloom season.

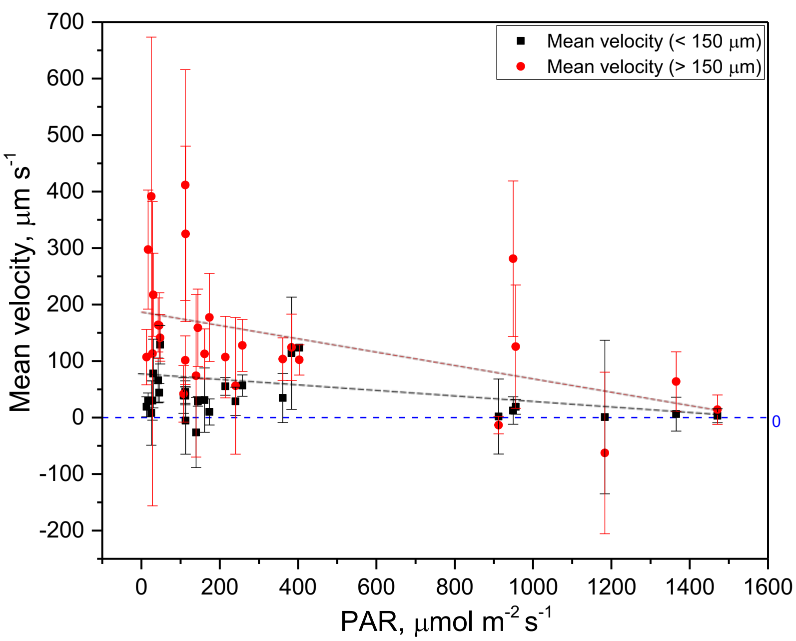

Figure 2.11 Regression of mean velocity versus PAR averaged over the preceding 6 hours for the two colony size classes. The linear regression statistics of both size classes along with overall data fitting is shown in Table 2.2 below. PAR was measured by the spherical sensor directly for clear bottles and converted using the 11.8% PAR transmittance of the neutral density filter.

Table 2.2 Mean velocity vs. PAR linear regression statistics. All slopes are significantly less than from zero.

Colony Size Group	Slope (a)	95% CI	Intercept (b)	95% CI
< 150 μm	-0.03	0.02	46.23	8.96
> 150 μm	-0.12	0.04	185.04	24.96
All	-0.07	0.01	98.88	10.10

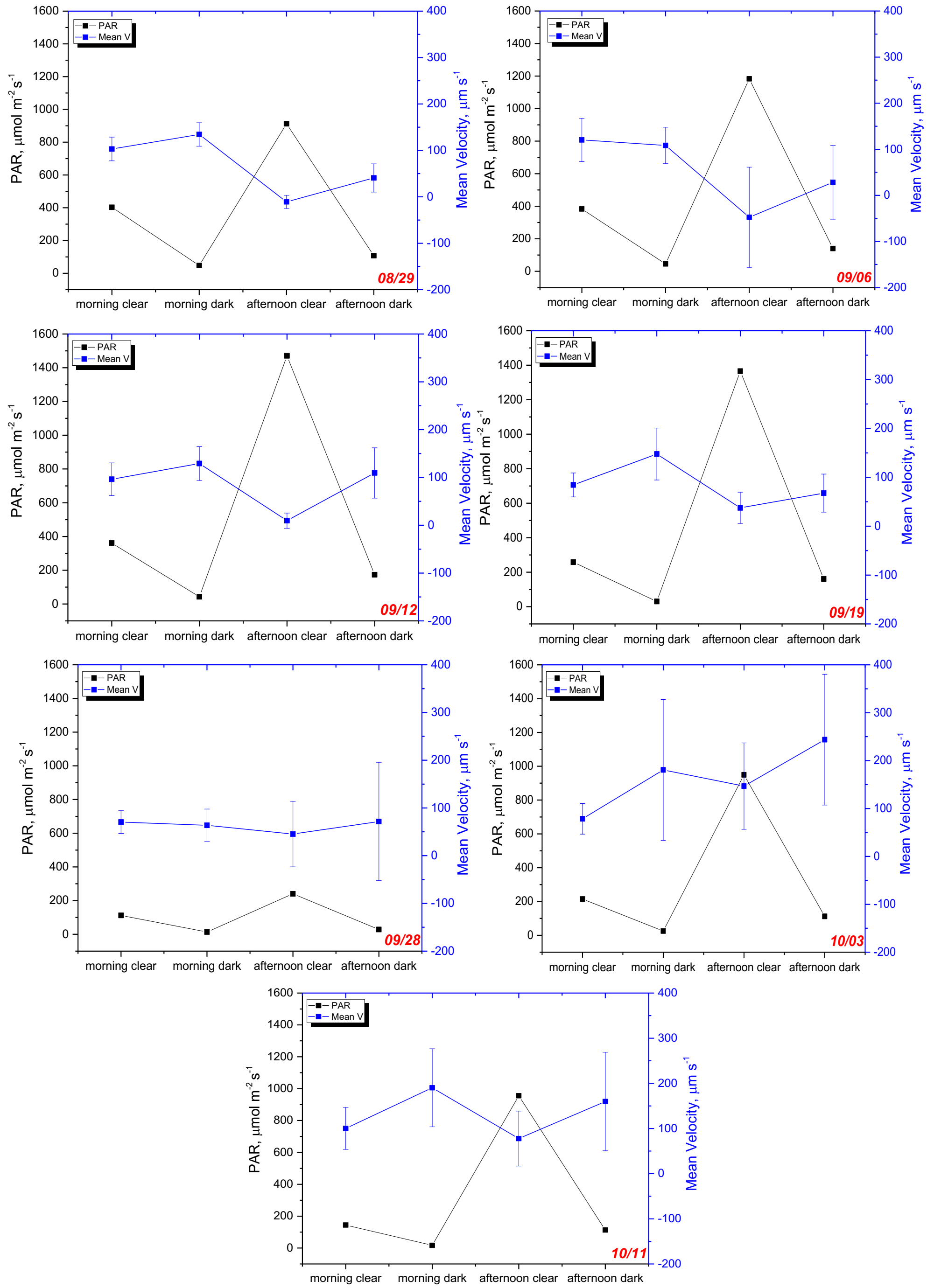

Figure 2.12 Mean velocity data & PAR plotted together under four different light conditions for each sampling week. Generally, higher PAR exposure corresponded to lower buoyant velocity.

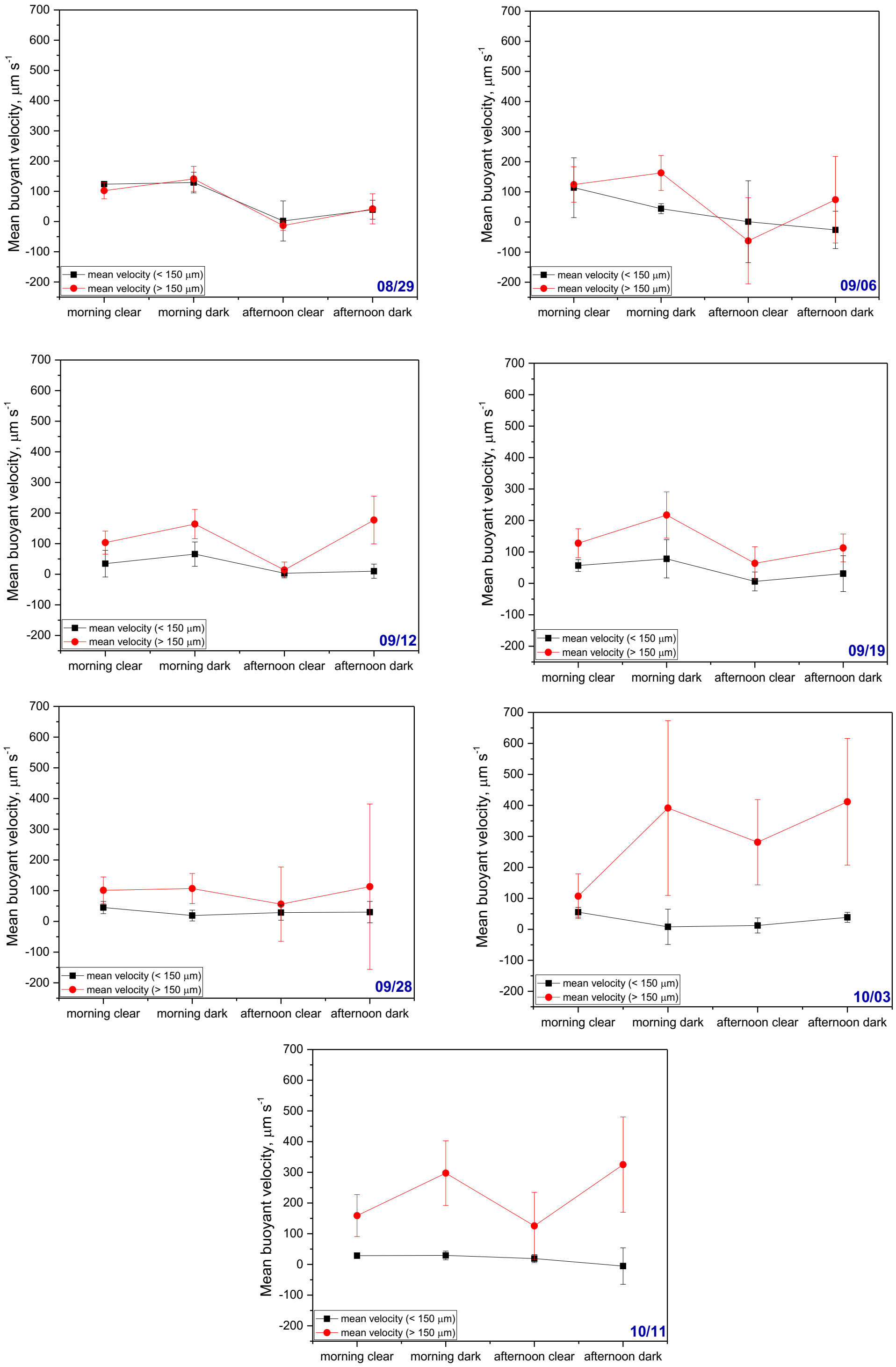

Figure 2.13 Mean velocity averaged for different light conditions and two colony size classes (>150 µm and <150 µm) on each sampling day. Larger colonies were getting more buoyant later in the season.

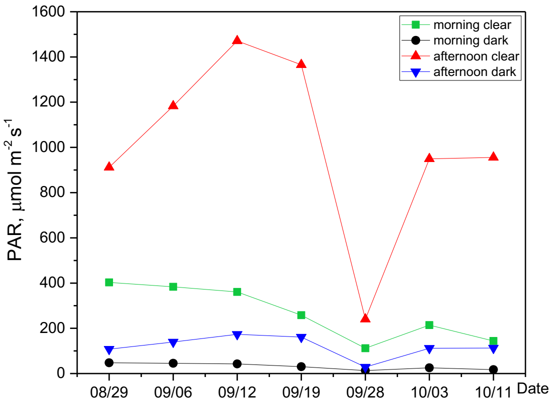

Figure 2.14 Averaged six-hour PAR for experimental light conditions on each sampling day during the bloom season.

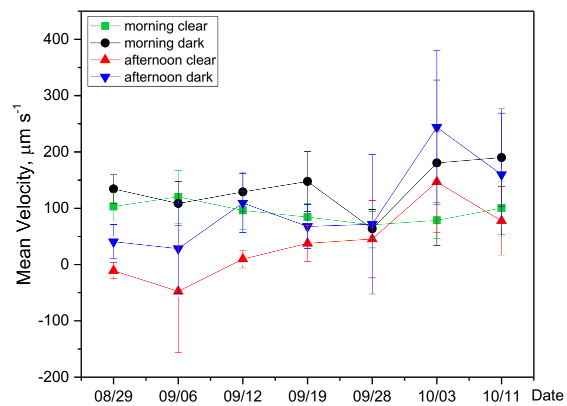

Figure 2.15 Mean velocities for all colonies under different light conditions on each sampling day during the bloom season.

2.4.5 Nutrient Effects on Buoyancy & Growth Rate

Molar seston ratios of C: N (Fig 2.16) and C: P (Fig 2.17) varied throughout the bloom season, and both ratios were highest at the beginning and end of the season (data shown in Table 6.1.2 in Appendix I). Mean velocity of *Microcystis* colonies under different light conditions also had a varied relationship with the associated N: P molar ratio across sampling days (Figure 2.18, Table 2.3). Additionally, growth rates of *Microcystis* colonies in sample bottles under light conditions were higher than dark conditions. Under light conditions, Sep 19th sample had the highest growth rate comparing to samples on Sep 6th and Oct 3rd, while there was no growth of *Microcystis* colonies at all on Oct 3rd (Figure 2.19). FluoroProbe results showed generally decreasing *Microcystis* concentrations (expressed in chlorophyll units) in the sample bottles, except for relatively high results for Oct 3rd sample (Sep 4th & 5th, Figure 2.20).

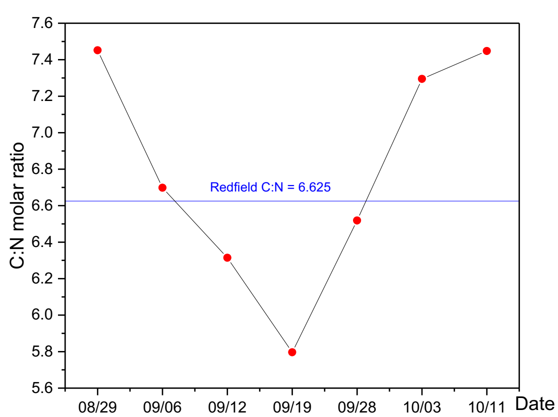

Figure 2.16 Particulate C: N ratio throughout the bloom season for each week.

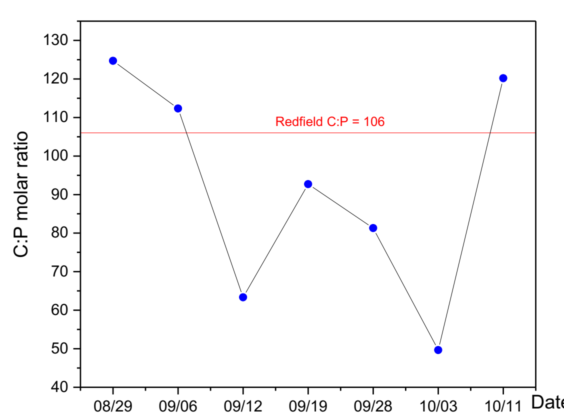

Figure 2.17 Particulate C: P ratio throughout the bloom season for each week

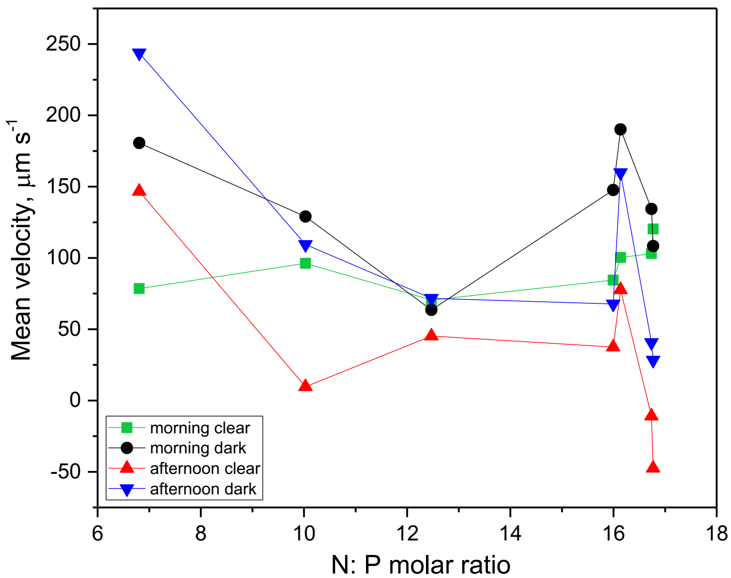

Figure 2.18 Mean velocity of *Microcystis* colonies under different light conditions on each sampling day versus the associated N: P molar ratio.

Table 2.3 Linear regression statistics of mean buoyant velocity versus N: P molar ratio. Relationship was positively significant for morning clear, nonsignificant for morning dark, and negatively significant for both afternoon samples.

Linear regression equation y = ax + b; y = mean velocity, x = N: P molar ratio				
Light Conditions	slope (a)	95% CI	intercept (b)	95% CI
morning clear	2.48	1.57	59.68	22.04
morning dark	-1.34	4.87	154.45	68.39
afternoon clear	-10.53	5.46	179.70	76.62
afternoon dark	-14.27	5.89	296.63	82.68

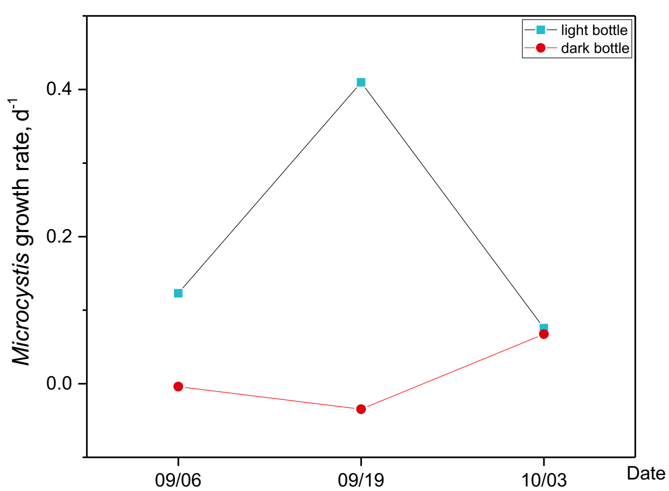

Figure 2.19 Growth rate of *Microcystis* colonies for light and dark treatments on Sep 6th, Sep 19th and Oct 3rd, 2016. Table 6.1.3 (Appendix I) shows the detailed data used to calculate the growth rates.

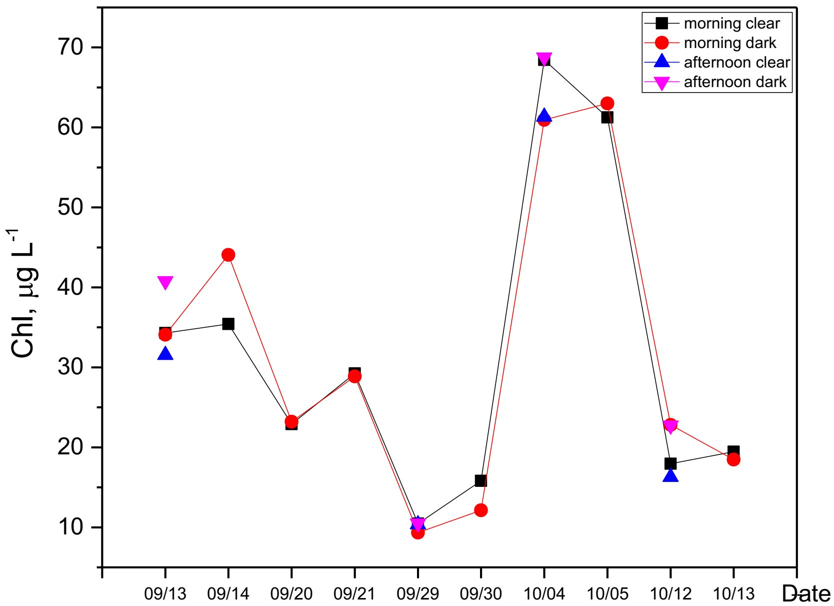

Figure 2.20 *Microcystis* concentration expressed as chlorophyll in the bottles on Sep 12th, Sep 19th, Sep 28th, Oct 3rd and Oct 11th under different light exposure conditions (data missing on Aug 29th and Sep 6th). The highest *Microcystis* concentration in the sample bottles on Oct 3rd contributed to its lowest growth rate in Figure 2.19.

2.5 Discussion

2.5.1 *Microcystis* Velocity vs. Colony Size

As described by Stoke's Law, particle motion would result in a log-log plot of velocity versus particle diameter to produce a straight line for a given condition with a slope of two in a quiescent fluid (water); if on the other hand, particle motion is controlled by turbulence, we would expect to see no relationship between velocity and particle diameter. Due to the fractal structure of *Microcystis* colonies, the colony specific gravity approaches that of the water as the size increases (Nakamura et al., 1993), which would cause the *Microcystis* colony density change. As a result, the slope obtained from experiments would be less than two. Figure 2.21 and Table 2.4 indicate a slope of 1.41 for Aug 3rd sample and 1.14 for Sep 18th sample (Nakamura et al., 1993), while year 2015 data has a slope of 0.80, and we found a slope of 0.92 for year 2016 data.

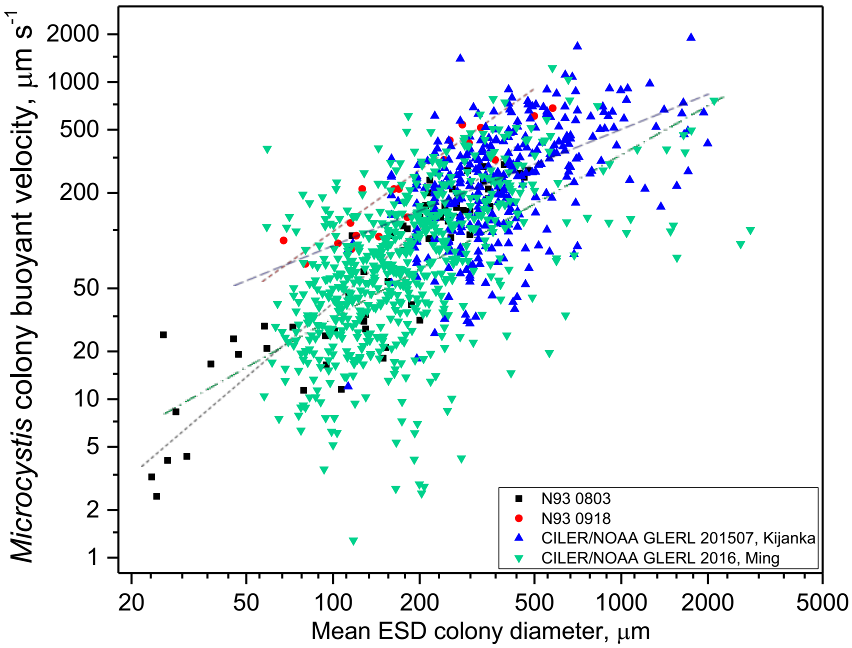

Figure 2.21 *Microcystis* buoyant velocity vs. colony size relationship for data collected summer 2016 and historical data (Nakamura et al., 1993, black – 930803; red – 930918; blue – Kevin Kijanka data, Jul 2015; green – 2016 data). Linear regression statistics are shown in Table 2.4. Only buoyant velocities from 2016 data are shown in this figure.

Table 2.4 Linear regression statistics of buoyant velocity vs. colony size for all data (historical & 2016 data). 95% CI means the 95 percent confidence interval for both sides of mean slope and intercept. All slopes are positive and significantly different from zero.

Linear regression equation y = ax + b, y=$\log_{10}$(velocity), x=$\log_{10}$(ESD)				
Date	slope (a)	95% CI	intercept (b)	95% CI
N930803	1.41	0.08	-1.25	0.18
N930918	1.14	0.11	-0.25	0.26
Jul-15	0.80	0.07	0.29	0.18
2016	0.92	0.06	-0.23	0.13

In comparison to Kijanka's velocity measurements in 2015, we introduced a method verification process using microspheres, which verified our methods and indicated our velocity measurements were accurate without turbulence effects; additionally, we improved the optics and successfully measured a larger amount (729 colonies) and a wider size range (53 µm to 2809 µm) of *Microcystis* colonies, comparing to Kijanka's results (355 colonies, size ranging from 113 µm to 1996 µm).

2.5.2 *Microcystis* Velocities vs. Light Exposure

Our results of velocity measurements and light exposure showed that buoyancy decreased with increasing light exposure, which was consistent with previous studies that explained this trend in terms of carbohydrate production by photosynthesis (e.g. Medrano et al., 2013). The results on each sampling day indicated three results: colonies in the morning were generally more buoyant than afternoon colonies; colonies in dark bottles were usually more buoyant than clear bottles; larger colonies tended to be more buoyant. In other words, higher light exposure and larger colony size contributed to greater buoyancy.

According to Medrano et al. (2013), the colony density change depends on solar irradiance (their Fig. 2a). The PAR detected in our experiments varied from 0 to 1700 μmol m^{-2} s^{-1}, which means 0 to 300 W m^{-2} after unit conversion (1 W m^{-2} ≈ 4.6 μmol m^{-2} s^{-1}). The fastest density change rate would be about 2.5 x 10^{-3} kg m^{-3} s^{-1}, which is 9 kg m^{-3} h^{-1}. As indicated in methods, we used a 6-hr period for PAR averaging, which would cause a density change of 54 kg m^{-3} of the colony. Assuming colony diameter to be 150 μm, velocity change of -830 μm s^{-1} to 1277 μm s^{-1} is associated with density change of 906 kg m^{-3} to 1061 kg m^{-3}, which means a change of 155 kg m^{-3}. Thus, 54 kg m^{-3} density change represents a 35% density change, which can cause a measureable velocity change. As a result, 6-hr period of PAR exposure was long enough for colonies to respond to changing light conditions.

2.5.3 *Microcystis* Velocities and Nutrients

Comparison of the ratios that indicate nutrient deficiency levels from Table 1 of Hecky et al. (1993) with molar ratios as well as Redfield ratio (Hecky et al., 1993) in C: N (Figure 2.22), C: P (Figure 2.23) and N: P (Figure 2.24) suggested that at no time was there significant P or N limitation for the *Microcystis* used in our experiments. However, there was a fluctuating but decreasing trend of *Microcystis* colony velocity towards P deficiency under higher light exposure conditions (Figure 2.18).

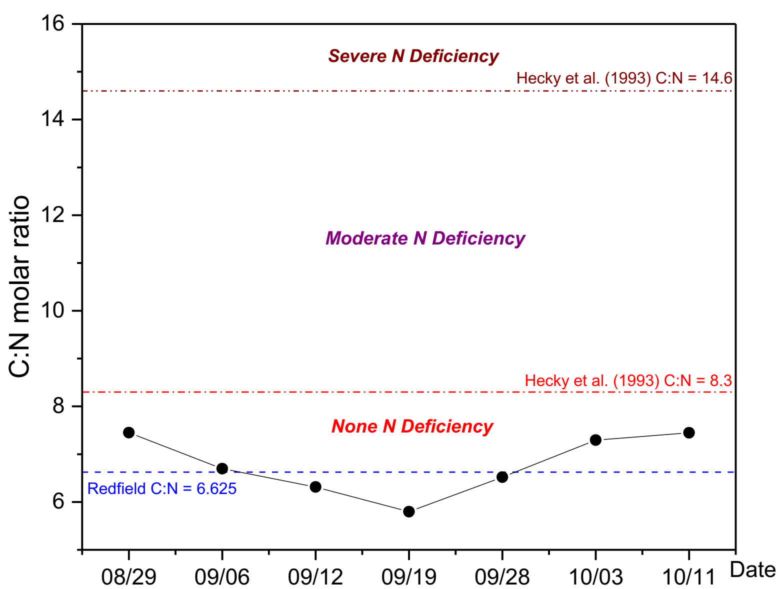

Figure 2.22 Particulate C: N ratio throughout the bloom season for each week with Redfield ratio and nutrient deficiency ratio by Hecky et al. (1993). Our results fell within N no-deficiency range.

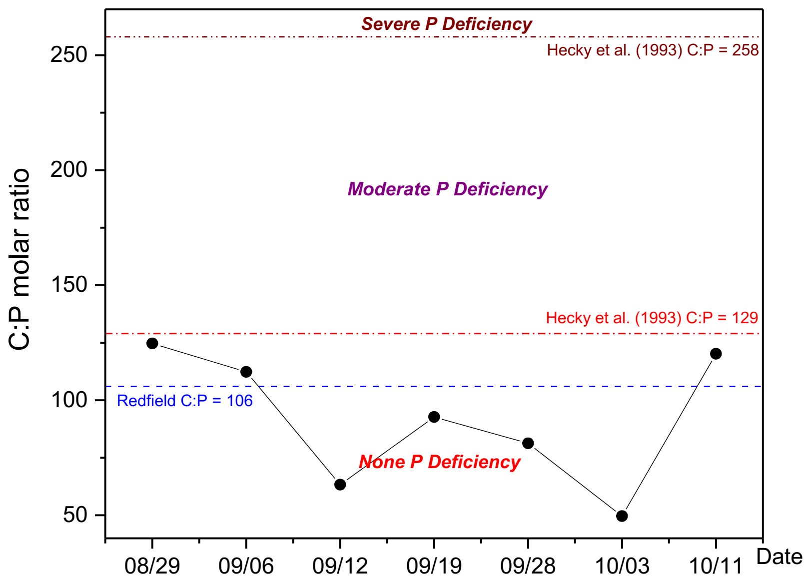

Figure 2.23 Particulate C: P ratio throughout the bloom season for each week with Redfield ratio and nutrient deficiency ratio by Hecky et al. (1993). Our results fell within P no-deficiency range.

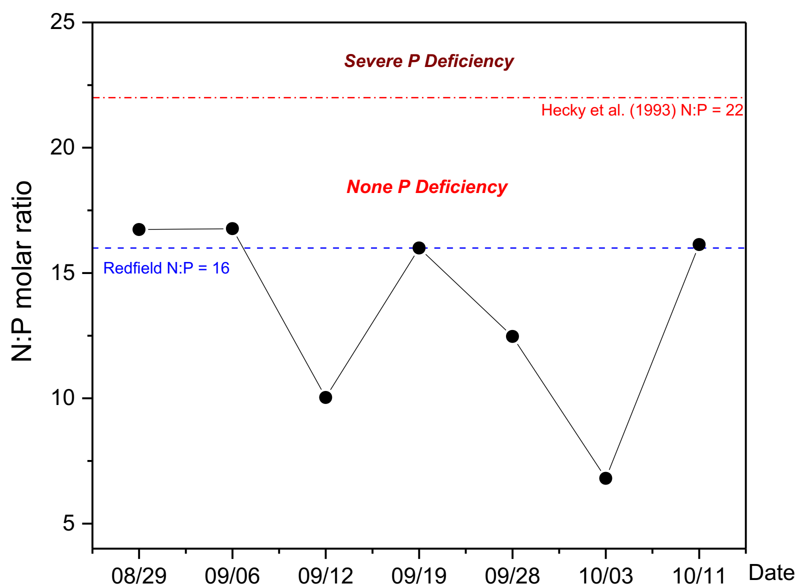

Figure 2.24 Particulate N: P ratio throughout the bloom season for each week with Redfield ratio and nutrient deficiency ratio by Hecky et al. (1993). Our results fell within none deficiency range.

Results of growth rates and nutrient analysis on Sep 6th and Sep 19th indicated that higher growth rate on Sep 19th was correlated with lower C: N and C: P molar ratios (Figure 2.19, 2.22 & 2.23), which represented conditions with higher N and P abundance; additionally, this higher growth rate on Sep 19th was also related to lower N: P molar ratio (Figure 2.24). On Oct 3rd, there was no growth because of the high *Microcystis* concentrations in sample bottles.

2.6 Conclusion

In this study, we used an improved videographic system to measure *Microcystis* velocity and then developed statistical relationships between *Microcystis* velocity, colony size, light exposure and nutrients. The hypothesis that light exposure during the day has a negative effect on *Microcystis* velocity was tested and we found a significant and negative relationship between light exposure and *Microcystis* velocity. We also found a significant and positive relationship between colony size and *Microcystis* velocity. As for the nutrient effects, we did not observe nutrient deficiency during the bloom season, however, there was a trend indicating a decrease of velocity towards increasing N: P molar ratio.

Chapter 3: Hindcast Skill Assessment Using the Fractions Skill Score

3.1 Background

This research sought to improve the approach to assessing the skill of the Lake Erie HAB Tracker model in an effort to provide more useful information to the stakeholders. In this study, the model skill was defined as a measurement of the model's ability to correctly predict the presence and non-presence of events, where the observations of events were considered to represent reality (Hogan & Mason, 2012). A skill score was calculated to represent the level of skill for a model under certain conditions. The existing hindcast skill assessment for the HAB Tracker model (Rowe et al., 2016) used the Pierce skill score (PSS) method described by Hogan and Mason (2012). Modeled and observed values at each pixel were compared to develop the components of a contingency table. The contingency table is a two-by-two table that contains the distribution of forecast outcomes in terms of pixel counts in four categories: hits, false alarms, misses, and correct rejections. Rowe et al. (2016) then calculated PSS from the elements of the contingency table, and compared the hindcast skill score to a "benchmark" forecast, the persistence forecast. The persistence forecast was obtained from the assumption of no change in HAB distribution since the latest satellite image. Rowe et al. (2016) concluded that the model provided useful information to the end users because it had greater skill than the persistence forecast, which was considered to represent the best available information in the absence of a forecast model.

An alternative way to assess the hindcast skill is through comparing the skill of the model at various spatial neighborhood sizes to eliminate double penalty which double-counts small spatial mismatch, a miss and a false alarm (Mittermaier et al., 2013). Due to double penalty, the PSS method may result in a low skill score when the model output is spatially offset compared to the satellite image data, even though small degrees of spatial mismatch may still provide a useful forecast. In Figure 3.1, an idealized example forecast demonstrates that the model has a low PSS of 0.32 (PSS range: -1 to 1), while the overall pattern is predicted. In this example, the low skill score provided by the PSS method does not reflect that the model correctly indicated the location of the event in the left half of the domain. This penalty effect is often large when evaluating the accuracy of predictions for sparse HAB events.

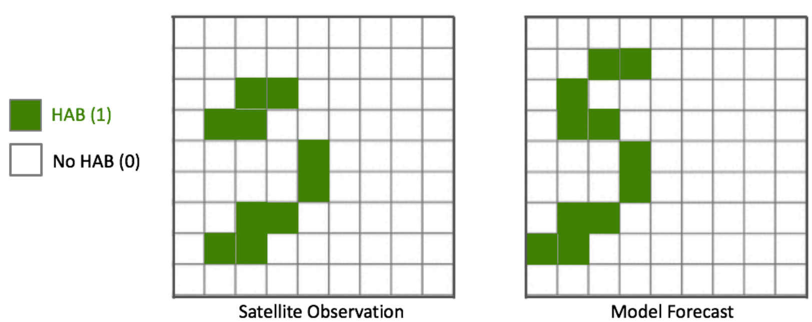

Figure 3.1 An idealized example of a HAB forecast, illustrating the concept of "double penalty" that can result from a small spatial mismatch in pixel-by-pixel skill scores. Note that the model HAB patch is correctly located in the left half of the domain even though many event pixels are in disagreement.

Two neighborhood-based methods were identified as potentially useful alternative skill assessment methods. The first method, the multiple resolution comparison (MRC), was evaluated by Pontius et al. (2004) for the validation of land-change models. This method aggregates the pixels within a defined neighborhood to form a coarser resolution. The aggregation occurs in a geometric progression of resolution. As illustrated in Figure 3.2, the four adjacent pixels are aggregated to form the second resolution, and four of the coarser adjacent pixels are aggregated to form the third resolution and so on. The mean value of the aggregated pixels is then assigned to the new pixel.

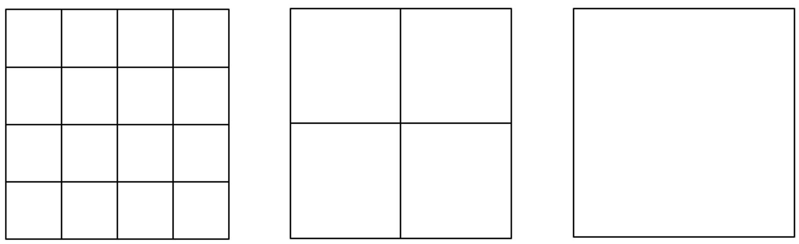

Figure 3.2 Pixel aggregation in the multiple resolution comparison (MRC) method of Pontius et al. (2004).

The second neighborhood-based method was described by Roberts and Lean (2007), and was referred to as the fractions skill score (FSS). It has been applied to the skill assessment of rainfall forecasts (Mittermaier et al., 2013). This method offers potential advantage in comparison to the MRC method because it preserves the original resolution of the model output while generating spatial smoothing of the model output. Figure 3.3 demonstrates the calculation of FSS at increasing neighborhood sizes. To smooth the pixel value, the FSS method also assigns each pixel with the mean value of the pixels within the neighborhood, which is similar to the MRC method. However, the value of a central pixel is changing with the changes in neighborhood sizes, and the original spatial resolution of the model output was maintained.

FSS can be applied to the HAB forecast because the HAB forecast is similar to a rainfall forecast. The rainfall forecast of Mittermaier et al. (2013) and the HAB Tracker's forecast both used remote sensing data as the observed data, which are raster data composed of pixels. Mittermaier et al. (2013) used a map of precipitation from Doppler radar, while the HAB Tracker model used satellite-derived maps of HAB intensity. For these reasons, we applied the FSS method to the HAB Tracker in an effort to determine the neighborhood size where model skill is maximum, suggesting that it may be advantageous to smooth the model output at an identified optimal neighborhood size for presentation to the model users.

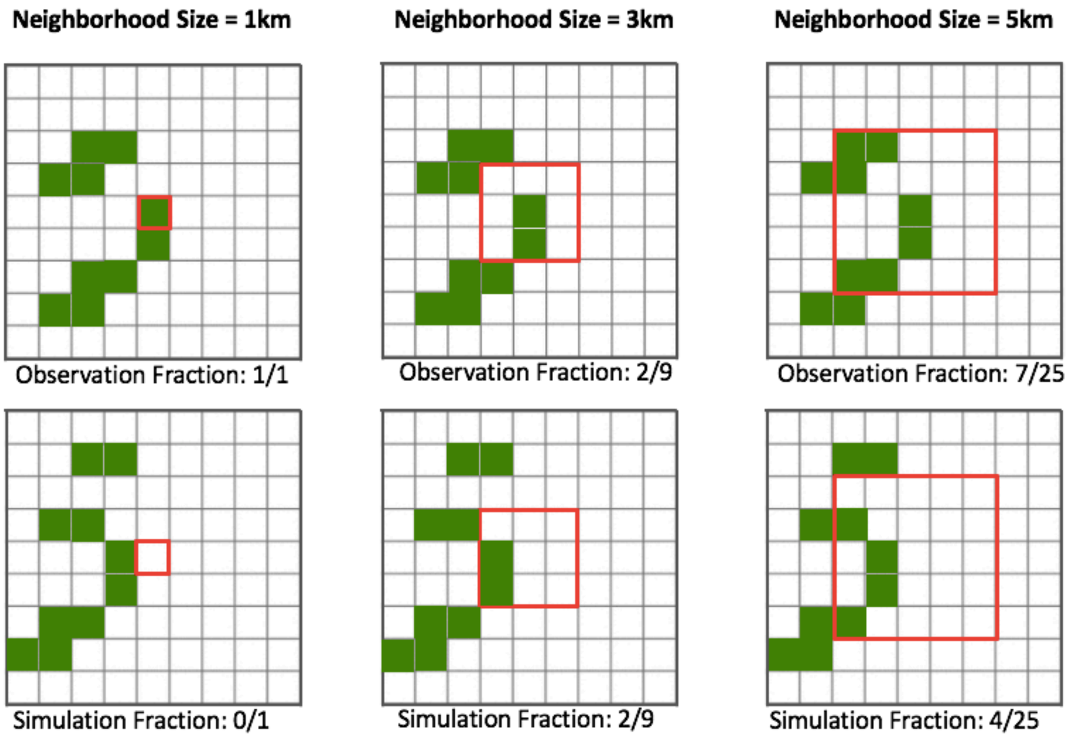

Figure 3.3 Example illustrating how to calculate FSS for the pixel at the center of the neighborhood at increasing neighborhood sizes (red squares). Note that at the neighborhood size of 3 km, the fraction of the events is in total agreement in the red square (neighborhood), while the pixel locations of the events completely disagree.

3.2 Research Objectives & Hypotheses

The following research objectives were identified:

1) Determine the neighborhood size at which the model will result in an overall maximum skill by comparing the fractions skill score over a range of neighborhood sizes.

2) Determine if the model will have greater advantage over the persistence forecast if presented after spatial smoothing over a neighborhood size larger than 1 km.

Based on these objectives, the following hypotheses were developed:

1) The skill of the HAB Tracker model increases with increasing neighborhood size from the finest spatial scale of 1km to a maximum, then decreases at larger neighborhood sizes beyond the maximum.

2) The neighborhood size at which the fractions skill score of the HAB Tracker model exceeds that of the persistence forecast is coarser than the 1-km-resolution of the satellite-derived HAB images.

3.3 Methods

3.3.1 Data Description

The satellite images of the cyanobacterial blooms in Lake Erie from July to October 2011 derived from MERIS (Wynne and Stumpf, 2015) were used for the hindcast skill assessment. The cyanobacteria index (CI) was obtained by Wynne and Stumpf (2015) based on the MERIS standard level 2 data sets (in units of sr^{-1}) with a spectral shape algorithm based around 680 nm (Wynne, T. et al., 2008) to measure the concentration of HABs. The satellite images were generated on a daily basis for cloud-free days, and 25 images having >50% cloud-free views of western Lake Erie were used to initialize model simulations. Subsequent satellite images within the simulation period served as observations for skill assessment. For each image, a 10-day model simulation was initialized in both 2-dimensional and 3-dimensional. This hindcast skill assessment used 3-dimensional simulations which predicted the change in surface chlorophyll concentration over time using a Lagrangian particle dispersion model and random walk vertical mixing to simulate the vertical distribution of buoyant *Microcystis* colonies in the water column (Rowe et al., 2016).

The satellite-derived observation data and the simulation data were further processed for the hindcast skill assessment. The hindcast skill assessment followed the approach to censoring satellite data in the existing HAB Tracker method used by Rowe et al. (2016). Due to frequent false positive values along the shoreline of Lake Erie in the satellite images, a buffer width was applied to eliminate those values. The buffer width is 1 km to the shoreline in Western Lake Erie, and 1.5 km elsewhere. Values were removed and re-assigned as missing data (N/A) within the buffer zone. To avoid comparing the missing data in the satellite images to the model output, the values at the location of missing data were removed from the model output as well.

The satellite data and the model output were clipped to the same spatial extent in raster data format. The domain for the hindcast skill assessment was targeted at the Western Basin of Lake Erie, which has an irregular shape. To simplify calculations, the domain was expanded to a square that contains the Western Basin of Lake Erie with side lengths equal to 84 km. After processing the data, the model simulation and the observation which had a matching date were selected for the FSS computation. The original spatial scale of the satellite image was 1 km. Due to aliasing issues when assigning model and observed values to a uniform grid for the FSS calculation, the actual spatial scale for the hindcast skill assessment was set to 1.2 km, which is the smallest spatial scale that avoided aliasing.

3.3.2 The Fractions Skill Score Computation Process

a. Conversion of the data to binary categories

The satellite data of surface chlorophyll concentration were converted to binary categorical values of 1 (HAB) and 0 (no-HAB) according to a threshold. This binary conversion enabled focus on the spatial distribution of the events instead of the concentration at each point. The pixel with a value of 1 was referred to as a HAB event, and a value of 0 indicated the non-presence of the HAB event. A CI value of 10^3 was approximately equivalent to 10^5 cells/ml, which was set as the threshold of significantly increased risk to human health according to the World Health Organization (Chorus and Bartram, 1999). Rowe et al. (2016) converted the CI to chlorophyll concentration based on an empirical relationship, where a CI of 10^3 was approximately 23 µg /L Chlorophyll concentration. Thus, we assumed that 23 µg /L Chlorophyll concentration was an appropriate threshold to determine the presence of HABs.

b. Calculation of the fraction HAB coverage in the neighborhood surrounding each pixel

According to Roberts and Lean (2007), a neighborhood was defined as a square of given side length of *n* for each pixel point, where *n* was the neighborhood size (Figure 3.3). The pixel at which the calculation was made was located at the center of the neighborhood with equal lengths between the pixel and each side of the square. A fraction was assigned to the pixel at the center, calculated by averaging the binary values of all of the pixels within the neighborhood. The neighborhood sizes increased as odd numbers starting with 1 until the size reached the full domain extent. The largest neighborhood size aimed to cover the full domain. Therefore, the largest square length was equal to *2K– 1* (139 km in our case), where *K* was the number of pixels on the longer side of the domain. Fraction computations were done using the R statistical software (Comprehensive R Archive Network), using the “focal” function from the “raster” package (Hijmans, R. et al., 2016).

c. Computation of the fractions skill score

The calculation of FSS followed the equations in Roberts and Lean (2007). After the fraction for each pixel was computed, the Mean Square Errors (MSE) between the satellite and forecast fractions were then calculated using the following equation:

$$\mathrm{MSE} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{O_i} - \mathrm{M_i})^2 \tag{3.1}$$

Where O_i (Observation) and M_i (Model) are the fractions at pixel *i,* and *N* is the number of pixels within the domain. If the forecast does not contain any errors, the MSE should be equal to 0. The MSE itself is not very informative because it is highly affected by the fraction of events. The MSE needs to be compared to a reference defined as MSE_{ref}, which is the largest possible MSE that can be obtained for a neighborhood size.

$$\mathrm{MSE_{ref}} = \frac{1}{\mathrm{N}}\left(\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{O_i}^2 + \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{M_i}^2\right) \tag{3.2}$$

The FSS is then computed using the following equation:

$$\mathrm{FSS} = 1 - \frac{\mathrm{MSE}}{\mathrm{MSE_{ref}}} \tag{3.3}$$

The ratio of MSE and MSE_{ref} reflects the FSS, which ranges from 0 to 1. The perfect skill is defined as 1, and no skill is defined as 0 (complete mismatch). Values close to 1 represent a better skill, whereas values closer to 0 represent a poorer skill.

As neighborhood size increased to cover the full domain (2*N*-1), the FSS would gradually reach an asymptotic value, referred to as the asymptotic FSS (AFSS). The AFSS reflects the overall bias of the model because it is computed at the neighborhood scale of the full domain. When there is no bias, the AFSS has a value of 1. The AFSS is given by:

$$\mathrm{AFSS}=1-\frac{(f_O-f_M)^2}{f_O^2+f_M^2} \qquad (3.4)$$

The base rate, f_O, is defined as the observed fraction of events over the full domain. The variable f_M is defined as the fraction of events over the full domain in the model output. In the example shown in Figure 3.1.1, the pixels in green represent events. The ratio of the events to the total number of pixels is calculated as f_O or f_M. In this example, the f_O is measured as 10/81, while the f_M is measured as 10/81. The frequency bias is defined as the ratio of the number of forecasts events to the number of actual events (Hogan & Mason, 2012). Typically, the FSS increases rapidly towards the AFSS as neighborhood size increases, which causes the model output to be spatially smoothed at large neighborhood sizes as shown in Figure 3.4.

Figure 3.4 Schematic graph of skill against spatial scale.

3.3.3 The Modified Fractions Skill Score Method

By smoothing both images (model forecast and observation), the model was compared to the smoothed observation rather than to the original observation. Thus, the model skill was the greatest at maximum smoothing, which was not representative of the actual utility of the model forecast. We modified the FSS method by replacing the smoothed observation image with the original observation image in the FSS calculation process, and plotted the modified FSS over increasing neighborhood sizes. Here we referred to the modified FSS as non-smoothed, or FSSns. The strength of the FSSns method was that it could help determine the neighborhood size at which the model had maximum skill. This was because a moderately smoothed forecast image should become more approximate to the observation image when only small spatial mismatch existed, and the forecast image would lose this resemblance when it became over-smoothed.

3.3.4 Data Analysis

A reference forecast was identified as a benchmark against which to evaluate the advantage of the model. Roberts and Lean (2007) considered the uniform forecast as the benchmark of useful skill. We used the persistence forecast as the benchmark in our application because it represented the best available information in the absence of a model, as was done in previous work on the HAB forecast model for Lake Erie (Rowe et al. 2016; Wynne and Stumpf 2013). The satellite image on the day when the model forecast was initialized served as the persistence forecast over the following 10-day simulation period. We calculated FSS of the persistent forecast in the same way that we did for the model.

Our primary research question was whether the model skill could be improved by spatial smoothing. To address this question, we first analyzed the trend of the FSSns against variable neighborhood sizes of all the model simulations to determine if the model skill was increased by spatial smoothing. Second, we analyzed the advantage which the model forecast had over the persistence forecast calculated from the FSSns method to see if this advantage was increased by spatial smoothing. To quantify this advantage, we calculated a pairwise difference (referred here as ∆FSS) between the skill scores of the two forecasts. If ∆FSS calculated was a positive value, then the model performed better than the persistence forecast. We then calculated 95% confidence intervals to determine if there was a significant difference among the 10 simulation days and among the neighborhood sizes.

3.3.5 Method Verification

To verify that our computation of FSS that was developed in the software R behaved as described by Roberts and Lean (2007), two groups of idealized pattern tests were created. The idealized test served to improve our understanding of the effects of displacement errors and of the irregular boundary.

To test the effects of the displacement errors on the FSS, a 15 x 15 km square of the observed HAB pattern was created and placed approximately at the center of the domain as shown in Figure 3.5 (a). This square was then shifted to specified distances to represent four forecasts. In other words, the forecast and the observation were identical except for their locations. The square was shifted to the west by 1, 3, 5, or 10 km. Each shifted square contained a displacement error in terms of the shift in distance, thus a larger shift in distance resulted in a larger displacement error. The test on the effect of displacement error was also done for the FSSns calculation in which the smoothed observation image was replaced by the original observation image.

In terms of the boundary, Lake Erie has an irregular shoreline shape, which is different from the rainfall forecast in Roberts and Lean (2007). Therefore, to determine whether there was any change in the FSS caused by the irregular boundary, a second group of tests was repeated in which the square was placed near the shoreline instead of at the center (Figure 3.5 (b)).

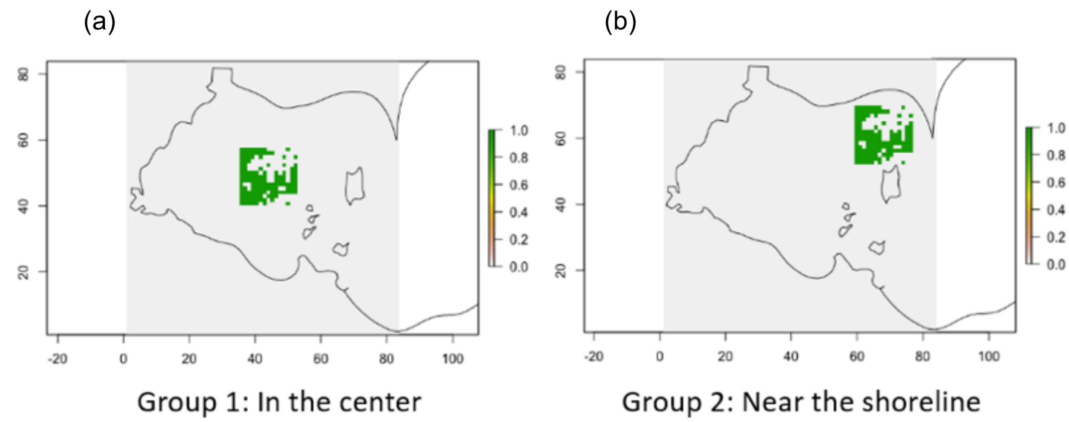

Figure 3.5 The locations of the idealized pattern for the two groups of method verification tests

3.4 Results

3.4.1 Method Verification

To test the effects of the displacement error, FSS curves were plotted for group one and group two. The shapes of the curves were similar between the two groups, and were illustrated with group one. FSS curves of the four shift scenarios tested in group one demonstrated that when the displacement error was smaller, the FSS increased more rapidly and reached the asymptote at a smaller neighborhood size (Figure 3.6 (a)). In addition, at the same neighborhood size, the FSS of a forecast with a smaller displacement error was always higher than that of a forecast with a larger displacement error. These results were comparable to what was expected because when the shift distance was smaller than the neighborhood size, the displacement error should be reduced by spatial smoothing.

The same verification process was also applied to the FSSns method. Although the shape of the FSSns curves differed, the ranking of the FSSns curves was the same as the FSS curves (Figure 3.6 (b)). Also in general, the neighborhood size at which the FSSns reached the peak value of a smaller shift distance was smaller than that of larger shift distance (Figure 3.6 (b)). For all four shift scenarios, the FSS at 3 km was higher than the FSS at 1km, which indicated that the model skill was improved by smoothing at 3 km.

To compare the results of group one and group two, which were placed at different proximities to the shoreline, the two FSS curves were plotted together in different colors (Figure 3.7). For each shift distance, the two curves almost completely overlap each other. Thus, we found that FSS is not likely to be affected by the irregular shape of the shoreline, even with a relatively large displacement error.

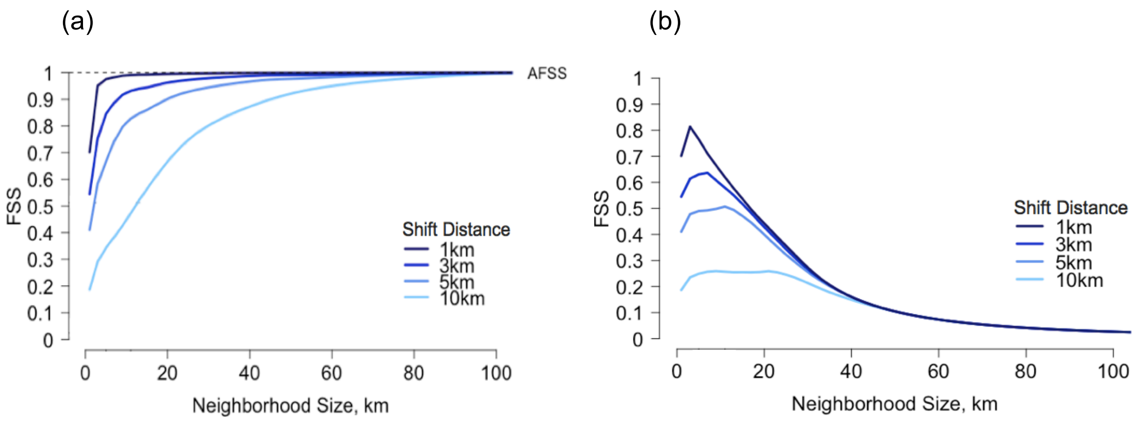

Figure 3.6 Method verification using the idealized pattern test at four shift distances in group one, for which the square pattern is located at the center of the domain. Figure (a) shows the test results calculated by the FSS method. Figure (b) shows the test results calculated by the modified FSSns method. Note that the modified FSSns method reaches a maximum skill at an intermediate neighborhood size, which facilitates selection of an optimum neighborhood size for presentation of model output.

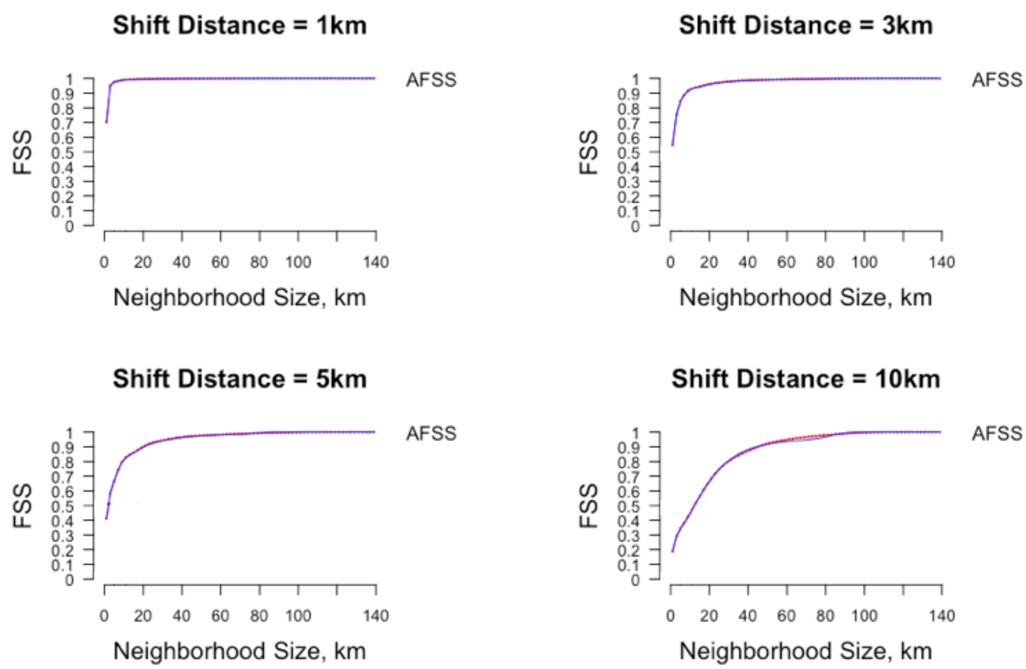

Figure 3.7 The idealized pattern test result from both groups for each shift distance, showing that proximity of the test pattern to the shoreline did not affect the results. The FSS of group one is plotted in red, and that of group two is plotted in blue.

3.4.2 The Hindcast Skill Statistics of the HAB Tracker

To assess model skill, we identified 56 matching hindcast triplets of three images consisting of the satellite observation, the model forecast and the persistence forecast from the 25 simulation runs (Table 3.1). Then, for each hindcast triplet, we computed the FSS and the FSSns which was plotted over increasing neighborhood sizes. Among the 56 hindcast triplets, two hindcast triplets having a typical FSS trend were chosen to illustrate the hindcast skill (Figure 3.8 and Figure 3.9). For both examples, FSS increased rapidly at smaller neighborhood sizes and gradually plateaued at the asymptote. After examining all the FSS plots, we found that all the FSS curves generally showed a trend of FSS increasing as neighborhood size increased.

The comparison between the model and the persistence forecast was assessed by visual comparison to the observed HAB distribution, and by comparing the difference between the model and the persistence forecast in the FSS curves. For example, on 26 July 2011 the model HAB distribution had a more similar shape and a larger frequency bias (number of forecast events is higher than number of observation events for this example) than the persistence forecast (Figure 3.8 (a)). In this example, smoothing the model output over increasing neighborhood sizes further increased the advantage of the model over the persistence forecast, as reflected by the increasing difference between the two FSS curves (Figure 3.8 (d)); this difference increased rapidly between the neighborhood size of 1 km and 15 km. In other cases, both forecasts had similar skill as illustrated by the example from 7 August 2011 (Figure 3.9). The model and persistence forecast both had a relatively accurate prediction of the HAB in terms of the similar distribution and the high FSS. In addition, the difference between the two FSS curves was small and approximately fixed over increasing neighborhood size. Thus, in this case, the model forecast did not provide much advantage over the persistence forecast, and smoothing of the model did not improve the comparison.

The FSS curves were also plotted for the modified FSSns method, for the same two examples. Figures 3.8 (b) and (c), show the smoothed model forecast and observation images at 3 km and 5 km respectively, illustrating how the FSSns method differs from the FSS method by calculating skill in comparison to the non-smoothed observation image. We observed a similar trend of the difference between the model forecast curve and the persistence forecast curve for the example on 26 July 2011 (Figure 3.8 (c)). For the example on 7 August 2011, the persistence forecast had an advantage over the model forecast from the neighborhood size of 9 km, which differed from the original FSS curve (Figure 3.8 (c)). However, this advantage remained moderate over increasing neighborhood size which was similar to the original FSS curve. The most distinct result of the FSSns method from the FSS method was that the FSSns curve reached a maximum at an intermediate neighborhood size and decreased rapidly with increased spatial smoothing. In Figure 3.9 (c), the model skill at the neighborhood size of 3 km was larger than that of 1km, which indicated that the model skill was improved by spatial smoothing.

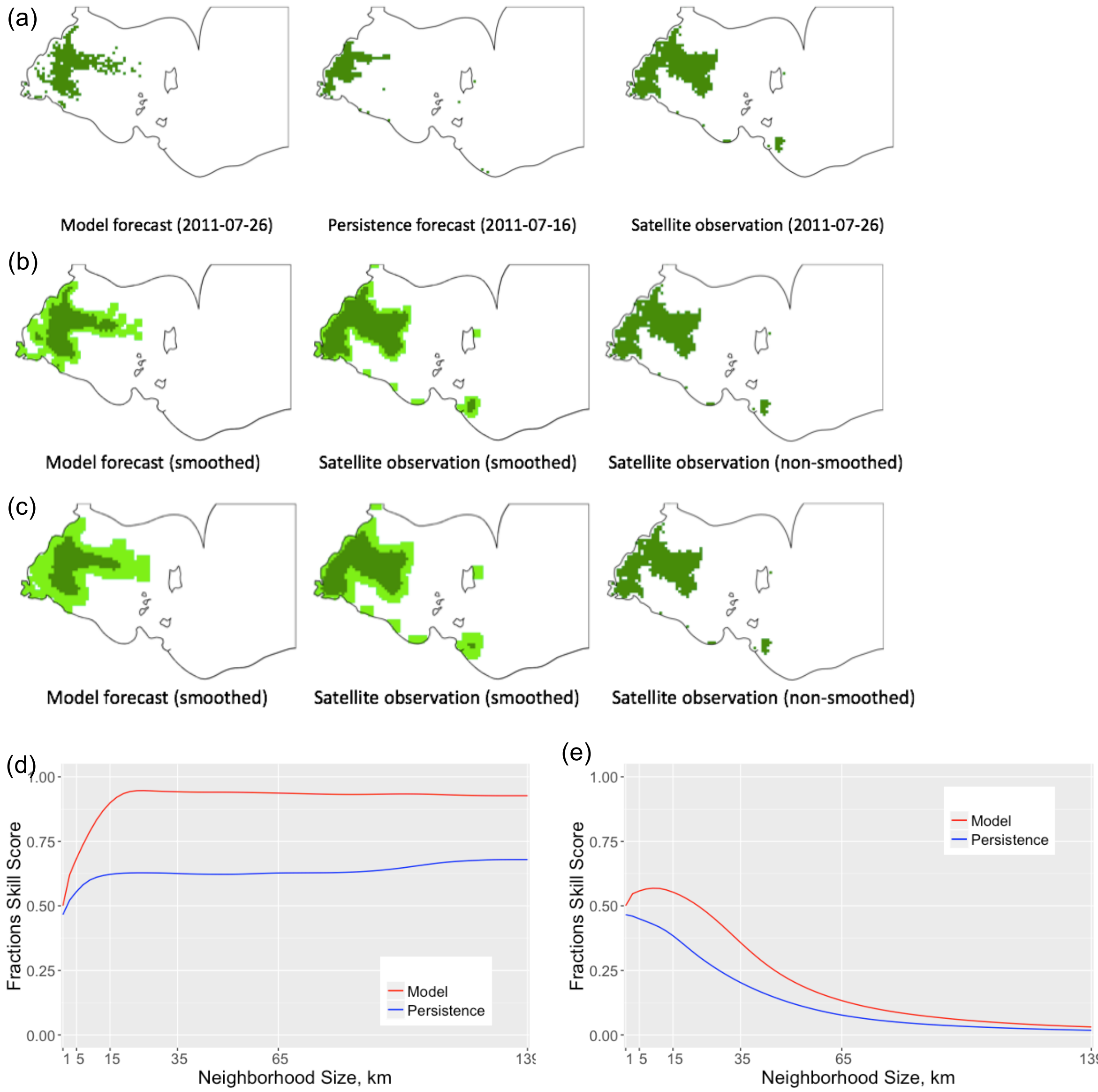

Figure 3.8 An example of a hindcast triplet from 26 July 2011, which the model forecast had much greater skill than the persistence forecast. Figure (a) shows the triplet of the three images of HAB distribution in binary category. Figure (b) shows the image output at 3 km, and Figure (c) shows the image output at 5 km. Note that the HAB events are smoothed at the neighborhood sizes of 3 km and 5 km, respectively. Pixels in green represents the presence of HAB. In the smoothed images, the light green color represents fractions between 0 to 0.5, while the dark green color represents fractions between 0.5 to 1. Figure (d) shows the FSS curve of the model forecast and the persistence forecast. Figure (e) shows the FSSns curve of the model forecast and the persistence forecast. Note that the skill of the model forecast exceeds that of the persistence forecast at all neighborhood sizes. The difference between the two forecast skills also increased as neighborhood size increased from 1 km to 15 km.

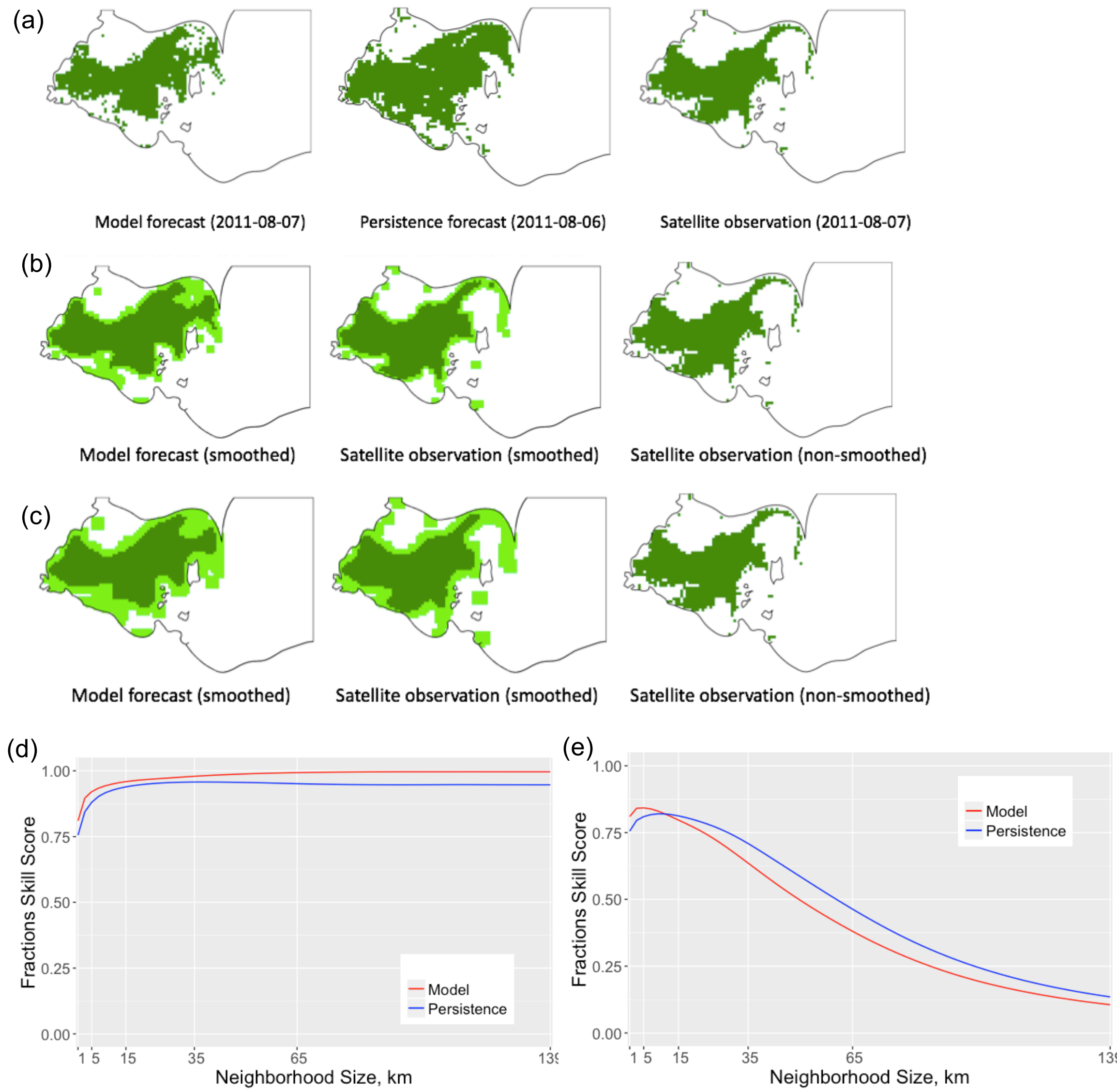

Figure 3.9 An example of a hindcast triplet from 7 August 2011, which the model forecast had similar skill as the persistence forecast. Figure (a) shows the triplet of the three images of HAB distribution in binary category. Pixels in green represents the presence of HAB. Figure (b) shows the image output at 3 km, and Figure (c) shows the image output at 5 km. Note that the HAB events are smoothed at the neighborhood sizes of 3 km and 5 km, respectively. In the smoothed images, the light green color represents fractions between 0 to 0.5, while the dark green color represents fractions between 0.5 to 1. Figure (d) shows the FSS curve of the model forecast and the persistence forecast. Figure (e) shows the FSSns curve of the model forecast and the persistence forecast. Note that at small neighborhood sizes (1km - 9km), the skill of the model forecast exceeds that of the persistence forecast.

Using the FSSns method, we determined the optimum neighborhood size for spatial smoothing which can improve the overall model skill. To determine the optimum neighborhood size, we summarized the neighborhood sizes of maximum skill of the 56 hindcast dates in Figure 3.10. Around 66% of the hindcast dates had a neighborhood size of maximum skill of 3 km, followed by 21% of 1 km. For most of the hindcast dates (79%), the model skill increased at the neighborhood sizes of 3 km or greater.

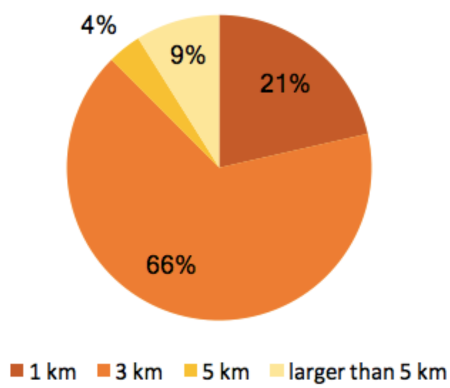

Figure 3.10 Summary of the neighborhood size of maximum skill using the FSSns method.

To quantify the advantage of the model forecast over the persistence forecast, we calculated a pairwise difference (ΔFSS) between the FSSns of the two forecasts. We focused on the ΔFSS for smaller neighborhood sizes because larger neighborhood sizes caused too much smoothing and were therefore less suitable for presenting the model output. Thus, we selected the neighborhood sizes of 1 km, 3 km and 5 km for further analysis.

At the neighborhood size of 1 km (Figure 3.11(a)), the ΔFSS was larger than zero on average over the 10 simulation days, indicating that the skill of the model forecast exceeded that of the persistence forecast over the whole prediction duration. Although the ΔFSS at day 3-4 is larger than the other simulation days, the error bars indicate that there was no significant difference of the ΔFSS among the simulation days. The ΔFSS and error bars for the neighborhood sizes of 3 km and 5 km showed a similar trend (Figure 3.11 (b) and (c)). To further analyze the ΔFSS, the FSSns of the model forecast and the persistence forecast were plotted together for the neighborhood sizes of 1 km, 3km and 5 km in Figure 3.13. The skill of both the model forecast and the persistence forecast were highest on simulation day 1-2 and decreased over simulation day 1-6 (Figure 3.13).

To examine whether the model forecast's advantage over the persistence forecast varied by neighborhood sizes, we plotted the ΔFSS against increasing neighborhood sizes for each group of simulation days (Figure 3.12). Over the 10 simulation days, the ΔFSS were almost identical at the three increasing neighborhood sizes. This suggested that the advantage of the model forecast over the persistence forecast did not increase as neighborhood size increased. However, we considered the ΔFSS to be less representative of the actual model skill than the FSSns method.

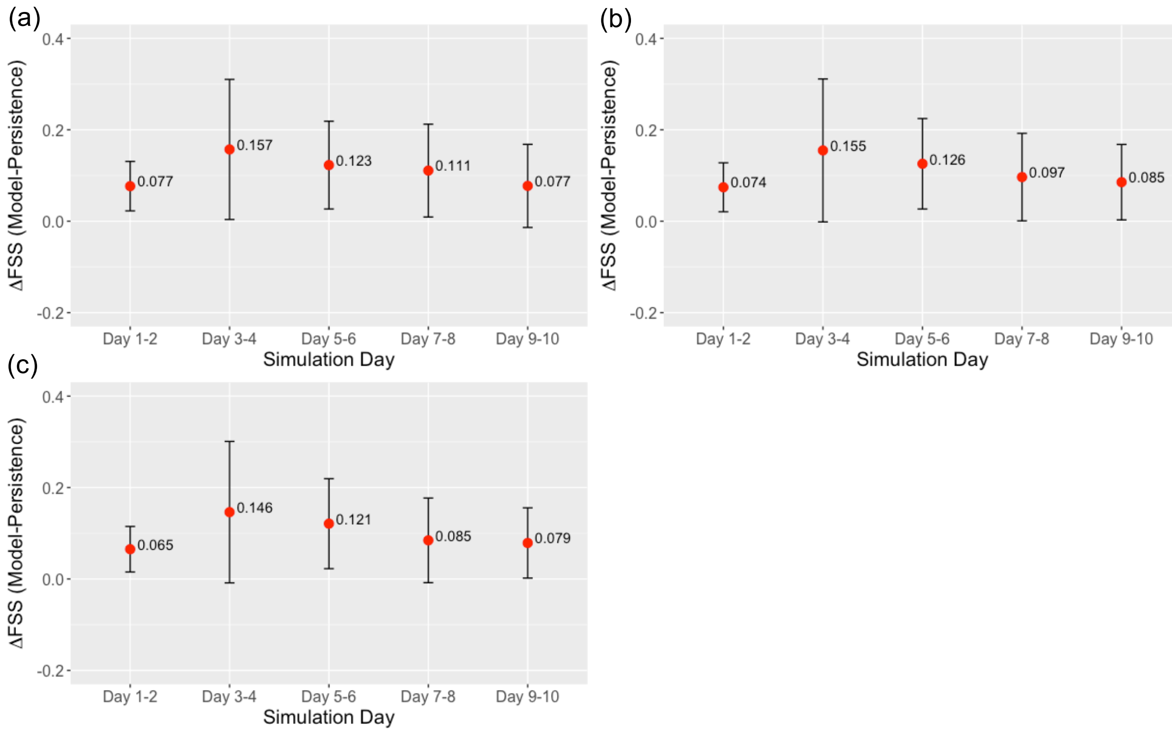

Figure 3.11 Average ΔFSS between the model forecast and the persistence forecast calculated from the FSSns method, and its 95% confidence interval over the five groups of simulation days. Figures (a) through (c) showed the data for the neighborhood size of 1 km, 3 km and 5 km, respectively. The skill of the model forecast always exceeded that of the persistence forecast over the simulation days.

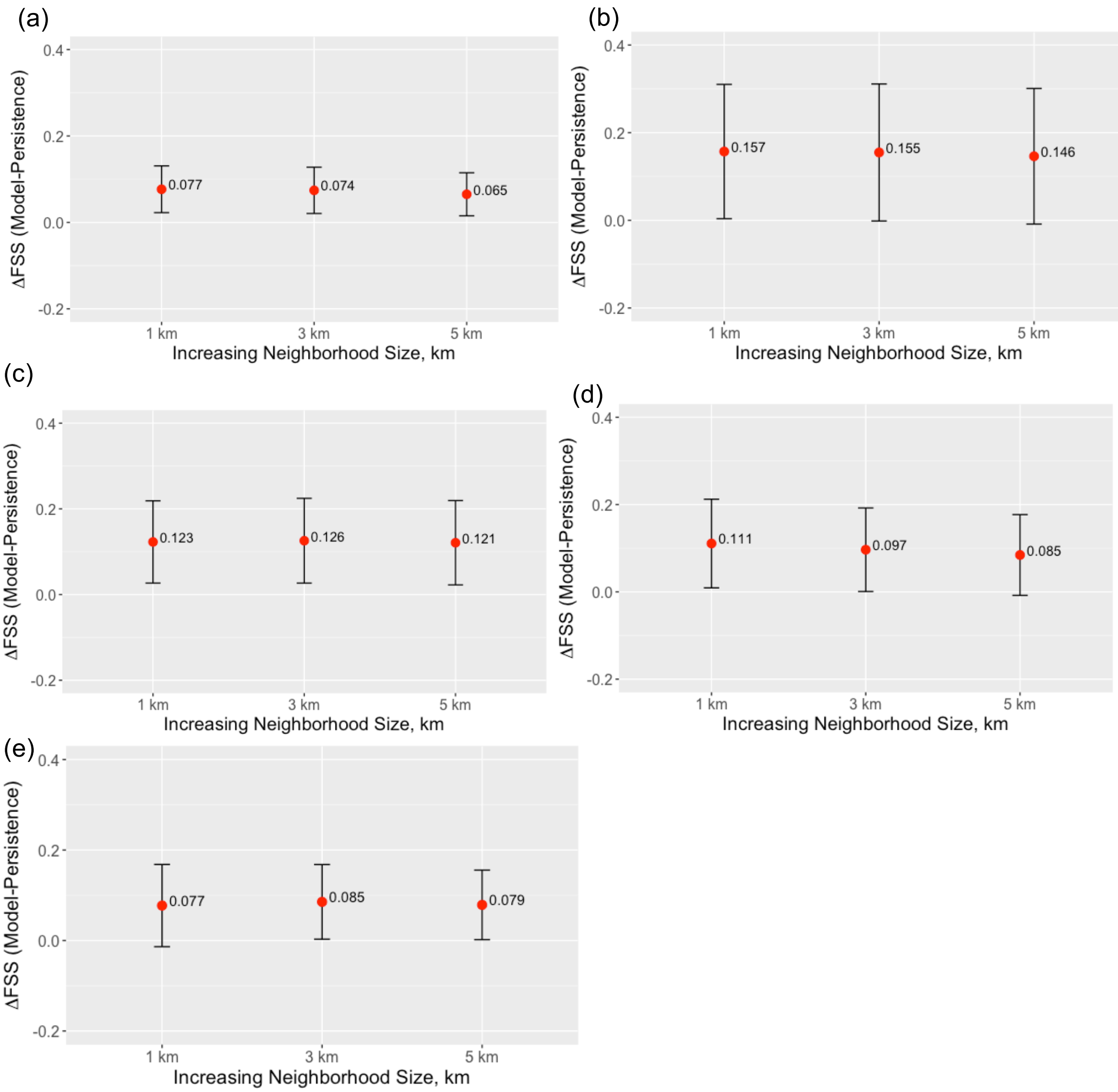

Figure 3.12 Average ΔFSS and its 95% confidence interval over increasing neighborhood sizes calculated from the FSSns method. Figures (a) through (e) showed the data for each group of simulation days of day 1-2, day 3-4, day 5-6, day 7-8 and day 9-10.

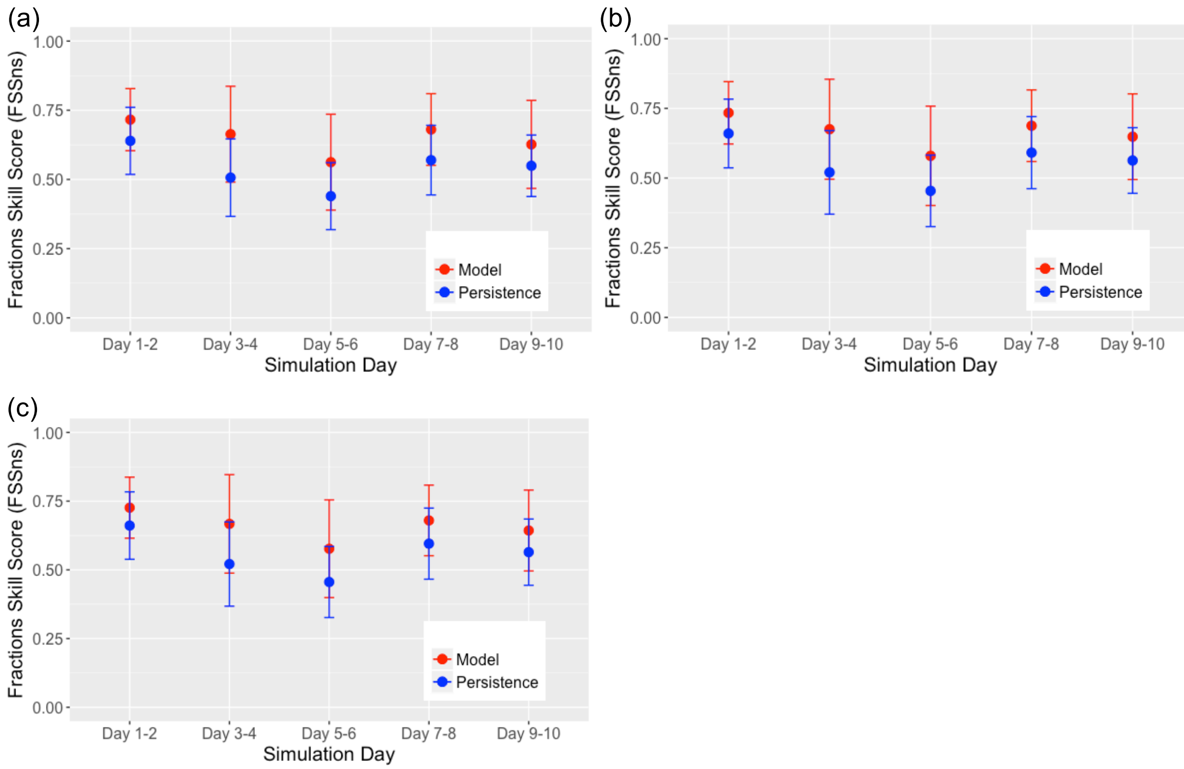

Figure 3.13 The average FSSns and its 95% confidence interval of the model forecast and the persistence forecast plotted over simulation days. Figures (a) through (c) showed the FSSns for each neighborhood size of 1 km, 3 km and 5 km.

Table 3.1 Summary of the 56 hindcast triplets identified in this study for the hindcast skill assessment. Each of the hindcast triplets consists of an observed satellite image, the corresponding model prediction, and the persistence forecast (satellite image used to initialize the model run).

Simulation Run ID	Observation Date	Model Forecast Date	Persistence Forecast Date	Simulation Day
1	July 19, 2016	July 19, 2016	July 16, 2016	3
1	July 21, 2016	July 21, 2016	July 16, 2016	5
1	July 24, 2016	July 24, 2016	July 16, 2016	8
1	July 26, 2016	July 26, 2016	July 16, 2016	10
2	July 21, 2016	July 21, 2016	July 19, 2016	2
2	July 24, 2016	July 24, 2016	July 19, 2016	5
2	July 26, 2016	July 26, 2016	July 19, 2016	7
3	July 24, 2016	July 24, 2016	July 21, 2016	3
3	July 26, 2016	July 26, 2016	July 21, 2016	5
4	July 26, 2016	July 26, 2016	July 24, 2016	2
4	August 1, 2016	August 1, 2016	July 24, 2016	8
5	August 1, 2016	August 1, 2016	July 26, 2016	6
6	August 6, 2016	August 6, 2016	August 1, 2016	5
6	August 7, 2016	August 7, 2016	August 1, 2016	6
6	August 9, 2016	August 9, 2016	August 1, 2016	8
7	August 7, 2016	August 7, 2016	August 6, 2016	1
7	August 9, 2016	August 9, 2016	August 6, 2016	3
7	August 15, 2016	August 15, 2016	August 6, 2016	9
8	August 9, 2016	August 9, 2016	August 7, 2016	2
8	August 15, 2016	August 15, 2016	August 7, 2016	8
8	August 17, 2016	August 17, 2016	August 7, 2016	10
9	August 15, 2016	August 15, 2016	August 9, 2016	6
9	August 17, 2016	August 17, 2016	August 9, 2016	8
9	August 18, 2016	August 18, 2016	August 9, 2016	9
10	August 17, 2016	August 17, 2016	August 15, 2016	2
10	August 18, 2016	August 18, 2016	August 15, 2016	3
11	August 18, 2016	August 18, 2016	August 17, 2016	1
11	August 26, 2016	August 26, 2016	August 17, 2016	9
12	August 26, 2016	August 26, 2016	August 18, 2016	8
12	August 28, 2016	August 28, 2016	August 18, 2016	10
13	August 28, 2016	August 28, 2016	August 26, 2016	2
13	August 29, 2016	August 29, 2016	August 26, 2016	3
13	September 2, 2016	September 2, 2016	August 26, 2016	7
13	September 3, 2016	September 3, 2016	August 26, 2016	8
14	August 29, 2016	August 29, 2016	August 28, 2016	1
14	September 2, 2016	September 2, 2016	August 28, 2016	4
14	September 3, 2016	September 3, 2016	August 28, 2016	5
15	September 2, 2016	September 2, 2016	August 29, 2016	4
15	September 3, 2016	September 3, 2016	August 29, 2016	5
16	September 3, 2016	September 3, 2016	September 2, 2016	1
16	September 11, 2016	September 11, 2016	September 2, 2016	9
17	September 11, 2016	September 11, 2016	September 3, 2016	8
17	September 13, 2016	September 13, 2016	September 3, 2016	10
18	September 13, 2016	September 13, 2016	September 11, 2016	2
18	September 14, 2016	September 14, 2016	September 11, 2016	3
19	September 14, 2016	September 14, 2016	September 13, 2016	1
21	October 2, 2016	October 2, 2016	September 27, 2016	5
21	October 5, 2016	October 5, 2016	September 27, 2016	8
21	October 6, 2016	October 6, 2016	September 27, 2016	9
22	October 5, 2016	October 5, 2016	October 2, 2016	3
22	October 6, 2016	October 6, 2016	October 2, 2016	4
22	October 8, 2016	October 8, 2016	October 2, 2016	6
23	October 6, 2016	October 6, 2016	October 5, 2016	1
23	October 8, 2016	October 8, 2016	October 5, 2016	3
24	October 8, 2016	October 8, 2016	October 6, 2016	2
25	October 22, 2016	October 22, 2016	October 17, 2016	5

3.5 Discussion

3.5.1 Selection of a Useful Neighborhood Size

From a practical view, the FSSns method is very useful in terms of determining the optimum neighborhood size for spatial smoothing. According to the summary of the neighborhood size of maximum skill (Figure 3.10), 79% of the 56 hindcast dates in total had an improved skill at the neighborhood size of 3 km than at 1 km. Thus, by smoothing the model forecast using the neighborhood size of 3 km, we can improve the overall accuracy of the model output as the presentation to the users. This result should be confirmed by analysis of data from other years in addition to 2011. Although 21% of the hindcast dates had maximum skill at the neighborhood size of 1 km, it is not practical to use multiple optimum neighborhood sizes for presentation of a forecast because the optimum neighborhood size for a particular date is only known after its hindcast skill assessment. However, the average difference between the FSS of 1 km and the FSS of 3 km for this 21% of the hindcast dates was very small (0.013). Thus, it is appropriate to smooth all the hindcast dates using the neighborhood size of 3 km.

3.5.2 The Advantage of the Model Forecast over the Persistence Forecast

The analysis of the ∆FSS over simulation days suggested that simulation day 1-2 has modest ∆FSS that indicates the model forecast has the lowest advantage over the persistence forecast in comparison to later days. This is mainly because during the HAB season, the HAB distribution did not change significantly for the first few days, and thus was preserved by the persistence forecast. This was reflected by the high FSS of the persistence forecast on day 1-2 (Figure 3.13). After day 2, the persistence forecast deviated from the observation, while the model forecast maintained more accurate predictions (Figure 3.13), which resulted in a larger ∆FSS on day 3-4.

In comparison to the findings of Rowe et al. (2016), we found that the trend of the mean ∆FSS over simulation days differed. Our result showed an increase on day 3-4 while Rowe et al. (2016) showed a maximum in day 5-6. Also, our hindcast assessment showed that the mean ∆FSS was larger than zero over the full 10-day simulation period, although this difference was only slightly significant or not significant on some days, while Rowe et al. (2016) found this difference was not significantly different from zero on day 7-10. This is likely because our method of hindcast skill assessment differed from that of Rowe et al. (2016). First, we used a different method to calculate the skill score: FSSns vs. PSS. Second, we calculated the uncertainty on ∆FSS using the spatially-averaged mean values from each triplet (hindcast date) of satellite observation, model forecast and persistence forecast, while Rowe et al. (2016) used a bootstrap sampling method to estimate the uncertainty on the ∆PSS, which resulted in a larger estimate of the number of independent observations, after accounting for spatial autocorrelation. Our method may have overestimated the size of the error bars by assuming that each triplet represented only one independent observation even though multiple independent observations may have occurred over the spatial domain on each date.

3.6 Conclusion

To improve the accuracy of the model output as presentation to the users, we developed a novel FSS method that applied spatial smoothing over a spatial neighborhood only to the model and not to the observed satellite image (FSSns). The FSSns method showed that the overall skill of the HAB Tracker model was improved by smoothing the model output at a spatial neighborhood size of 3 km. We also found that the HAB Tracker model performed better than the persistence forecast over the 10 simulation days and at the neighborhood sizes of 1km, 3 km and 5 km. Specific recommendations regarding how to utilize the optimum neighborhood size will be discussed in Chapter 5.

Chapter 4: A social science approach to understanding the impact of HABs on Lake Erie anglers

4.1 Background

During the development of the HAB Tracker, water utility managers were consulted as an intended user. The HAB Tracker provides water utility managers with forecasting information that allows them to prepare for any threat posed by microcystin to public drinking water. Researchers at NOAA-GLERL & CILER would like to know if the HAB Tracker may provide useful information to additional Lake Erie stakeholder groups, particularly the Lake Erie fishing community. As illustrated in the introduction, the fishing industry in Lake Erie is substantial, and may be negatively impacted by HABs.

To determine whether or not the HAB Tracker may be useful to the Lake Erie fishing community, it is important to first understand how anglers are impacted by HABs. There is limited empirical research on this topic. In a 2014 survey of Lake Erie recreational anglers, 96% of 533 respondents indicated that they were aware of HABs and 65% reported that their fishing behavior changed as a result of HABs on Lake Erie (Lake Erie Protection Fund, 2014). In a 2014 survey of Lake Erie charter captains 50% of respondents indicated that they change their behavior while fishing in HABs, including changing their location, deciding not to fish, or spending less or more time fishing (Sohngen et al., 2015).More information is needed in order to understand the decisions that different types of anglers make while fishing in HABs, and the factors influencing that decision-making. These variables will provide context for understanding angler perceptions of the HAB Tracker's utility.

By conducting a study to determine the usefulness of the HAB Tracker for Lake Erie anglers, this work will also address a need for increased stakeholder engagement research within HABs management (Bauer et al., 2010). Community engagement in research efforts has been cited as a critical component to addressing Great Lakes issues (Krantzberg et al., 2015). By asking Lake Erie anglers how their fishing has been impacted by HABs, anglers provided researchers with important insights that may contribute to the future development of NOAA-GLERL & CILER research priorities.

4.2 Research Objectives and Research Questions

The following research objectives were identified:

1) Determine potential needs of the Lake Erie fishing community based on their decision-making while fishing in HABs, and identify the variables that contribute to that decision-making.

2) Identify improvements to the HAB Tracker that will meet the HAB forecasting needs of Lake Erie anglers.

Based on these objectives, a set of research questions were developed:

Primary Research Question

1) Can the HAB Tracker be useful to Lake Erie anglers in their decision-making when fishing in the presence of HABs?

Secondary Research Questions

2) What variables contribute to determining the usefulness of the HAB Tracker to Lake Erie anglers?

3) How do HABs influence the decision-making of Lake Erie anglers?

4) What do Lake Erie anglers know about HABs?

5) What are the perceptions of Lake Erie anglers regarding HABs?

6) How do Lake Erie anglers communicate about HABs?

4.3 Methods

4.3.1 Using Grounded Theory to Understand Angler HAB Forecasting Needs

A grounded theory approach was used to gather base level information about how anglers are impacted by HABs (Glaser et al., 1968). This approach is appropriate when more data is needed to frame a research question on a topic with a limited body of research (O'Leary, 2007). According to grounded theory methodologies, qualitative data was first gathered during a series of focus groups, then transcribed, organized, and labeled into categories of similar data known as codes or nodes. Within this study, emerging categories of data will be referred to as nodes. Nodes were used to retrieve and categorize similar data relating to a particular research question or construct (Miles et al., 2014). Different nodes were then compared to each other in terms of frequency and context of occurrences. From these comparisons and additional readings of the transcriptions, themes emerged. Finally, these themes were analyzed to provide answers to our research questions and formulate recommendations for HAB Tracker improvement (Walker and Myrick, 2006).

4.3.2 Qualitative Data Collection Using Focus Groups, Polling, and a Survey

Focus groups were used as the primary method of qualitative data collection, because they allowed the opportunity for greater understanding of participant responses (Patton, 2002). Data from the focus groups provided researchers with an in depth look at the motivations, intentions, and concerns of the groups of participants. Within the focus groups, individuals were brought together that represent a diversity of opinions within the targeted population (Rubin, 2012). At the conclusion of each focus group, participants reported in a survey that they felt that the opinions expressed were representative of the diversity of opinions found within the larger Lake Erie fishing population (Appendix VI). However, focus group data cannot be extrapolated to the entire population of Lake Erie anglers, because the recruitment of participants was not a random sampling. Instead, the focus group data is intended to provide an in depth look at the complexity of thought and motivations behind angler decision-making and knowledge.

Furthermore, as opposed to individual interviews, the focus group seeks to mimic the social context within which decisions regarding fishing are discussed by anglers. The unit of study is the focus group, and not the individuals. Therefore, providing statistical data reflective of individual thoughts and behaviors is not appropriate for the focus group methodology (Morgan, 1993).

Additional qualitative data collection methods include the aforementioned survey and polling data. The survey was used to obtain participant feedback on their experience with the focus groups (see Appendix VII). Research participant polling data was also collected during the focus group to quickly determine individual familiarity with *Microcystis* and the HAB Tracker.

4.3.3 Focus Group Participants

The target audience for these focus groups was Lake Erie anglers who fish in the Western Basin who are impacted by HABs. Within this audience, two sub-categories of anglers were targeted: offshore recreational anglers and charter boat captains. Offshore recreational anglers and charter captains were identified as key potential participants, because these sub-groups are represented by a network of regional organizations within the Lake Erie basin. Below is a figure listing all of the organizations that were asked to participate within this study (Figure 4.1). An attempt was made to contact all known charter captain and recreational angling groups within the targeted study region via phone and email.

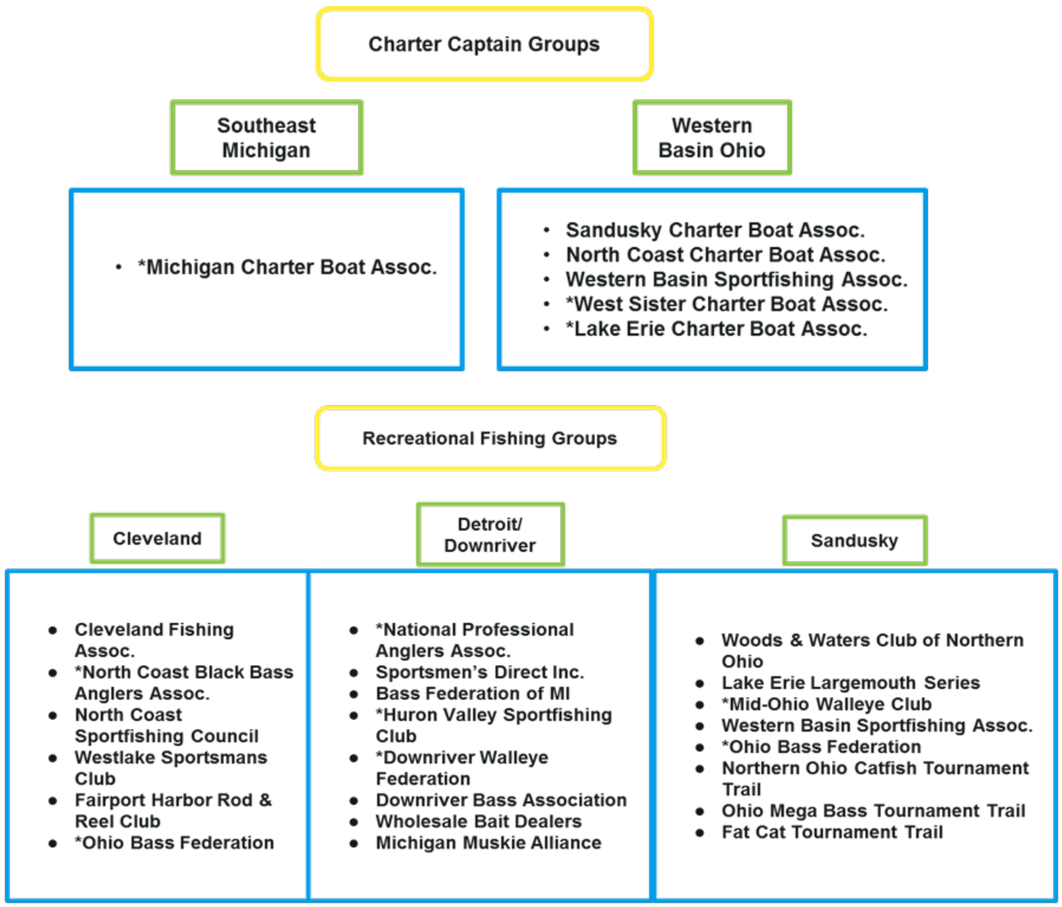

Figure 4.1 Charter captain and recreational angler groups that participated within the focus groups categorized by region. Organizations with an asterisk indicate those participated in the focus groups. Organizations without asterisks were contacted for the study, but either didn't respond or were unable to attend the focus group.

Representatives of these organizations acted as community gatekeepers, or individuals who enabled the researcher to successfully connect with the stakeholder group (Tushman, 1980). Gatekeepers facilitated researcher access to stakeholder communities through the use of their inside knowledge and social networks. These gatekeepers were found through existing professional social networks or by contacting well-known local sportsmen and charter captain organizations. Gatekeepers within both the charter captain organizations and the recreational angler organizations aided researchers in identifying participants who were representative of the diversity of perspectives and interests of their respective communities within Lake Erie. They also facilitated efforts by calling, emailing, and otherwise encouraging their contacts to attend focus group events.

An effort was made to recruit focus group participants who were unaffiliated with organizations or gatekeepers by engaging these individuals at major boat landings. However, this tactic was inefficient and did not yield any new participants.

Forty-one anglers participated in this study, twenty-one of which were offshore recreational anglers and twenty were charter captains. Ultimately, six participants (all recreational anglers) identified as being unaffiliated with a fishing organization. All six were recruited through the recommendation of professional colleagues or other participating anglers. These unaffiliated anglers did not express views that were markedly different from the other participants. All participants attended one of the seven focus groups.

Focus groups were organized in communities surrounding the Western Basin of Lake Erie in Michigan and Ohio. This region was chosen because it is the area most highly impacted by HABs. Focus group locations included the communities of Wyandotte and La Salle in Michigan, and Sandusky, Cleveland, and Oregon in Ohio (Figure 4.5).

Cleveland is located along the southern shore of the central basin of Lake Erie. After speaking with these participants and other anglers in the Cleveland area, it became evident that anglers from this region are not as impacted by HABs as anglers fishing further near the Western Basin. As a result, an additional focus group for recreational anglers was held in Oregon, OH to ensure equal participation by charter captains and recreational anglers who are impacted by HABs. The data from the Cleveland focus group are included within this study to enhance the data set, while noting the unique characteristics of this focus group.

4.3.4 Focus Group Structure

Focus groups consisted of homogeneous groups of five to ten individuals, because this number of participants allowed for a diversity of opinions while also ensuring that each individual perspective may be heard (Kruger and Casey, 2009). Homogeneity within focus groups is recommended to reduce response bias among individuals (Patton, 2002), therefore participants of focus groups were segregated into four groups of recreational anglers and three groups of charter captains. A total of seven focus groups were held in this investigation with twenty-one offshore recreational anglers and twenty charter boat captains (Figure 4.2).

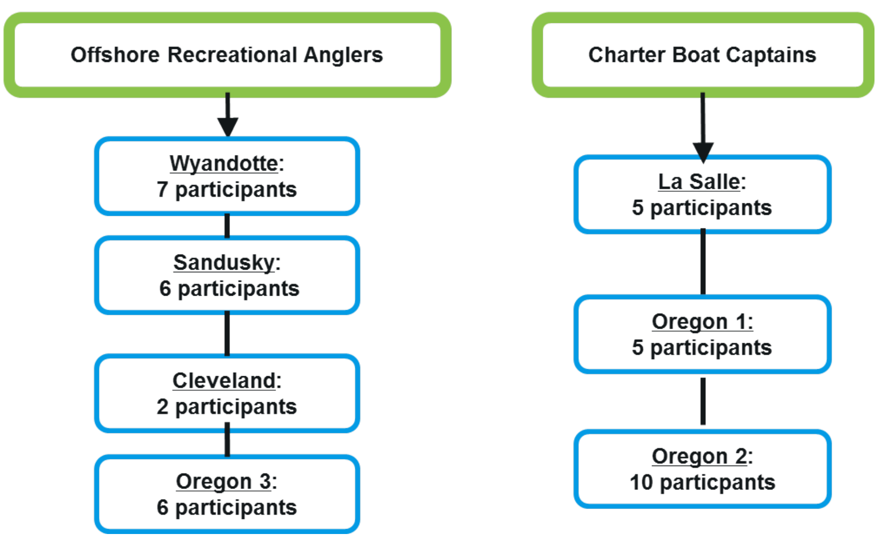

Figure 4.2 Focus groups listed by angler type and focus group location. Three focus groups were held at the same location in Oregon, OH. These groups have been labeled as Oregon 1, Oregon 2, and Oregon 3.

The key factor in determining the number of focus groups to hold within a study was based on the concept of data saturation. Data saturation was reached when additional interviews or focus groups fail to yield new revelatory themes or variables. A study of the process of data saturation conducted by Guest et al. (2006) offered evidence that data saturation can occur within the first twelve interviews, and major themes can be uncovered in as few as six interviews.

Each focus group lasted approximately two hours, and centered on discussion of questions developed in a semi-structured interview guide (see Appendix II). A semi-structured interview guide was designed to ensure that each focus group was structured around the same line of inquiry with questions that are strategically worded, but that enough flexibility exists within the question guide to explore new or key topics as they emerge during the discussion (Patton, 2002). Questions developed within the interview guide for this study were structured around six variables that were identified as key to addressing our research questions. These variables included: 1) angler knowledge about HABs, 2) angler perceptions about HABs, 3) angler communication about HABs, 4) the identity of angler participants, 5) angler decision-making while fishing in HABs, and 6) initial angler perceptions of the utility of the HAB Tracker (Figure 4.3).

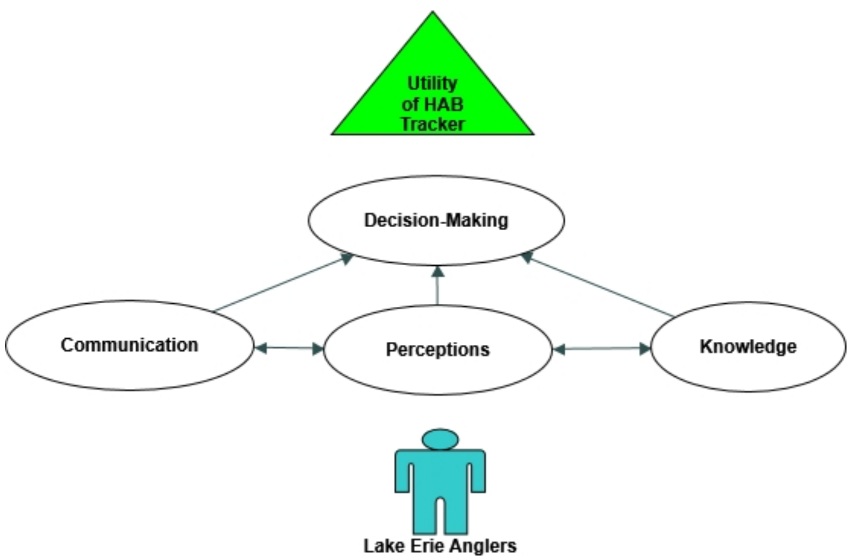

Figure 4.3 Initial concept map for the Lake Erie fishing community study, identifying key variables used to develop the interview guide.

Angler decision-making while in HABs was identified as a primary variable that can be used to understand angler perceptions of the utility of the HAB Tracker. The other variables (communications, perceptions, knowledge, and participant identity) informed this key decision-making variable.

Each focus group began with a brief introduction to the purpose of the study given by the researcher, followed by a self-introduction by each participant. These introductions were guided by prompts related to where, when, and for how long each angler had been fishing in Lake Erie. Next, questions were posed about angler knowledge, perceptions, communications, and decision-making while fishing in HABs in an order that facilitated conversation flow. At least 10 minutes were allowed for each question and responses. A brief knowledge assessment through polling technology was also conducted to determine angler ability to visually identify HABs in Lake Erie (see Appendix III). Following this collection of baseline data, the group paused for dinner. During this time, the researchers addressed any misinformation or lingering questions that participants had regarding the nature of HABs in Lake Erie. After dinner, a presentation was given to the participants to introduce the HAB Tracker and explain its function and intended utility (see Appendix IV). Screen shots were shown to direct anglers to the HAB Tracker website. A video demonstration of the HAB Tracker forecast from 2015 was shown to illustrate how the HAB Tracker functions during an intense bloom, and to educate participants on how to interpret the HAB Tracker forecast. At the conclusion of each focus group, participants were given a folder with additional information about HABs in Lake Erie and the work that NOAA-GLERL & CILER are undertaking to address the HAB issue (including a factsheet highlighting the work accomplished under the 2012 Great Lakes Water Quality Agreement, Annex IV). All focus group conversations were recorded with the use of a digital audio recorder, and were later transcribed.

4.3.5 Data Analysis Using Conventional Content Analysis

All interview transcripts were analyzed using Conventional Content Analysis (Hsieh, 2005), a process by which variables identified within the research questions and other emergent nodes were compared. After interviews were transcribed, they were read as a whole by the researcher to develop initial impressions of these variables and nodes and quotes that corresponded to them.

Although variables were identified prior to data collection to inform the creation of the interview guide, nodes were derived from the interview text using inductive category development (Hsieh, 2005). Inductive category development is a process by which researchers identify important concepts as they emerge from the data, rather than beginning the research process with preconceived ideas regarding the nodes informed by the literature. After each focus group transcript was coded for variables and emergent nodes, the relationships between these nodes were analyzed by the researcher to identify themes and recommendations relevant to the research questions.

Tools used to assist with data analysis included NVivo software, concept mapping, and memo-writing. NVivo qualitative data analysis software (QSR International Pty Ltd. Version 11, 2015) was used to categorize and organize data within focus group transcripts, create concept maps, and organize memo-writing. Concept-mapping was used to visually demonstrate the relationship between variables and nodes. This tool aided in the identification of themes that were used to answer research questions and formulate recommendations for NOAA-GLERL & CILER. Memo-writing was used as a reflective tool throughout the research process, and consisted of writing down key impressions, variables, and themes that the researcher observed while reviewing the data (Charmaz, 2015).

4.3.6 Quality Assurance

Efforts were made to identify and address any potential research limitations within this study. Some key issues that were addressed included the following:

- The semi-structured form of the interview guide approach created some variability in how questions were posed, and therefore the responses given by interviewees (Patton, 2002).
- Conventional Content Analysis relies upon the ability of the researcher to identify relevant variables. Therefore, it is possible that not all relevant variables were identified (Hsieh, 2005).
- The chosen interviewees may not have been representative of all opinions found within the target audience that they represent.

To address these possible limitations, interviewees provided insights into the data analysis through member checks (Denzin and Lincoln, 1994). Interviewees provided feedback on emerging themes during the 2017 Annual Charter Captains Conference in Huron, Ohio where initial results of the project were presented. Interviewees were also asked to provide immediate feedback on the focus group experience and representativeness of the sample participants immediately following the focus group through an anonymous written survey. Feedback from this survey indicated that anglers were satisfied with the diversity and representativeness of the focus group participants, given the goals of the study (Appendix VI). Several participants did suggest additional perspectives that were not included within their focus group. However, these perspectives were not members of the target audience, and included commercial fishermen, on-shore anglers, pleasure boaters, and tourists. A literature review also served to support the relevance of variables, emerging nodes, and themes within this study.

4.4 Results and Discussion

4.4.1 Interpreting Angler Decision-Making through Multiple Variables

<u>Participant Characteristics</u>

The characteristics of focus group participants provided researchers with information on participant backgrounds, which was used to enhance understanding of focus group responses to interview guide questions. At the beginning of each focus group, participants provided information about their age, fishing frequency, and their preferred fishing areas.

Participants were asked to report their age within one of the following brackets: 20-35, 35-50, 50-65, or 65+. Most participants (44%) were 65 or older. Thirteen anglers reported that they were 35-50 years old (32%). Only 5 participants were 20-35 years of age (12%), and 5 participants were 35-50 years old (12%). This focus group composition is reflective of a 2014 survey of 766 anglers living in Ohio, wherein the average age of respondents was 60 years old (Sohngen et al., 2015).

All participants reported fishing frequently during the fishing season. Charter captains reported fishing almost every day from May to September. Recreational anglers reported fishing at least once or twice a week during the fishing season. All anglers reported a preference for fishing close to their marina and within their state waters. Both groups reported making special trips on occasion to travel beyond state boundaries into adjacent state and Canadian waters. Anglers in Michigan reported fishing between the mouth of the Detroit river to the Ohio state line. Most anglers in the Western Basin preferred to fish between the Toledo intake structure west to Vermillion or Lorain (Figure 4.4). Anglers in Cleveland also reported a preference for fishing near Lorain. The Lake Erie islands (Kelleys, West Sister, Bass) were also reported as favorite fishing locations.

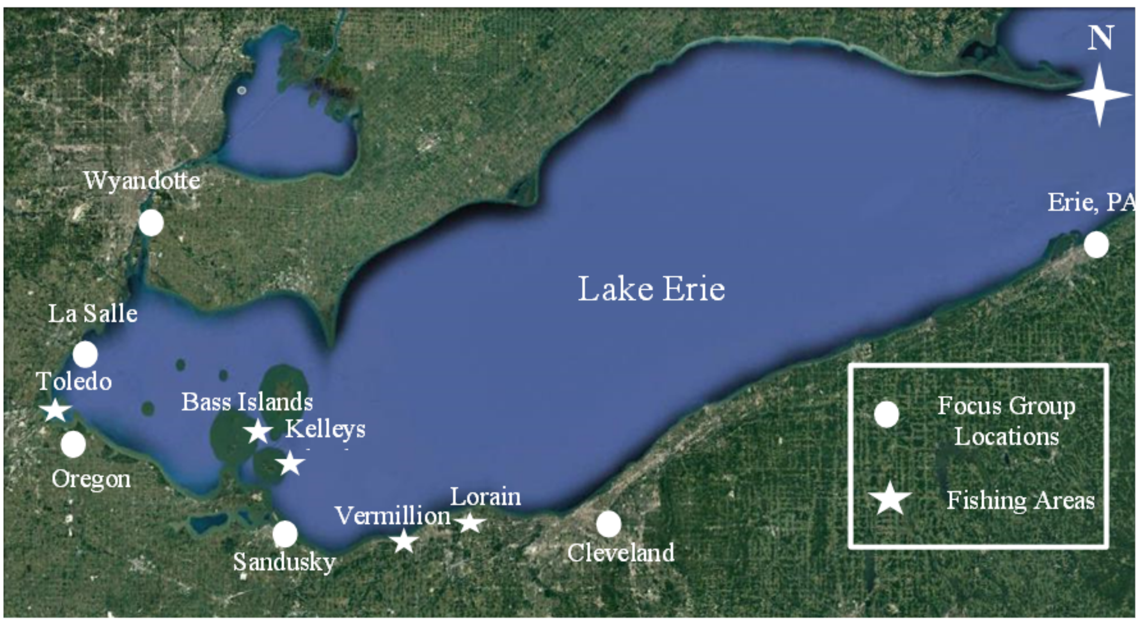

Figure 4.4 Map of focus group locations and common fishing areas identified by participants. Map created using Google Earth imagery.

It is important to note that several participants represented additional unique perspectives beyond that of a recreational angler. Three anglers reported having professional experience within the field of fisheries management. Five anglers indicated that they were also tournament fishers. One angler within the Sandusky focus group was a farmer, and a charter captain in the La Salle focus group works a chemical engineer for a company that manufactures water treatment chemicals. A range of individual backgrounds and experiences serve to shape the perspectives, knowledge, and decision-making of anglers relating to HABs.

Understanding the relationships between variables

Following introductions within each focus group, participants were asked questions that corresponded to four variables (decision-making, knowledge, perceptions, and communication about HABs). This was done to address the following research question: What variables contribute to determining the usefulness of the HAB Tracker to Lake Erie anglers? Concepts that emerged during responses to these questions were then coded as emergent nodes related to these variables. A concept-map was used to illustrate the relationship between variables, nodes, and the primary research question (Figure 4.5).

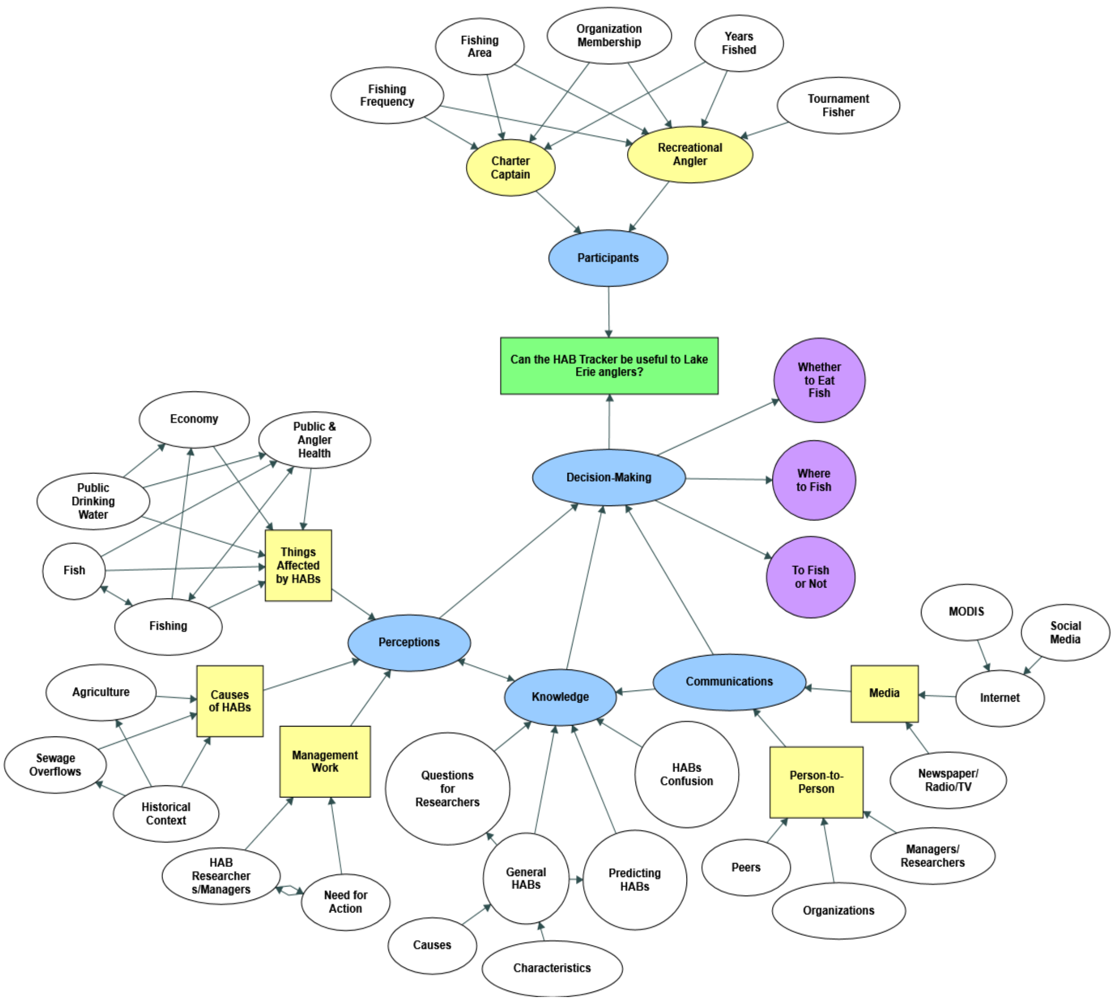

Figure 4.5 Map of nodes that emerged during coding of focus groups created with NVivo. The rectangle is used to indicate the research question. Each node connected to the rectangle indicates a variable that emerged during the coding of focus group interviews. Lines connecting the nodes indicate conceptual linkages between nodes. The nodes in blue are key nodes used to categorize variables that emerged during focus group discussions.

Only nodes that directly relate to angler perceptions of the HAB Tracker and fishing in HABs are discussed within this report. These nodes include perceptions of the impact of HABs on angler health, fish, and fishing. Nodes relating to knowledge include general HABs knowledge, predicting HABs, and specific questions about HABs that participants have for researchers. These questions are listed in Appendix VII. Nodes relating to the variable communication include communication about HABs with peers, organizations, researchers and managers, and communication through the internet, newspapers, radio, or television.

Variables that Impact Angler Decision-Making while Fishing in HABs

To understand how HABs influence the decision-making of Lake Erie anglers, participants were asked how their fishing practices have changed as a result of HABs, and what their greatest concerns are regarding the future of HABs in Lake Erie. In response to the interview guide questions, participants reported addressing three primary decision points: whether to fish, where to fish, and whether to eat the fish that they catch or not. These key decision-points emerged during discussions in all seven focus groups.

a. The Decision of Whether to Fish

The first decision-point that anglers face during a HAB event is whether or not to fish. Recreational anglers frequently indicated that in a heavy bloom, they would choose not to go fishing or fish in a nearby inland lake without HABs. Reasons cited by recreational anglers for not wanting to fish in the blooms included health concerns, the unappealing aesthetics of fishing in a bloom, and the perceived impact of the bloom on fish.

> *…Even though I don't know exactly why it's toxic, the fact that it's toxic algae….I mean, I'm not going to be swimming in it or anything, but the fish are coming up through that, and then I'm handling them and eventually eating them. We keep and we eat, so I would not fish in one. Not to mention that the aesthetics of it are just kind of gross. All logic aside, there's beautiful clear water two miles away, so we'll go there.*

This concern for aesthetics has been echoed by stakeholders of other lakes that experience HABs. In a survey of residents recreating in inland lakes with HABs in Washington State, respondents reported that water quality and lake aesthetics were their two greatest concerns (Billingham, 2012).

In two recreational angler focus groups, participants mentioned that they had fished during HABs, although they didn't care for the experience. They justified their decision to continue to fish by citing a time when they or someone they knew had successfully caught fish through a bloom.

> *…I've only fished through an algae bloom maybe half a dozen times in the last three years…or around or through them. On a few trips, I've actually found very successful fishing in an algae bloom.*

One angler explained that fellow anglers may continue to fish, because they feel desensitized by the many environmental hazards associated with the lake over the years.

> *I think…at least to a point…that we've almost become immune to it. Because every day if you're in this genre, you're paying attention to what you're reading about the Metro beaches closing because of water quality….It's closed today, but next week we'll all go fishing on Friday, and the water's not a whole lot different than it was last*

week…. With everything else that's happening, I think maybe we're not as concerned as we should be.

This observation is supported by ethnographic research on fishermen's risk perception, which suggests that professional fishermen are unique in their acceptance of perceived risk during fishing activities (Knudsen, 2010). All charter captains indicated that they continue to fish during HAB events. Charter captains in Ohio expressed that they fish in HABs, because they feel that they have no other choice.

Researcher: Has anybody ever fished in a bloom?

Captain 1: Sure.

Captain 2: Oh yeah, we have to.

Captain 3: Everybody here has to.

Captain 4: No place to go sometimes. Everybody has to.

In contrast, captains in Michigan seemed relatively unfazed by the prospect of fishing in HABs.

Researcher: Do you fish during HAB events?

Captain 1: Oh, heck yeah.

Captain 2: Oh, absolutely.

Captain 1: I don't even think twice about it.

For charter captains, deciding whether or not to fish in a bloom is a high stakes question, because they are dependent upon fishing with customers for their livelihoods. A few Ohio charter captains indicated their desire to cancel fishing trips in highly concentrated blooms, because of the negative impact they believed the blooms had on the fish and the embarrassment that they felt at offering their customers a fishing trip through such unappealing conditions.

…We were losing money last year [2015] right and left, because either our clients decided not to come because they saw the picture, or we decided on our own to say, "don't come." Because we reached a point where we couldn't catch the walleye anyway….

Most charter captains expressed great concern for the customer's decision regarding whether to fish in a bloom or not. One Ohio captain commented, "How it affects our fishing practices is that we'll be sitting at the docks tied up with no customers!" Captains reported responding to these customer concerns in different ways. Charter captains in Michigan expressed frustration at customer fears that they felt were unfounded and provoked by sensationalized media coverage.

Right after that water scare there in Toledo, I had a couple people cancel trips, because they were listening to the news….I had three or four more calls from people *that fish with me every year, and they had been eating the fish for 15 damn years. What's the difference? They didn't get sick. They didn't die. Their kids hair ain't falling out. Then they'll say, "Okay, we'll go."*

However, these captains also reported that most of their customers deferred to the captain's opinion regarding whether to continue with the fishing trip or not. One Michigan captain reported that he rarely receives questions from customers about algae while they book their trips. Instead, these questions came up almost as an afterthought while customers were already out on the water. The captain then assured the customer that he believed the impact of the algae on the fishing was minimal.

For charter captains who preferred not to fish during HABs, the extent of the bloom and whether or not they could avoid it dictated their decision whether or not to fish. Fortunately, anglers in a focus group in Ohio also said that often the wave action served to mix the bloom, which helped to minimize its negative impact on their fishing experience. However, when mixing doesn't occur, one angler said "you don't know if you have a walleye in tow until it gets out of the water."

b. The Decision of Where to Fish

The next decision-point that anglers face during a HABs event is where to fish. All anglers indicated their preference to avoid the HABs and fish in an area with clearer water, when possible. For some, avoiding the algae is a conscious choice. For others, it may be an unconscious decision.

Well, you don't realize that you're doing it, but sitting here and thinking about it, when we do go out perching, I hear him saying all the time, "Well, that's all algae in here. Let's go out that way. So, it is affecting us whether we consciously know it or not. It does affect where we fish.

When asked why they sought to avoid the blooms, anglers agreed that fishing in HABs detracts from the aesthetic experience of fishing in Lake Erie. The blooms are reported to have an "acrid smell" and unattractive appearance. For some, the smell is nauseating. The blooms were also reported to stain the boat and planer boards green, requiring the boat owners to wash their boats immediately following each trip. Boating through a bloom also reportedly caused the boat to lose speed, increasing the amount of gas needed for each trip.

Anglers also reported that they avoided fishing in locations with the blooms, because they felt that fish were negatively impacted by them. Several anglers felt that the blooms did not negatively impact the health of fish. These anglers would continue to fish through a bloom, even though they preferred clearer water, in an effort to follow the fish. When fishing in a bloom, charter captains in Michigan explained a technique by which they clear the surface scum surrounding the boat by running their propeller. This afforded the captains and their customers with a clearer space within which to cast. Michigan charter captains embraced this technique as a way to adapt to the presence of the blooms. The Ohio charter captains were less enthusiastic about adapting to fishing in HABs. This may be because the Ohio charter captains overall felt that the fish were more negatively impacted by the blooms, whereas the Michigan charter captains doubted that the fish were negatively affected. A few anglers expressed frustration specifically with trolling while trying to avoid the blooms.

When we troll, we have to have a pretty wide area to troll in. You could be trolling…you're catching fish, and pretty soon you look out and all around your boat is green, just solid green. You go, "Okay…it's going to break loose here pretty soon." But, no, no, no. It ain't working. So, you've got to pull up all of your stuff, turn around, get back out of that algae, because them fish aren't biting in it.

c. The Decision of Whether or Not to Eat the Fish

The decision whether or not to eat the fish was the decision-point that seemed to be of greatest interest to anglers, although not all participants felt that the level of risk was the same. A few recreational anglers indicated that they did not eat fish caught during a HAB event, because they feared the unknown impact of HABs on the fish. Other recreational anglers continued to eat the fish that they caught, but remained concerned regarding the possible implications of this decision. One recreational angler went to great lengths to minimize the level of potential HABs exposure to himself and his family.

The grandkids are still eating the fish, so I do everything that I can to make sure they're not getting the toxin. I rinse the fish with bottled water after I catch them, and I freeze the fish in bottled water. I just started doing that three or four years ago. Before that, I never did.

Some anglers felt that since they had been eating fish from Lake Erie all their lives, in spite of consumption warnings from the DNR about chemical contaminants like mercury, that the risk of consumption was often exaggerated. Several recreational anglers who did eat fish caught during a HAB event referenced a study where the concentration of microcystin found in the fish tissue was minimal and concentrated within the liver (Wilson et al., 2008). All charter captains indicated that they ate fish caught during HABs events, but the level of concern that they had for the personal risk they accepted in doing so differed. When customers asked whether or not it was safe to eat fish caught in the blooms, most charter captains cited the lack of evidence to the contrary as a safety assurance. Several captains also used the lack of regulation on the commercial fishing industry to assure customers that it's safe to eat the fish.

My favorite thing to ask people is if they eat Canadian Walleye from the market or at a restaurant, and they'll say "Well, yeah! It's fantastic!" Then I'll say, "Well, do you know where Canadian walleye comes from? It's right here in Lake Erie!" They'll go, "Really?!" Usually once you tell people that, they're okay. They'll say, "Oh! I didn't realize that I had been eating it my entire life."

One angler from the La Salle focus group posited that the fish they catch grow so quickly that the microcystin doesn't have time to bioaccumulate within the fish to levels that would be harmful to humans. Several anglers expressed concern for the impact that an advisory on fish consumption related to microcystin would have on their business: "Oh, we get a consumption advisory and we're done. You won't be able to sell your boat to anybody else." Even so, anglers expressed an emphatic desire for more research on the potential health effects of the consumption of fish exposed to HABs.

Knowledge

The knowledge that anglers possess about HABs in Lake Erie inform their decision-making while fishing in HABs, as well as their perceptions of the utility of the HAB Tracker. For this reason, anglers were asked what they know about the causes of HABs in Lake Erie and how to describe HABs to someone from outside the region who has never heard of HABs before. Additionally, anglers were asked to participate in a knowledge assessment activity to determine their ability to differentiate *Microcystis* from other non-harmful algae found within the region.

a. Microcystis Identification

During the knowledge assessment to test visual *Microcystis* recognition, the majority of the participants were able to correctly identify the images depicting *Microcystis* (41 anglers correctly identified *Microcystis* 98 times out of 127; Figure 4.6). The images shown for this assessment are included in Appendix III. When anglers answered the identification questions incorrectly (29 out of 217 times), anglers most often mistook Cladophora or Lyngbya for *Microcystis*. The most common incorrect answers to the knowledge assessment were images of Cladophora piling up on beach shores or clinging to ropes in the water. During focus group discussion, anglers described *Microcystis* as the “small flakes you see in the water all of the time”, or the algae that gets so thick that it looks like “green paint” or “pea soup.” However, a few anglers mistakenly referred to Microcystis as the “green stuff that gets caught on your fishing line.” Likely, these anglers are mistaking a long, filamentous alga, like *Cladophora* or the cyanobacterium *Lyngbya*, for *Microcystis*. The differences between the knowledge assessment results of charter captains and recreational anglers were minor (Figure 4.7), as were the differences between Michigan and Ohio anglers (Figure 4.8). The knowledge assessment and focus groups discussion indicated that the majority of participants had a clear understanding of what *Microcystis* was and how to differentiate it from other types of algae that the HAB Tracker does not forecast.

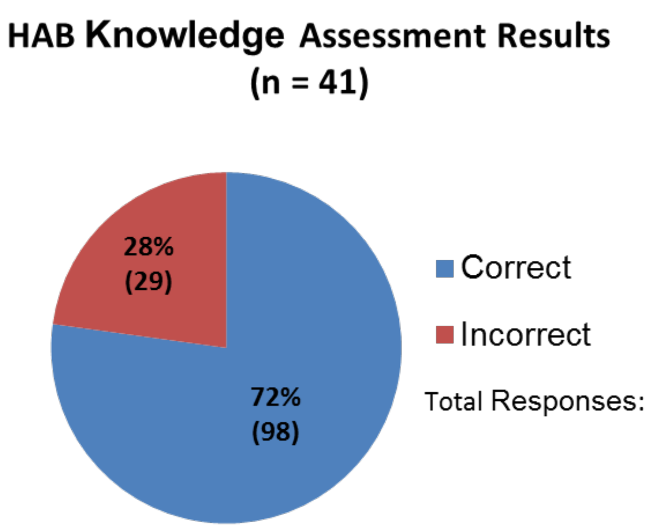

Figure 4.6 Results from the knowledge assessment data set assessing the ability of participants to distinguish between photos of *Microcystis* and other algae. 41 participants were assessed, providing a total of 127 responses.

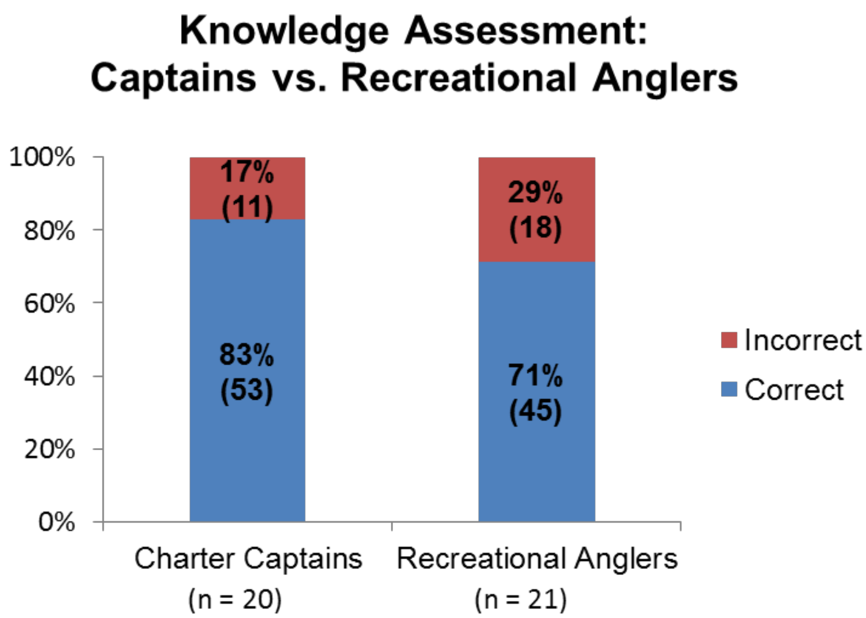

Figure 4.7 Results from the knowledge assessment data set comparing charter captains and angles. 20 of the participants were charter captains and 21 were recreational anglers with a total of 41 anglers sampled. The number of total responses was 127.

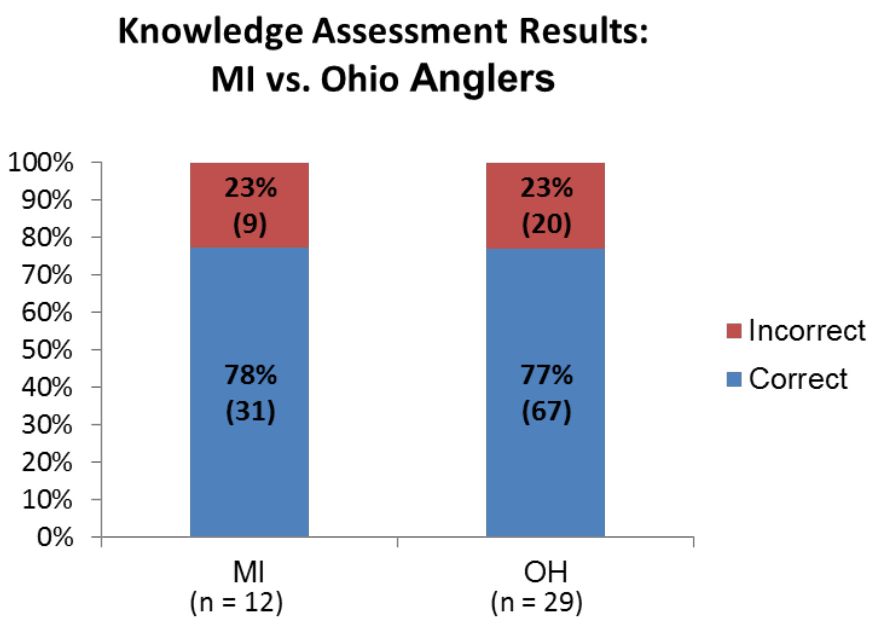

Figure 4.8 Comparison of knowledge assessment results between Michigan and Ohio anglers. Twelve of the anglers were from Michigan and 29 were from Ohio with a total of 41 anglers sampled. The number of total responses was 127.

b. Causes of HABs

Another key aspect of angler knowledge that informs their perception of the utility of the HAB Tracker is their knowledge of the cause of HABs in Lake Erie. Angler understanding of the causes of HABs informs their perceptions of the severity of the HAB problem, and their feelings toward the need to avoid the blooms. At least one angler in every focus group stated that *Microcystis* is naturally occurring within Lake Erie, and that the HAB events today were caused by changes in anthropogenic inputs into the lake.

> *I guess I assumed that it [HABs] was something that just naturally happened, but that the fertilizer and run-off specifically was going overboard, making it too much.*

While anglers sought to explain what they knew about HABs, they frequently referred to changes they had seen in Lake Erie over the last several decades to frame their response. The majorities of the participants within the focus groups were fifty years old and older, and had been fishing on Lake Erie for most of their lives. As a result, they had seen changes in water quality and algae concentrations in the lake over the years. This gave them a greater appreciation for the HAB problems of today, and provided context for their understanding of the source of the HABs.

> *Years ago, the main thing that they stopped was the phosphorous and laundry detergent. That was the biggest problem that we had. When we eliminated a lot of that stuff, it really did clean up and everything got better….I believe that's a part of the problem out there today….*

All focus groups indicated that the agricultural industry was a major contributor to HABs in Lake Erie, and five out of seven focus groups expressed their frustration that farmers weren't doing more to decrease the amount of nutrients that they released into Lake Erie in the form of run-off.

> *You're combatting forces up the Maumee River, you know…3 to 400 miles up the watershed…and do they really care about Lake Erie? You know, does the guy that's living in Benton Harbor really care that much about what's going on in Lake Erie? He probably really doesn't care. He's growing his tomatoes and that's that. But you know, those are the people who will need to get results before the problem will go away.*

A few anglers also expressed frustration toward municipalities for not eliminating instances of sewage overflow into Lake Erie. One recreational anglers expressed his opinion that in order to effectively address the HAB problem, everyone needed to take responsibility for reducing nutrient loading, not just the farmers or the sewage treatment managers. He felt very passionately that collective action by all residents within the Lake Erie watershed was required in order for the HABs to be controlled.

> *Everybody needs to do their part. If you're going to take care of a problem, you've got to look at all of the issues and all of the causes. What can we all do to help take care of it.*

A few charter captains and recreational anglers expressed an awareness of the impact of HABs on the entire Lake Erie ecosystem, and speculated as to the factors, like invasive zebra and quagga mussels, that might serve to exacerbate the blooms.

> *I think one of the big reasons that it [Microcystis] is such an issue is that it's non-palatable. Things don't eat it. Zooplankton can't consume it. Zebra mussels don't eat*

it. So, it’s not really fueling that food web….It’s at the base of the food web, but it’s not useful to anything.

This awareness of the connectivity of life within Lake Erie colored their perceptions of the severity of the HAB problem.

Perceptions

Angler knowledge about *Microcystis* and the causes of HABs inform the perceptions that they have about the impact of HABs on fishing. To assess perceptions, anglers were asked what concerns they have about the future of HABs on Lake Erie, and how they think HABs are affecting fish and the fishing industry.

a. Impact of HABs on Fish

There was some disagreement among anglers about the impact that HABs have on fish within the Western Basin. Given the large extent of the blooms, many anglers feel intuitively that it must be having an impact on ecosystem functioning, and therefore on game fish. If the harmful alga is out-competing the algae that plankton and planktivorous fish eat, then it is likely disturbing the food web from the bottom up. Charter captains in Ohio speculated that the declines in bait fish populations over the past ten years, specifically Emerald Shiners, may be somehow linked to recent increases in HABs. However, charter captains in Michigan indicated that there was an abundance of forage fish in their waters. Overall, it seems that most anglers believe that the extent of HABs coverage over the Western Basin, the depth of the mixing, and the level of toxicity may determine the impact of HABs on fish.

If it’s a light bloom, then it doesn’t matter….Walleye don’t like a lot of light. But if it becomes toxic, it’s not alright and it’s a flip of a coin. We don’t know if it’s releasing toxins yet, but the fish know….Those fish know if that algae bloom goes from more than a light bloom to a heavy bloom, and I guarantee then that there are no fish in it.

When the extent or the toxicity of the bloom becomes severe, then some anglers have observed that this drives fish out of the Western Basin.

This much I do know as a fisherman. If I see the algae bloom coming on, you can pretty much set your clock as to when the fish take off. They will entirely leave our end of the lake, if it’s heavy enough.

Several anglers expressed concern that blooms may be changing the historical migration patterns of the walleye. When the blooms begin to die in the early fall, anglers also speculated that the increased release of microcystin causes the fish to swim out of the area.

Angler 1: *The perch seemed to be scared the last two years in the fall when the algae died and went to the bottom. Then there was nothing. There were no perch around!*

> *Angler 2:* *I think they didn't have enough oxygen or something. They all moved out, but you could catch them on the other side of Kelley's island where the water is deeper.*

Several charter captains and recreational anglers expressed that they felt the impact of HABs on the fish was minimal. These anglers believed that walleye and perch may seek the edges of the blooms for protection from the sun. It made sense to them that these gamefish would seek water that has a "green tinge" and that isn't "gin clear with nothing in it", and that a light bloom may provide this quality of water. These anglers cited instances when they or someone they knew had a successful fishing trip when casting through the bloom. This perception was more common in Michigan than in Ohio, where the blooms are often not as highly concentrated. An angler in the Wyandotte focus group said that when he caught fish in a HAB, he often found them "lying flat on the bottom", possibly under the bloom in clearer water.

> *I've anchored in water when it was green, and guys are pulling up perch left and right….If you're in 20 or 27 feet of water out on the line, I'm not sure exactly how far the algae sinks down, but the perch are coming off the bottom. Is it all the way down to the bottom, I don't know, but it doesn't seem to affect the amount of fish you catch.*

Another angler from the Wyandotte group countered this claim with his belief that given the right set of circumstances, fish can be found in a wide range of habitats, even those that do not provide preferred conditions. Finding fish below a bloom may not mean that fish prefer the bloom. It may mean that the fish have found a depth of clear water to hide in below the bloom. Two anglers also speculated that the blooms have less impact on "rough fish, like smallmouth bass and catfish." Even though some anglers still felt that fishing was possible in a bloom, they indicated that it was not preferable. As one anglers said, "Once this algae blows up….you're rolling the dice a little more in where you're fishing until you find clearer water."

b. Impact of HABs on Angler Health

The level of angler concern for their health while fishing in a bloom ranged widely. Charter captains in Michigan didn't see any cause for concern, while captains in Ohio explained how they felt their health had been directly compromised by microcystin exposure. Recreational anglers in both states expressed concern for how much they didn't know about the health risks they may be exposing themselves to while fishing in HABs.

All focus groups indicated that they were aware of the health concerns associated with HAB exposure. Given this knowledge, the degree of microcystin exposure required by anglers while fishing was alarming for some.

> *Angler 1:* *One of the biggest concerns…is handling the fish and reaching in. It's soaking through your skin or absorbing it. They recommend evidently washing your hands. Keep them clean or wear gloves. Don't walk in the water. Stay out of the water. No swimming.*

> *Angler 2:* *I've got enough health problems! I don't need a skin rash! I think the kidney issue, that's more rare. But if you have your grandkids and you all go to the beach, are you going to let them go in it? No! I mean, it's just not a healthy situation.*

Others were less concerned about reducing exposure to microcystin while fishing.

> *I mean, they give warnings to avoid skin contact and all that, but on the other hand most of us have washed the slime off our hands on the edge of the boat and don't pay any attention to it. But you do wonder about that, the toxicity of the break down products.*

Some anglers felt that they had observed correlations between personal ailments and microcystin exposure. A large number of charter captains in Ohio associate a seasonal cough with exposure to decomposing *Microcystis*. One angler took a trip in a bloom with a customer who experienced an acute asthma attack that they associated with water spray from the back of the boat while fishing in a bloom. Another angler had been advised by his doctor to stop his scuba diving activities and otherwise reduce microcystin exposure, because of kidney problems. Other anglers speculated whether or not the skin irritation that they experienced later in the fishing season was exacerbated by microcystin exposure.

> *I get super dry skin after I've been in the water a few times, and I never had that prior to the algae. I've always been kind of an oily skin person, but my ankles will start itching. That's the only part of me that's out of the wetsuit, and that's the only part that itches.*

In contrast, charter captains in Michigan doubted if the microcystin in Lake Erie ever reached concentrations that would be harmful to humans or animals.

> <u>Angler 1</u>: *I know it's toxic to animals. Well, milk is probably toxic to animals if they drank enough.*
>
> <u>Angler 2:</u> *I don't even know if it could get so bad in this lake from what I understand, because there is so much water flowing in and out through the system. The level would have to be so ridiculously high.*

c. Impact of HABs on Fishing Industry

Regardless of the actual impact of HABs on fish and human health, the fishing industry in Lake Erie is facing a problem with public perception. Charter captains in Ohio stated that the "effect on our business is massive." By most accounts, the Ohio charter fishing industry has been negatively impacted by the spread of HABs in the past few years.

> *Just looking at last year [2015], typically every one lost 25% of their business. Now, think about the fact that we only run from April until November. You've got to earn your living during that short time. We lost 6 weeks, because of the bloom last year….Typically, last year versus the previous year, we lost 10 grand within that six week timeframe….It doesn't sound like a lot of money, but for that guy that 10 grand has to carry him until next year.*

Recreational anglers in Sandusky and Wyandotte who are not dependent upon Lake Erie for their livelihood expressed concern regarding the impact of HABs on Lake Erie's reputation as a desirable area to recreate.

> *What's the perception of Lake Erie? By Great Lakes standards, it's the dirty one. That bothers me a lot more than the concerns about fish.*

All anglers worried that if the HABs persist, then local economies will suffer.

> <u>Angler 1:</u> *It's not only the fishing industry that's affected. It's bait stores, hotels, condos, restaurants, the whole gambit. People come up here to fish for a couple days. I have some people that come up for a week, and they're renting places and eating out every night. If they don't show up, you're losing money.*

> <u>Angler 2:</u> *My neighbors come up every single weekend. It's just a summer cottage to them. When they see the algae, they wouldn't come up. They wouldn't go to the islands; they wouldn't go swimming and hanging out. They didn't want any part of it.*

<u>Angler Communication regarding HABs</u>

Angler knowledge about HABs is shaped by their sources and means of gathering information, which is defined as the variable, communications, within this study. To understand how anglers communicate about HABs, participants were asked which people and outlets they refer to when they seek to gather more information about the blooms.

All anglers communicated about HABs with organizations and peers or by following media reporting. Many anglers learn about HABs by accessing information online through website or Facebook pages. Participants most frequently mentioned visiting the webpages of the following organizations for information on HABs: Ohio Sea Grant, Ohio DNR, NOAA-GLERL, and Ohio EPA. A few anglers mentioned receiving HAB information through newsprint, the radio, or the television. Outlets that were mentioned included the Monroe Newspaper (MI), the Toledo News (OH), local television stations, and local marine radio channels. When focus group participants were asked how they receive information about HABs, most focus groups discussed conversations that they had with their fishing/charter fishing organizations, peers, or searches they had done for HAB information on the internet.

As referenced in the section on angler recommendations for the HAB Tracker, anglers who belong to organizations rely greatly on communications from these organizations as a source of trusted information about HABs. When asked "What is the best way to communicate with anglers about HABs?", most anglers recommended reaching out to large Lake Erie angler organizations. The information circulated within these organizations frequently extends beyond the membership through peer to peer conversations and Facebook posts
.

> <u>Angler 1:</u> *There's a kind of community of fishermen, too. Most of the time we're calling our friends saying, "Hey, did you go out yesterday? How did you do? Where did you go?"*

> <u>Angler 2:</u> *There's a lot of radio chatter. You know, floating through the pea soup or trolling around the bloom or the algae. People are hollering out where it's at.*

Charter captains in particular emphasized the important role that peer to peer communication plays in the transfer of HAB knowledge. Captains also explained that they felt responsible for educating themselves on HAB information, because they are an important source of HAB information for their customers.

> *We want to have answers for ourselves, but if our customers ask, we want to be able to answer some of those questions and at least speak intelligently about what we're talking about. We're not just here to throw our line in the water and catch a fish. The lake matters to us. It's our livelihood.*

A study of the social networks of charter captains in Lake Michigan also found that peer-to-peer communication played a key role in information sharing among captains (Mueller et al., 2008). In addition to communicating with peers and organization members, many charter captains also communicate directly with HAB researchers and fisheries managers. The charter captain organizations that participated within this study were contacted frequently by academics for participation in Lake Erie research. Through connections with researchers, members of these organizations regularly attend workshops and speaker events where they are educated on the latest HAB research. This high level of engagement with researchers was a commonality between the Ohio charter captain groups and the Michigan charter captain group. There seemed to be a direct link between the level of angler knowledge and the relationship of these anglers with HAB researchers.

However, a familiarity with HAB researchers and their work did not always correlate with an increased interest in the HAB Tracker. Even though charter captains in Michigan and Ohio had experience working directly with Lake Erie researchers, their opinions differed on the perceived utility of the HAB Tracker. Charter captains in Michigan stated that they didn't think the HAB Tracker would be useful to them while fishing. Charter captains in Ohio felt very strongly that the HAB Tracker would be a useful tool for all anglers. It is likely that many variables involving angler knowledge, perception, and participant characteristics served to shape perceptions of the HAB Tracker and HABs in general. A predominant attitude within the Michigan charter captain focus group was that HAB researchers and media partners were primarily motivated by their own personal gain instead of presenting accurate information about the state of HABs in Lake Erie. One of the points of greatest concern for these captains was the inappropriate and inaccurate reporting of the media about HABs. These anglers expressed frustration that sometimes the alga depicted by media in photos is not *Microcystis*, but a nuisance alga like *Cladophora*.

> *The news media can do a lot of damage. They said on the Toledo News that if you take a shower in it, it will kill you. It was bad. They shut down all the water, telling people don't bathe in it….Customers were literally cancelling their trips, and it was a big news thing like the whole world is going to end.*

In order to communicate effectively with Lake Erie anglers about HABs and the potential utility of the HAB Tracker, this knowledge of angler communication preferences and attitudes should be considered.

4.4.2 Participant HAB Tracker Recommendations

<u>General Recommendations</u>

After questioning anglers about their decision-making, perceptions, knowledge, and communication regarding HABs, interview guide questions focused specifically on angler impressions of the HAB Tracker. First, data was collected on participant familiarity with the HAB Tracker through a polling activity. Next, participants were asked interview guide questions regarding their general impressions of the HAB Tracker, as well as specific recommendations for HAB Tracker improvement.

Of the forty-one anglers who participated in this study, only eleven anglers had heard of the HAB Tracker prior to participation in the focus group (Figure 4.9). Ten of these anglers first heard about the HAB Tracker from the researcher during a participant recruitment presentation which took place at an Ohio Sea Grant outreach event for charter captains at Ohio State University's Stone Lab on August 22nd, 2016. The angler who found the HAB Tracker independently did so while exploring NOAA-GLERL's website. Of the eleven anglers who had heard of the HAB Tracker, only four had visited the HAB Tracker website prior to participation in the focus group. None of the anglers indicated that they had used the HAB Tracker to plan a fishing trip. However, their opportunity to do so was likely limited by the relative sparseness of the bloom during the 2016 season.

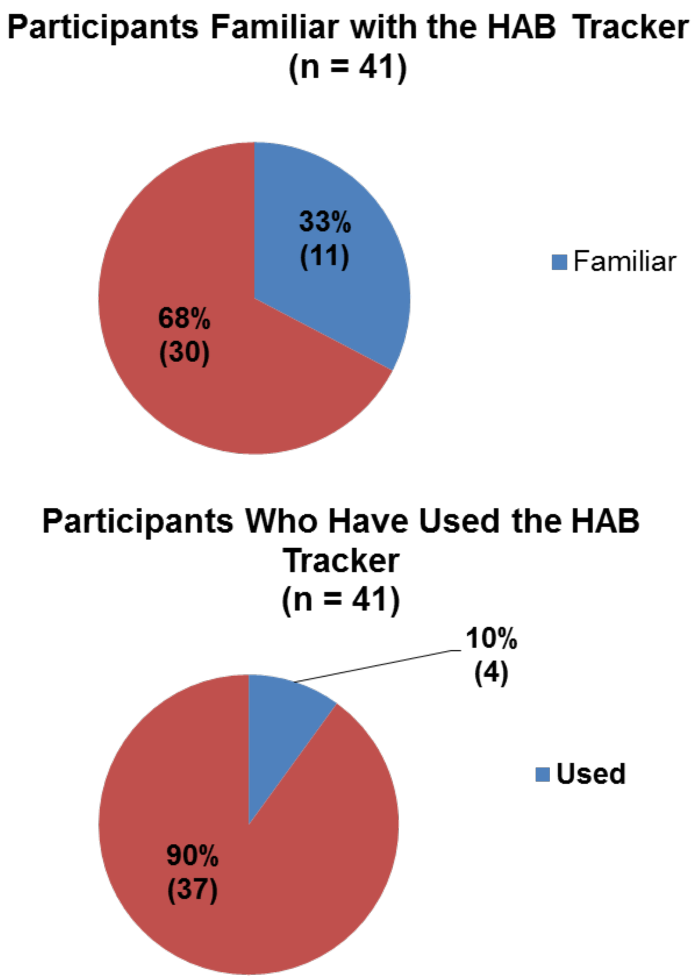

Figure 4.9 Number of participants who had heard of the HAB Tracker, and the number of participants who had used the HAB Tracker.

Overall, most anglers said that they thought the HAB Tracker would be useful to them, because it would help them identify desirable fishing locations (saving them time and fuel) and enhance their current methods of tracking HABs in western Lake Erie.

> *A lot of times we didn't know…we'd take off for one spot, and then go look after another spot. Now, we just know where to go instead of wasting gas running around.*

For these reasons, all charter captains and several recreational anglers are already keeping close watch on the movement of the blooms, and have developed their own methods of HAB tracking.

a. MODIS Satellite Imagery

Currently, many charter captains and a few recreational anglers indicated that they use NOAA's Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery of the Great Lakes to track heavy concentrations of HABs in western Lake Erie. Anglers indicated that they access MODIS satellite imagery of Lake Erie by visiting the NOAA CoastWatch webpage for the Great Lakes region (www.coastwatch.glerl.noaa.gov/modis). Typically anglers view the MODIS satellite imagery of Lake Erie the night before a fishing trip to identify where clear fishing areas might be located the following morning. However, anglers did express frustration with using MODIS. One angler commented that the website is "hard to get to", and another said that MODIS was useful "so long as it's not a cloudy day." The frequency of complete or partial cloud cover over Lake Erie decreases the reliable utility of the satellite imagery of MODIS for anglers. MODIS also does not differentiate between HABs and sediment plumes in its surface imagery. In the opinion of some anglers, this lack of differentiation didn't matter, because they were seeking boundary areas where "changes in water color" are likely to occur. These boundaries are preferred for fishing, because of the perception that fish seem to be attracted to this type of transitional water. Other anglers said that they would like to be able to distinguish between the causes of changes in water color, and know specifically where the high concentrations of HABs are located. Anglers also expressed frustration over the frequent occurrence of "cloud days", which resulted in a lack of Lake Erie surface image reporting by MODIS. The HAB Tracker would present these anglers with more reliable imagery.

b. Angler Ability to Predict HABs

One focus group consisting of charter captains determined that the HAB Tracker was of little use to them. These anglers explained that they felt confident enough in their own ability to predict the movement of HABs in Lake Erie that they didn't need the HAB Tracker. These anglers said that they already had access to tools like MODIS, and were able to observe lake conditions while fishing every day. When certain environmental conditions arise at the right time of year, large blooms occur with reliability. Anglers identified favorable conditions for HABs as calm water and warm temperatures in the months of July through early October.

> *If it's a flat, sunny day and there's been a lot of run-off, it's going to happen. It's going to happen fast.*

These anglers will refer to MODIS to confirm their predictions or add support to what they've experienced while fishing the Western Basin. These anglers with an interest in tracking conditions in the Western Basin are also looking at additional web sites to gather information about wind direction and velocity, wave height, and depth of water clarity. The websites that the anglers reported visiting ranged widely, although each angler had one or two preferred sites that they visited for information on lake conditions. Websites or applications that were mentioned included iWindsurf (www.iwindsurf.com), WindAlert (www.windalert.com), Sailflow (www.sailflow.com), as well as the NOAA-GLERL webpage. This additional information further informs their predictions for the depth of mixing of the bloom and direction of bloom movement for the next day. For these anglers, the HAB Tracker is providing a more reliable, scientific version of the predictions they are already making themselves. A few anglers were so confident in their ability to predict the movement of the blooms, that they questioned the utility of the HAB Tracker.

> *It kind of tells us what we already know…..So for us, this is kind of old news, getting on the computer and all. I don't mean to be putting it down, because it's a good thing. It's just not anything that we're not seeing already.*

Anglers in two focus groups also expressed deep distrust in the reliability of forecast models, citing the frequent inaccuracy of Lake Erie wind and weather forecasts.

> Angler 1: *They can't predict the weather 5 days in advance. How are they going to predict this!*
>
> Angler 2: *They can't predict tomorrow's weather!*

Anglers in three different focus groups questioned the reliability of the HAB Tracker, and emphasized that a reliable forecast supported by ground-truthing was essential to the utility of the HAB Tracker for anglers. However, it's important to note that these anglers had never used the HAB Tracker during a bloom season.

c. Negative Impact on customers

A charter captain discussed the potential negative impact that the HAB Tracker could have on customers. If the customers are able to easily access images of the extensive coverage of HABs on Lake Erie, then they may be deterred from hiring a charter captain. This angler speculated if information about the HAB extent is something that should be advertised to customers.

> *I guess what concerns me about this tracking device is that it's not going to be good for me to be advertising….To me it sounds like this is becoming the way of the future. Let's not take care of the algae, let's just start tracking it…and I don't get it. I appreciate it, but if I'm going to go out there and wave this to the public, "come and take a look at what I'm fishing in! Take a better look at it!" …I just don't know.*

d. Research Priorities

At least one individual in every focus group expressed concern that the HAB Tracker represents an effort by researchers to adapt to the HAB problem, rather than seek to mitigate it. Anglers were concerned that researchers were not prioritizing addressing the source of the HABs issue, and that perhaps federal research funds were being misdirected. The anglers explained that the HAB Tracker would be of no use to them on days, like in 2015, when the entire Western Basin was covered in a thick algal boom.

> *Instead of focusing on the algae bloom itself, you're going to focus on getting more sophisticated with tracking things. We need the problem fixed; we don't need to track it. I'm a fisherman. I can tell you where it's at it. I can tell you this: once it starts, I can set my watch to two weeks before my end of the lake is going to get covered with it…if the conditions are right. I like what you have going on here, but like I said, I'm not going to go out and publicize it. It's not good to publicize it. I don't want people to know about it.*

This distrust of researchers and their intent in developing the HAB Tracker led one focus group to conclude that the HAB Tracker was of no use to them, illustrating that perceptions of HAB researchers deeply influence perceived utility of the research products. These angler perceptions argue for increased communication of the intent and purpose of NOAA & CILER's work. To address this need, fact sheets were given to participants at the close of the meetings highlighting the extent of NOAA-GLERL & CILER's efforts to address HABs in Lake Erie. Further insights on this matter will be explored in the chapter on HAB Tracker recommendations.

Specific Recommendations

In addition to discussing general impressions of the HAB Tracker, anglers also suggested specific recommendations for improvement. These recommendations can be categorized as suggestions for improved data interpretation and increased accessibility.

a. Improvement of Data Interpretation

Many anglers felt that additional data could be provided within the HAB Tracker to improve its usefulness. For example, a color scale is provided on the map of the Western Basin to identify higher and lower concentrations of cyanobacterial chlorophyll. However, no further context is given for this information to aide anglers with data interpretation. What are the implications for anglers when fishing in a yellow area of the map? What does yellow mean in terms of health risk, impact to fish, or even what they can expect to see in terms of visual concentrations of HABs? The concept of chlorophyll concentration is abstract, and difficult for anglers to interpret.

As stated previously, anglers are visiting a range of web sites (including NOAA-GLERL's website) the evening before a fishing trip in order to gather information on water clarity, wave height, wind direction, and velocity. It would be helpful to the angler if this information were aggregated onto a single web page, like the HAB Tracker webpage. Anglers expressed a pointed interest in having information about water turbidity and dissolved oxygen coupled with concentrations of HABs.

> *I wish that NOAA would have a one-stop place where I can see what the wind and weather forecasts are, the current conditions, water visibility, temperature…you know, the whole ball of wax without having to look at different sections.*

Other visual tools could be provided to enhance the utility of the HAB Tracker. For example, the map of the Western Basin could be made bigger for easier visibility. One angler also suggested that lines of latitude and longitude or a map zoom function could be added to the map to aide anglers with wayfinding and trip planning.

b. Improve HAB Tracker Accessibility

Anglers offered suggestions for how the accessibility of the HAB Tracker might be improved. Many anglers emphasized the need for a mobile friendly web page or application. Of specific concern was the map presenting information on vertical mixing. Within this map, users click on different monitoring sites on a map of the Western Basin to populate data into the vertical mixing model. It is easy to select these sites with a mouse or cursor, but much more difficult to click on a monitoring site on a phone or tablet if the user is using their finger and a touch-screen.

Other concerns relating to accessibility included name recognition and the ability to find the HAB Tracker website. Several anglers suggested that the name "HAB Tracker" may be confusing and esoteric for most anglers.

> *If you put the name "HAB Tracker" up there, 90% of the people out there aren't going to know what that means!*

The acronym "HAB" is rarely if ever used by anglers to speak about harmful algal blooms. Anglers also expressed that the HAB Tracker website was difficult to find. In order to access the HAB Tracker, anglers must click through several pages on NOAA-GLERL's website. Anglers suggested that the HAB Tracker be more prominently featured on the NOAA-GLERL webpage, and that a simpler web link be created to make it easier to share this text with other anglers.

4.4.3 Participant Recommendations for Communications about HABs

In addition to making recommendations to the HAB Tracker tool, participants also provided insights into how NOAA-GLERL & CILER can improve their communication efforts with the Lake Erie fishing community to raise greater awareness of the HAB Tracker. The most common suggestion for improving communications about the HAB Tracker involved outreach to angler organizations. Five out of the seven focus groups suggested that representatives of NOAA-GLERL & CILER should attend more angler organization meetings to promote the HAB Tracker, including the organizations that participants were affiliated with (Figure 4.1). These organizations included the Lake Erie Charter Boat Association, West Sister Charter Boat Association, Downriver Walleye Federation, Downriver Bass Association, Huron Valley Sportfishing Club, Ohio Bass Federation, North Coast Black Bass Anglers Association, and Mid-Ohio Walleye Club. Some of the participants at the Wyandotte focus group had seen a previous presentation given by a CILER employee about the HAB Tracker at a Michigan Sea Grant event, and offered suggestions for improving HAB Tracker presentations.

> *When you guys came to our club before, it wasn't as extensive as this. I don't think anybody really got the gist of, you know, how valuable it could be. A few of us guys*

afterwards, we talked about it and I don't know…I mean, I wrote down the website. At this point, what you did tonight was a lot more extensive and very good!

Anglers also suggested that the frequency of contact with organizations should be increased through emails or even phone calls to organization leaders. Four of the seven focus groups suggested connecting with the social media presence of angler organizations to promote the HAB Tracker.

Suggestions for communication that were less personalized included an online video tutorial of how to access and interpret the HAB Tracker. Several focus groups proposed connecting with regionally important newspapers, radio stations, television stations, and fishing reports. These anglers emphasized the importance of promoting the HAB tracker within media that anglers were already consuming. Multiple anglers would like to see a link between the MODIS website (which a majority of the angler interviewed used) and the HAB Tracker.

I like the idea of linking with MODIS, because then people are on the same wavelength with that one. When they're looking for mud lines and algae blooms that would be the place to go.

In terms of broader communication work, a few anglers expressed a desire for greater visibility of HAB researchers to the general public. They would rather hear about HAB research from the researchers firsthand, rather than through a second media source. However, one angler also cautioned that researchers should be conscious of the need for effective communication skills.

The problem is that most scientists are kind of dry and boring when it comes to, you know…you usually just hear blah, blah, blah. There are some who are very, very good speakers. We have a fall meeting every year for three days…and they always bring in fisheries guys and all that…Well, not all those DNR guys and all that are very good speakers. I see the guys start with their heads going down. So that has a lot to do with it, too. If you have a representative go out to different groups, choose a good speaker, ya know? Because you can put a lot of people to sleep really fast….

4.4.4 Summary of Themes that Support Answers to the Primary Research Question

The following three themes were identified as additional points to consider while identifying ways to increase the utility of the HAB Tracker for Lake Erie anglers: 1) the need for greater trust between anglers and institutions, 2) the preference for receiving HABs communications from researchers directly, 3) targeting charter captains for stakeholder engagement, because of the key role they play within the Lake Erie fishing community. Specific recommendations for HAB Tracker improvement guided by these themes and all data analysis will be presented in Chapter 5.

Anglers in many of the focus groups expressed a distrust of the HABs communications that they receive from institutions and the media, because these communications are often perceived as biased. Participants in the La Salle focus group spoke extensively on their distrust of HABs communications from the media.

<u>Captain 1:</u> The biggest concern that I have for the future of algae and Lake Erie is just the perception that the news media throws out there. We're kind of at their mercy.

<u>Captain 2:</u> Yeah, the facts mean nothing at all to the media.

<u>Captain 3:</u> I know the media is what's going to change things, and unfortunately no matter what you [the researcher] say, they're going to pick it a part and pick out the three words that make it look the worst.

This distrust of researcher motives was also raised in two focus groups, specifically during discussion of the Toledo Water Crisis, and how this event spurred an influx of funding for HAB research.

Originally, they weren't getting any grant money [the HAB researchers and managers]. Then they had the Toledo water scare, and the money started pouring in from everywhere. That was the smartest thing they could've done to get money, was to shut that water off for a day.

In every focus group, at least one angler questioned whether HAB researchers were doing everything that they should be doing to address the HAB problem in Lake Erie.

<u>Angler 1:</u> It seems like it would be a whole lot simpler to just fix the source, and then we don't have to do anything with forecasting.

<u>Angler 2:</u> That's true.

<u>Angler 3:</u> They'd [the researchers] lose their jobs!

<u>Angler 1:</u> Instead of spending all this money when you're not really fixing anything….

Two focus groups suggested that pursuing the development of the HAB Tracker forecast model may be a misguided use of tax-payer funds.

<u>Angler 1:</u> But then, you just can't throw money at [HABs]. You've got to put that money where it's going to be effective.

<u>Angler 2:</u> How many years of research do you have to do before you start saying you need to throw money at it? You're throwing a lot of money at research, and that's all good stuff, but unless it goes toward actually doing something, you might as well use it in the shitter.

Even though only a few anglers verbalized their distrust of HAB researchers, this issue was pervasive enough that it should be addressed by NOAA-GLERL & CILER through their stakeholder engagement efforts. It was not clear to the anglers what actions NOAA-GLERL & CILER had taken to address the HAB problem. Information regarding NOAA-GLERL & CILER's involvement in recent policy initiatives to reduce phosphorous inputs into Lake Erie and other related efforts were disseminated to participants at the close of the focus group, but the problem remains that without intervention the anglers within these focus groups didn't appear to understand NOAA-GLERL & CILER's role in mitigating HABs. It is also worth noting that many focus group participants interacted directly with HAB researchers and managers in the past through collaborative research efforts. None of these interactions involved NOAA-GLERL & CILER staff. Despite these interactions, a few of these participants remained unconvinced of the detrimental impact of HABs to Lake Erie and the trustworthiness of HAB researchers.

Issues of distrust between the fishery community and researchers has been documented in the literature, and often stems from a lack of clear and consistent communication (Dedual et al. 2013; Holmes and Lock, 2010). Creating both trust and effective communication promote successful interactions with collaborative stakeholders (Karlsen et al., 2008). In a case study analysis of researcher/fishery communications from across the globe, Dedual et al (2013) identified common barriers to communication. These included the use of jargon, the oversimplification of scientific research by the media (which fosters distrust), and a lack of researcher knowledge regarding the experience and knowledge of anglers. The qualitative data contributed by Lake Erie anglers within this study supports these findings. Charter captains from the focus group that most vehemently voiced their distrust of the news media proposed that researchers should speak to the Lake Erie fishing community about HABs more directly, instead of through intermediaries like local television and newspaper reporters. This recommendation supports the findings of Dedual et al. (2013), who recommend communicating with anglers directly to understand 1) what they know about the issue, 2) and to break down social barriers that may shape negative perceptions of researchers. These focus groups can be a first step toward developing better communication with this stakeholder group. Every focus group expressed appreciation for this study to seek input from the Lake Erie fishing community

When anglers were asked for specific recommendations regarding how NOAA-GLERL & CILER can improve their communications with the Lake Erie fishing community, every focus group suggested that representatives of NOAA-GLERL & CILER attend more meetings of Lake Erie fishing organizations in person. In some cases, specific meetings and organizations were suggested by the anglers. However, the broader intent of their comments seemed to be that anglers would prefer to establish relationships with NOAA contacts on a personal level. Again, this data supports the existing literature on recommendations for effective communication between researchers and the fishing community (Dedual et al., 2013; Holmes and Lock, 2010; McNie, 2007).This communication preference also aligns with how anglers prioritize their own communications and knowledge sources about HABs. Most anglers expressed a preference for HAB communications from their peers and the leadership of the fishing organizations of which they were members. In a study of the social networks of Lake Michigan charter captains, Mueller et al also found that charter captains invest social capitol in their relationship with other anglers in order to gain information (Mueller et al., 2008). When asked how the HAB Tracker can be best shared with anglers, many participants noted that peer-to-peer sharing of the tool is the most prominent method of HAB communication.

> <u>Angler 1:</u> *Well, if I'm using it [the HAB Tracker], and he says, "Well, how do you know that?", the next thing that I'm doing is saying "Well, look at this!" It mushrooms out from there.*
>
> <u>Angler 2:</u> *You do just like Joe* just did. He passed the phone to Al* to make it happen.*

> *<u>Angler 3:</u> Yeah, I started out with using the satellite [MODIS online imagery of Lake Erie], and it went all around the bait shop. Everybody had to have it after that.*

During the focus groups, it became clear that anglers had many questions for HAB researchers about the state of HABs in Lake Erie (a summary of these questions can be found in Appendix VII). By providing anglers with reliable opportunities to answer their questions, NOAA-GLERL & CILER can promote a higher level of HAB knowledge among the Lake Erie fishing community, and build confidence in the work of NOAA-GLERL & CILER. Overall, the participants were highly knowledgeable about HABs in Lake Erie. They likely have important insights about HABs that may be of use to HABs researchers by virtue of angler's high frequency of fishing activities on Lake Erie and exposure to HABs. The literature supports the potential utility of angler field experience and practical knowledge to promote the accuracy and timeliness of collecting fisheries management data (Yochum et al., 2011; Vellucci, 2007; Phillipson et al., 2012). Anglers can provide beneficial insights into changes that occur within the lake system, and contribute to the ground-truthing of data (Yochum et al., 2011). Establishing a flow of information to and from the angling community has the potential to benefit both NOAA-GLERL & CILER and the Lake Erie fishing community. A two-way flow of information is essential to improving the quality of interactions between fisheries managers/researchers and the fishing community (Holmes and Lock, 2010).Many anglers within this study already possess a self-motivated interest in becoming educated on HABs. By supplying anglers with the information they desire, these anglers are more likely to disseminate accurate information throughout the fishing community and support the future research efforts of NOAA-GLERL & CILER. It is also critical that researchers acknowledge the worth of angler knowledge and contributions to the work of researchers, because this will further build trust between them (Hartley and Robertson, 2008).

Another important theme that emerged during this study is role that charter captains play within the Lake Erie fishing community to communicate information about HABs and educate other anglers. Several captains expressed their desire to become educated on HAB issues and research, because they felt responsible for sharing that information with their customers.

> *<u>Angler 1:</u> You educate yourself, because you kind of have to when these people [customers] call. I just had one guy on the boat tell me…"Well, you're just a regular Lake Erie encyclopedia, aren't you?"*
>
> *<u>Angler 2:</u> Most people do ask about the algae.*
>
> *<u>Angler 3:</u> It's a fairly regular questions: what causes the algae? Those kinds of questions.*

It's important to note that these captains are reaching a broader audience and different demographic than what NOAA-GLERL & CILER may currently reach. The charter captains also indicated that they communicate frequently with fellow captains and other members of the fishing industry, like bait dealers, fish cleaners, local restaurant owners, and local tourism organizations. Charter captains are unique in their ability to access a wide range of individuals within the Lake Erie fishing community (Mueller et al., 2008). Several anglers mentioned during the focus groups that they are frequently sought out by others for the knowledge that they possess about Lake Erie and the state of HABs.

I've had guys call me up from my website, just private boaters saying, "hey, would you mind giving me a little information?"

Most charter captains appeared to be aware of this unique role that they play within the Lake Erie community, and embraced this role with integrity. Many charter captains expressed deep concern for the health of Lake Erie, and felt responsible for stewardship of the lake. This sense of responsibility motivated captains within the Lake Erie Charter Boat Association to take action on many levels to promote the health of Lake Erie. The Lake Erie Charter Boat Association organizes informative events for their members where HAB researchers and lake managers are invited to speak, they participate in research efforts by Universities to better understand the impacts of HABs on Lake Erie, lobby local congressmen to action on HABs, volunteer to assist Ohio Sea Grant and the Ohio DNR in their efforts to educate other Lake Erie stakeholders about the HAB issue, and organize other activities for their members to take action on HABs. A select few charter captains were exceptionally self-motivated to take action on HABs, but the majority of the captains did express interest in doing what they can to assist with efforts to mitigate HABs in Lake Erie. Identifying highly engaged leaders within the fishing industry and soliciting their support for stakeholder collaboration is key to promoting successful communication and interactions between researchers and the fishing community (Hartley and Robertson, 2008). These self-motivated anglers could fill this needed leadership role for collaboration efforts between NOAA-GLERL & CILER and the Lake Erie fishing community.

4.5 Conclusion

This study sought to address whether the HAB Tracker may be useful to Lake Erie anglers in their decision-making while fishing in HABs. We predict that if Lake Erie anglers use the HAB Tracker, they will find it to be useful, because the majority of anglers in all but one focus group spoke positively of their perceptions of HAB Tracker utility. The HAB Tracker has the potential to improve the efficiency of angler decision-making related to whether to fish and where to fish during a HAB event. These are two important decision-points that anglers face while fishing in HABs. These decision-points are informed by angler knowledge, perceptions, and communications about HABs.

For most anglers in this study, the knowledge and perceptions that they had about HABs contributed to their decision to avoid blooms while fishing. Specifically, anglers emphasized a desire to know more about the risks that may be involved with consuming fish that have been exposed to HABs, as well as the risk that they faced while recreating in Lake Erie during a bloom. Anglers were generally aware of broader health risks associated with HAB exposure (skin irritation, liver toxicity), but they were unclear regarding the specific level of risk they were subjected to while recreating on Lake Erie. For some, this uncertainty and lack of knowledge was reason enough to avoid HABs. For others, blooms were avoided only as a matter of preference. There was general agreement among the participants that the blooms were repugnant. Knowledge of the causes of HABs and the difficulties of addressing non-point source pollution contributed to angler frustration about the lack of action to address HABs. For some, this frustration compounded their desire to avoid the HABs.

Additional perceptions that anglers voiced about HABs included their thoughts on the impact that HABs have on fish and the fishing industry. Most anglers felt that HABs negatively impacted the fish and the Lake Erie ecosystem in some way, but a deeper understanding of this impact was unclear. Some anglers reported that they were successful fishing during a bloom if they casted for walleye and perch at a depth below the HABs. Concerns regarding the impact of HABs on the fishing industry focused primarily on public perceptions of Lake Erie and HABs. Charter captains were particularly concerned about the negative perceptions of their customers. Most charter captains and recreational anglers reported that the fishing industry in Lake Erie would suffer as a result of continued HAB events.

The knowledge and perceptions that anglers have about HABs are a function of their methods of communication. There was general consensus among anglers (particularly charter captains) that they relied upon their peers for trust-worthy communications about HABs. Although anglers would reference website and news outlets as additional information sources, information distributed from person to person possessed the highest value. A large number of anglers sought new information about HABs from Lake Erie managers and related government offices. However, this information was sometimes viewed with skepticism. Participants encouraged NOAA-GLERL & CILER to pursue a higher level of interaction with anglers to better promote awareness of the HAB Tracker and related HAB research. By adopting recommendations for HAB Tracker improvement given by focus participants, angler awareness of the HAB Tracker will likely increase as will the perceived usefulness of this tool.

Chapter 5: Recommendations for the HAB Tracker

5.1 Recommendations on *Microcystis* Buoyancy

- We suggest updating the relationship between buoyant velocity and colony diameter in the HAB Tracker model with the relationship obtained from this study.

- We suggest including the effect of light exposure on buoyancy in the HAB Tracker model.

- For future study on *Microcystis* buoyancy, we suggest taking into consideration the nutrient conditions of the environment - lower buoyancy is associated with lower nutrient levels.

5.2 Recommendations on Hindcast Skill Assessment

- Model skill was improved after spatial smoothing with a neighborhood size of 3 km, thus we suggest smoothing the model output, and present the fraction of HAB distribution at 3 km for the users.

- For future hindcast skill assessment, we suggest continuing the application of the FSSns method to track the changes in the optimum neighborhood size.

    - If a smaller optimum neighborhood size is observed in the future, it is likely that the model is improved in terms of displacement error.

5.3 Recommendations on Utility of the HAB Tracker Model for Lake Erie Anglers

1. Adopt angler recommendations for HAB Tracker improvement

    - Seek to include a link to HAB Tracker on the NOAA CoastWatch webpage for the Great Lakes region (www.coastwatch.glerl.noaa.gov/modis), and clearly label the MODIS input on the HAB Tracker page to help anglers make this connection

    - Elaborate on methods that NOAA-GLERL & CILER are using to improve the reliability and accuracy of forecasts.

    - Include a link on the HAB Tracker page so that anglers can go to another page to learn more about what NOAA-GLERL & CILER is doing to address the HAB problem.

    - Explain how to interpret the color scale for cyanobacterial chlorophyll concentration. Is it possible to include a visual example of the aesthetic appearance of the water corresponding to specific cyanobacterial chlorophyll concentrations?

- Include more of the input data such as weather, wave height, wind direction, and wind velocity.

- Identify a name for the HAB Tracker that is more readily recognized. I.E. Harmful Algae Tracker.

- Feature the HAB Tracker more prominently on the NOAA-GLERL website, making it easier for website visitors to find. Consider creating a shorter web address for the webpage that can be more easily shared.

- Increase size of the maps and include lines of latitude/longitude.

- Consider implementing a “zoom” feature.

- Implementing as many updates suggested by anglers as possible will illustrate to the fishing community that their thoughts matter. NOAA-GLERL & CILER should advertise this work to begin building strong relationships with the fishing community.

2. Increase Angler Engagement Efforts

    - Attend more meetings of prominent fishing organizations within the region, like those whose members participated in this study (Figure 4.1)

    - Prioritize engagement with charter captains

3. Additional Recommendations:

    - Consider incorporating a citizen-science ground-truthing component to the HAB Tracker. Alternatively, simply solicit feedback from anglers while attending organization meetings.

Chapter 6: Appendix

6.1 Appendix I

Table 6.1.1. Field sample depth information and lab data of nutrient concentrations in Lake Erie.

Date	***Field Data***			***Lab Data***			
	Site	Sample Depth (m)	Sample Depth (category)	TP (µg/L)	TDP (µg/L)	POC (mg/L)	PON (mg/L)
2016/8/29	WE4	0.75	surface	37.8	16.6	1.02	0.16
2016/9/6	WE8	0.75	surface	110.4	23.9	3.76	0.66
		4.00	bottom				
		0.00	scum				
2016/9/12	WE9	0.75	surface	157.9	39.3	2.91	0.54
2016/9/19	WE13	0.75	surface	47.2	15.3	1.14	0.23
		7.90	bottom				
		0.00	scum				
2016/9/28	WE6	0.75	surface	60.0	23.7	1.15	0.20
2016/10/3	WE13	0.75	surface	132.3	45.9	1.66	0.27
		7.90	bottom				
		0.00	scum				
2016/10/11	WE8	0.75	surface	59.6	29.0	1.43	0.22
		4.00	bottom				
		0.00	scum				

Table 6.1.2. Processed nutrient concentrations in the experimental bottles and molar ratios.

	POC mg/L	PON mg/L	POP µg/L	POC/PON molar ratio	POC/POP molar ratio	PON/POP molar ratio
2016/8/29	1.02	0.16	21.2155	7.451	124.712	16.737
2016/9/6	3.76	0.66	86.5180	6.698	112.325	16.769
2016/9/12	2.91	0.54	118.5855	6.315	63.335	10.030
2016/9/19	1.14	0.23	31.8215	5.796	92.716	15.996
2016/9/28	1.15	0.20	36.3885	6.519	81.289	12.470
2016/10/3	1.66	0.27	86.4280	7.295	49.649	6.806
2016/10/11	1.43	0.22	30.6370	7.448	120.180	16.137

Table 6.1.3. Particulate Organic Carbon data within sample bottles before & after one-day light exposure.

Date	C, mg/L				Time, day	Growth Rate, /day	
	$C_{0,\ light}$	$C_{0,\ dark}$	$C_{t,\ light}$	$C_{t,\ dark}$		dark	light
2016/9/6	8.93	8.01	10.10	7.98	1	-0.004	0.123
2016/9/19	2.35	2.70	3.54	2.61	1	-0.035	0.410
2016/10/3	6.16	5.52	6.65	5.90	1	0.067	0.076

6.2 Appendix II

Improving NOAA HAB Tracker:
A Forecasting & Decision Support Tool for Lake Erie Harmful Algal Blooms

University of Michigan, School of Natural Resources & Environment
Cooperative Institute for Limnology & Ecosystems Research
NOAA - Great Lakes Environmental Research Laboratory

INTERVIEW GUIDE

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1. Before we talk about HABs, I'd like to know a little bit about you as a fisher. How long have you been fishing in Lake Erie? *(Introduction)*
- Where do you like to fish generally?
- How frequently do you fish?
- What memberships or affiliations do you have with fishing associations/groups?

2. How would you describe a harmful algal bloom? *(Knowledge)*
- Why is it harmful? What have you heard about the toxins it produces?
- Do you have another name that you use for it? (*Communications*)
- How do you know it when you see it?

3. How have HABs changed your fishing practices? (*Decision-Making)*
- Do you fish during HABs events? Do you fish around them? Why?
- Do you modify your fishing techniques/equipment that you use during a bloom?

4. What concerns do you have about the future of HAB occurrences on Lake Erie? *(Perceptions)*
- Have you observed HABs having an impact on fish? Does it affect fish movement?
- Would you eat fish from Lake Erie during large blooms?/Have you eaten fish during a bloom?
- How might HABs influence the fishing industry?

5. When you want to know whether algal blooms are going to be an issue on a particular day, where have you gone for information? *(Decision-Making/Communications)*
- Who or what would you look to as a source of information?
- How would you access that information (telephone, online, face-to-face, etc.?)
- How would you share this information with others? What others?
- Do you use social media or any other forums for sharing information about HABs?

(*Photo identification task break to identify Microcystis for the purpose of knowledge assessment)*

6. Why do you think HABs are in Lake Erie? (*Knowledge/Perceptions)*
- Where did they come from?
- How long have they been there?

7. Is there anything so far about HABs that we haven't talked about that you think we should?

(Break for Dinner & Demonstration of NOAA HAB Tracker)

8. How did you first hear about the National Oceanic & Atmospheric Administration Great Lakes Environmental Research Lab (NOAA-GLERL)?
- What have you heard about the research that we do with harmful algal blooms (HABs)?

9. How might the HAB Tracker be useful to Lake Erie anglers? *(Perceptions)*
- How could the HAB Tracker be made *more useful* for anglers?
- Should the information be displayed differently?
- Should additional information be included? What information?
- What did you like/dislike about the HAB Tracker?

10. In what ways might the HAB forecast information change your fishing plans? *(Decision-Making)*
- If you have used the HAB Tracker before, how has it changed your fishing plans in the past?
- Under what conditions would you consider using the tool?

11. How could NOAA-GLERL improve their communications with you about HABs information?
(*Perceptions/Communications)*
- What changes in words and language GLERL uses to communicate about HABs be improved?
- How might the method of communicating be improved?

12. If you could ask the researchers to investigate any question that you have about HABs in Lake Erie, what would it be? *(Perceptions/Knowledge)*

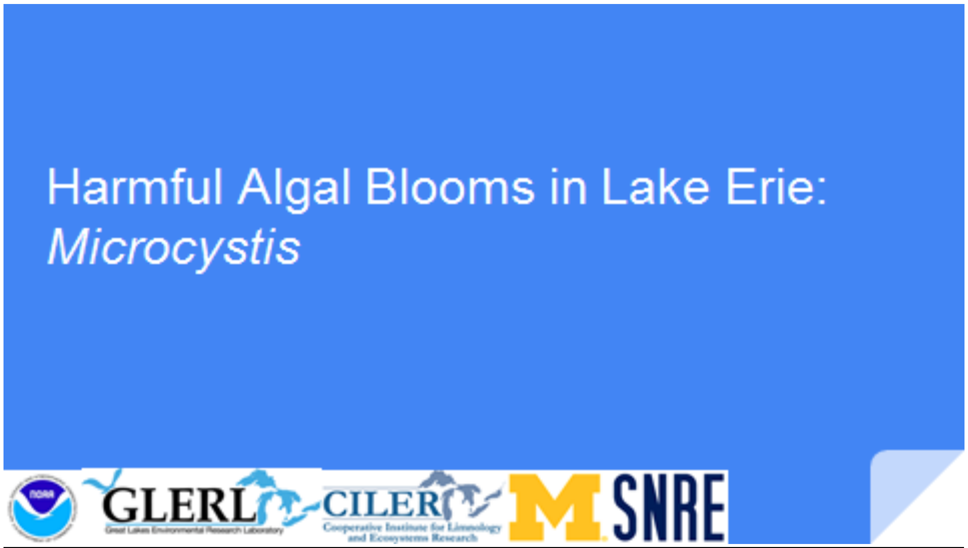
13. Is there anything else that you'd like to tell me or that you think the researchers at GLERL should know about your experience with HABs?

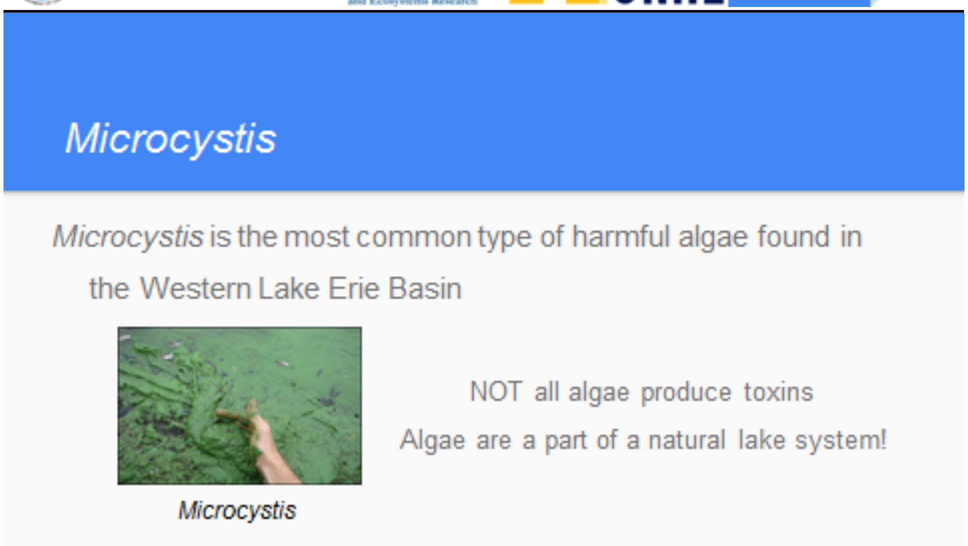
14. Would you be willing to use the HAB Tracker for the next 6 weeks, then participate in a follow-up interview over the phone to discuss your experience with the HAB Tracker?

15. Would you also be willing to review my summary of our focus group discussion and offer your feedback on the accuracy of my summary?

6.3 Appendix III

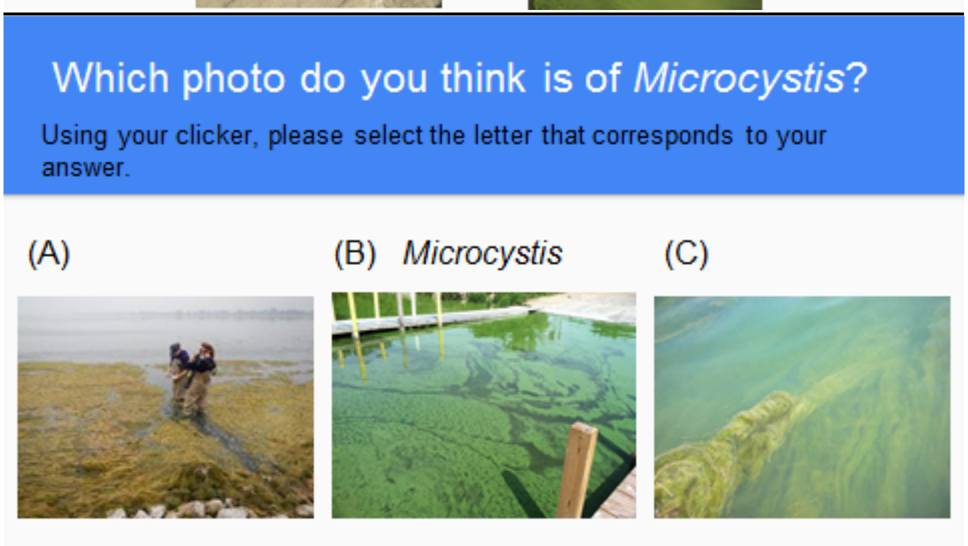
<u>Focus Group HAB Knowledge Assessment Presentation</u>

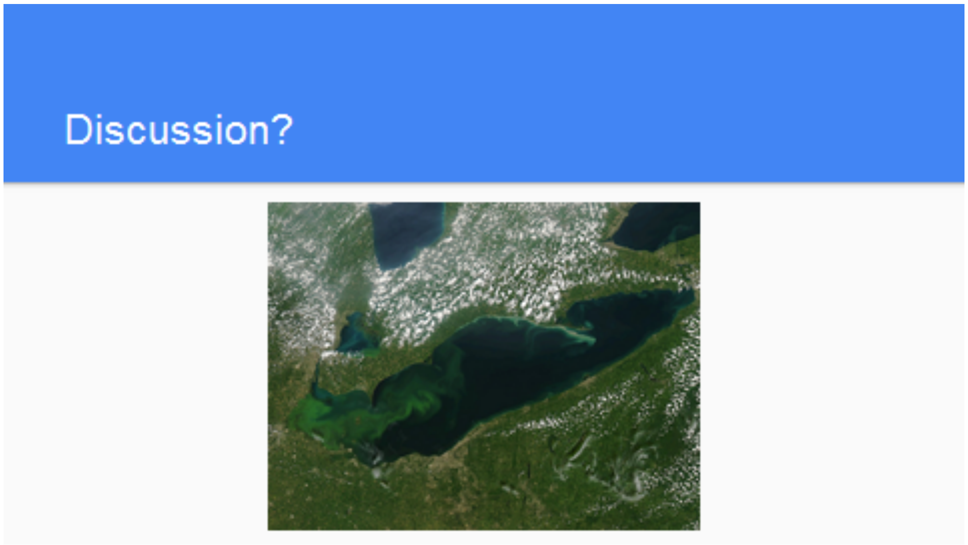





Which photo do you think is of *Microcystis*?
Using your clicker, please select the letter that corresponds to your answer.
(A)
Microcystis
(B)
(C)
(D)

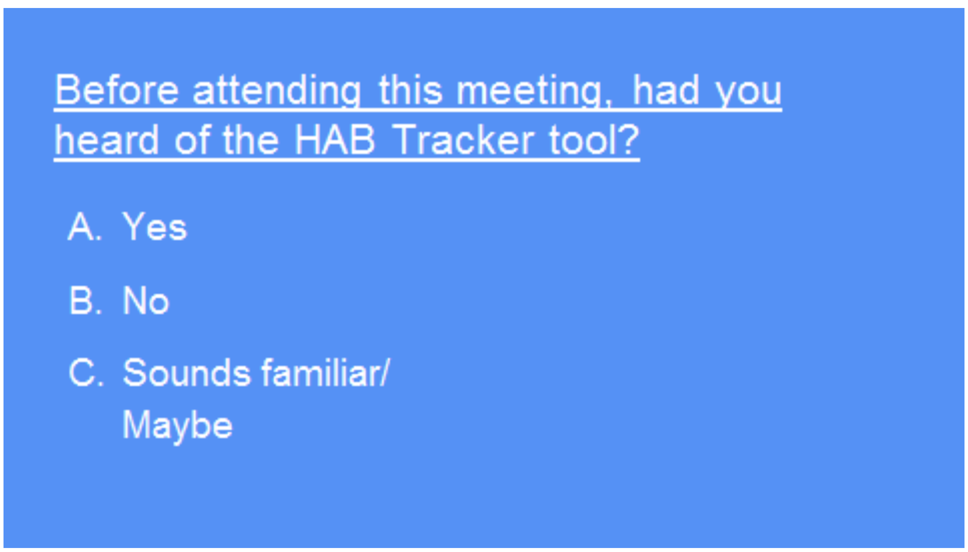

Which photo do you think is of *Microcystis*?
Using your clicker, please select the letter that corresponds to your answer.
(A)
(B)
(C)
(D)
Microcystis


Which photo do you think is of *Microcystis*?
Using your clicker, please select the letter that corresponds to your answer.
(A)
(B) *Microcystis*
(C)


Discussion?

6.4 Appendix IV

HAB Tracker Focus Group Presentation



Have you used HAB Tracker before?

A. Yes

B. No

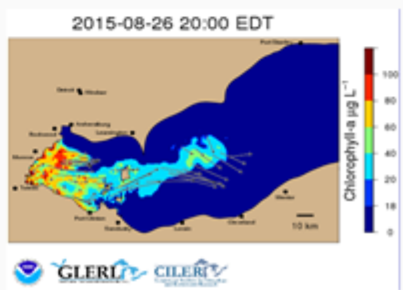
C. Not sure

NOAA's HAB Tracker

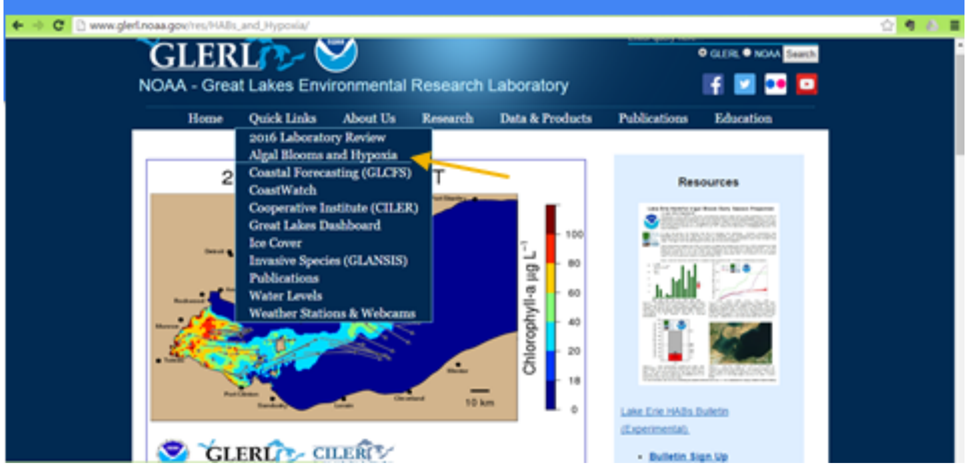
- Experimental, short-term forecast model
- Daily updates & 5 day predictions

Purpose:

- Where are blooms?
- How big are they?
- Where are they likely headed?

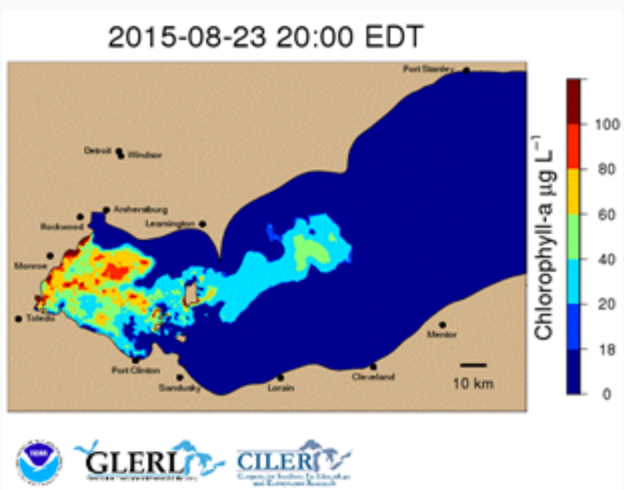


HAB Tracker: www.glerl.noaa.gov



HAB Tracker: www.glerl.noaa.gov

HAB Tracker: Animated Forecasts



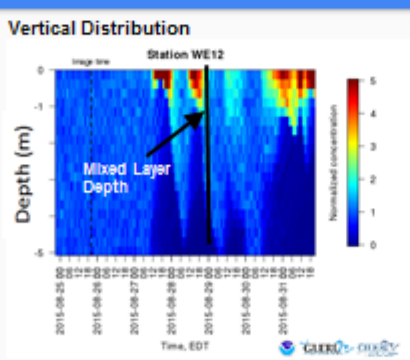
HAB Tracker: Interpretation?

- Animated 5 day forecast of surface concentrations
- 5 day forecast images with displacement arrows
- Latest satellite true-color image of HAB extent
- Satellite image in HAB Tracker format

HAB Tracker: Hindcasts

- Looking at monitoring & buoy data from prior years to evaluate model accuracy

HAB Tracker: Improving Forecasts

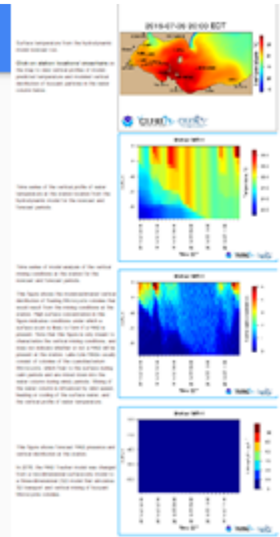


Vertical Mixing

- What's happening below the surface?
- Will it mix to the bottom?

HAB Tracker: Vertical Mixing

- Current surface temperatures
- Predicted vertical profile of water temp at station over time
- Predicted potential for vertical mixing of bloom at station
- HAB Tracker prediction for vertical mixing of bloom at station



Thank You!
Questions?

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GLERL
CILER
Cooperative Institute for Limnology and Ecosystems Research

6.5 Appendix V

2016 Lake Erie Anglers & HABs
Focus Group Evaluation

1. Do you identify primarily as a Lake Erie recreational fisher or Charter Boat Captain? (Circle one)

   Recreational Fisher Charter Captain Other

2. Do you have any recommendations for how this focus group might have been improved?

   For questions 3 - 6, please indicate how much you agree or disagree with the statement. Please also provide comments to explain your response.

3. I felt that my thoughts and opinions were heard by the group.

   Strongly Agree Agree Neutral Disagree Strongly Disagree

   Comments:

4. I feel that I am more knowledgeable about harmful algal blooms in Lake Erie.

   Strongly Agree Agree Neutral Disagree Strongly Disagree

5. Are there members of the Lake Erie recreational fisheries community who are not represented here?

6. Are there any questions or concerns about HABs that the focus group did NOT cover, that you felt it should have? Please list them below.

6.6 Appendix VI

Table 6.6.1 Focus group survey responses.

Focus Group	Q1	Q2	Q3a	Q3b	Q4a	Q4b	Q5	Q6
Wyandotte	Recreational Fisher		Strongly Agree	Great opportunity for everyone attending to share their thoughts and opinions without interuptions or time limits.	Strongly Agree	I felt I was fairly knowledgeable with regards to the issues, but there is much to learn and share with others	Younger people and the charter fishermen	
Wyandotte	Recreational Fisher	I thought this focus group was really good. Keep up the good work.	Strongly Agree		Agree		No	
Wyandotte	Recreational Fisher	Powerpoint screen could be larger	Agree		Agree			
Wyandotte	Recreational Fisher	No. Good meeting.	Strongly Agree	All fishermen shared similar thoughts	Agree			
Wyandotte	Recreational Fisher	Not at this time	Agree		Strongly Agree		Probably, but I believe it was very well represented	No
Wyandotte	Recreational Fisher		Strongly Agree	In my opinion, every person had time to talk	Agree		No	
Sandusky	Recreational Fisher	Start with overview of issue, then ask how it has affected the participants	agree		Strongly Disagree	I have a strong history with this issue. I worked with many researchers who were investigating HABs on Lake Erie through my job	Perhaps under-representation of urban shoreline anglers whof ish public piers, such as Port Clinton/Sandusky during blooms	
Sandusky	Recreational Fisher	People seem interested in the cuases of the phosphorous issues, so a small bit of that woud be great (so long as this doesn't derail the info)	Strongly Agree		Neutral	This is my background though, so that isn't a reflection on the group or presenters in any way!	The tourists who come up on weekends and summer folks. Only locals are really represented.	Human and environmental health effects of HABs, we tried to discuss, but didn't have any info about it.
Sandusky	Recreational Fisher	No. Very good class and a good idea to have a mix of different backgrounds in the class	Strongly Agree	Very open meeting and people fed off each other's ideas	Strongly Agree	People just hear about it, and not a lot of talk about how it hapens and the effects of it	No. Good mix of backgrounds. Maybe commercial fishermen?	No.
Sandusky	Recreational Fishers	This was very well-done. You might add some additional slides for individual maps on the HAB Tracker. The column of four was hard to see. Good program & product.	Strongly Agree	Very friendly	Agree		This covered anglers who are affected by HABs pretty well	pretty thorough
Sandusky	Recreational Fisher	Not really -- very well organized	Stronly Agree		Agree		No	No.
Sandusky	Recreational Fisher	No, I think it was a good discussion. Hopefully you were able to glean some info from us that will be helpful.	Agree		Agree		This was a good representation.	
Cleveland	Recreational Fisher	Great Job	Strongly Agree		Strongly Agree		Charter boat captains, shore	No
Cleveland	Recreational Fisher	N/a it was great & interesting. Good Food, too!	Strongly AGree		Agree		n/a	n/a
La Salle	Charter Boat Captain	More info on what is currently being done to improve lake conditions	Agree		Neutral		Yes, city water commission.	No.
La Salle	Charter Boat Captain	Not it was fine as is.	Strongly Agree		Agree		There were no private boate	No, all questions I had got a
La Salle	Charter Boat Captain	More visuals and better hands on stuff involving the algae.	Strongly Agree	Very Open Group	Strongly Agree	Learned a lot about algae	Pleasure boaters or small sa	None. Just more about long
La Salle	Charter Boat Captain	None	Strongly Agree		Agree		Don't know	None.
La Salle	Charter Boat Captain		Agree		Strongly Agree		Not that know	No
Oregon								
Oregon								
Oregon								
Oregon								
Oregon								

Oregon 2	Charter Boat Captain	Have more than charter cpatins. I.e. farmer, sewer workers, water plant workers	Strongly Agree		Strongly Agree		No	No
Oregon 2	Charter Boat Captain	Well done	Strongly Agree		Strongly Agree			
Oregon 2	Charter Boat Captain		Agree		Agree		Bait store owners, hotel owners, marina owners. They all	
Oregon 2	Charter Boat Captain		Agree		Neutral		Yes	No
Oregon 2	Charter Boat Captain		Agree		Neutral		No	No
Oregon 2	Charter Boat Captain	Solving Problem	Strongly Agree		Agree		Business	No
Oregon 2	Charter Boat Captain		Agree		Agree		Recreational non-charter fishers	
Oregon 2	Charter Boat Captain	Teach	Agree		Agree			No
Oregon 2	Charter Boat Captain		Agree		Strongly Agree		Yes	No
Oregon 2	Charter Boat Captain		Agree		Neutral		Yes	

6.7 Appendix VII

<u>Questions from Focus Group Participants for NOAA-GLERL & CILER Researchers</u>

Questions regarding HAB forecasts

- Can researchers clearly display for stakeholders how variable levels of spring rainfall impact the extent of HAB occurrences that summer/fall in Lake Erie?
- Is there a way to forecast HAB toxicity in Lake Erie?
- Will climate change increase the severity and extent of HABs in Lake Erie?

The impact of HABs on Fish

- Do HABs bioaccumulate in predatory fish?
- Does microcystin accumulate within the flesh of the flesh, specifically the flesh used in a filet?
- Would it be possible to produce long-term HAB forecasts predicting the impact that HABs will have on fish populations?
- Are fish eating *Microcystis*?
- Does *Microcystis* get caught within fish gills?

The impact of HABs on Human Health

- What are the health risks associated with consuming fish exposed to microcystin in Lake Erie?
- What are the health risks of exposure to varying concentrations of microcystin within the water?
- Can you provide a list of recommendations for minimizing HAB exposure while fishing?
- What are the long-term health risks associated with chronic exposure to microcystin? Are there any short-term health risks?

The impact of HABs on Lake Erie Ecosystems

- Are HABs related to recent observed decreases in forage fish populations, specifically Emerald Shiners?
- What is the impact of HABs on the amount of beneficial algae within the lake? How might this relationship effect food availability for fish? If beneficial algae are negatively impacted by the blooms, how quickly can their populations recover after a bad bloom year?
- What is the impact of zebra mussels on the spread of HABs in Lake Erie?
- Do gobies eat *Microcystis*? If they do, will this help to mitigate HABs in Lake Erie?
- What is the relationship between HABs and hypoxia?

Causes of HABs

- Is there a link between specific synthetic fertilizers and increases in HABs in Lake Erie in the past 10 years?

Actions being taken to decrease HABs in Lake Erie

- What actions are being taken to reduce HABs in Lake Erie?
- Are researchers exploring new, innovative solutions for reducing the proliferation of HABs?
- How can we effectively reduce the amount of phosphorous coming from agricultural fields? What policies tools or technologies can effectively reduce nutrient loading within Lake Erie?

Chapter 7: References

Bauer, M., P. Hoagland, T. M. Leschine, B. G. Blount, C. M. Pomeroy, L. L. Lampl, C. W. Scherer, D. L. Ayres, P. A. Tester, M. R. Sengco, K. G. Sellner, and J. Schumacker. 2010. The importance of human dimensions research in managing harmful algal blooms. *Frontiers in Ecology and the Environment* 8 (2):75-83.

Bernard, H. R. 2006. *Research Methods in Anthropology*. 4 ed. Lanham, MD: Altamira Press.

Bertram, P. E. 1993. Total phosphorous and dissolved oxygen trends in Lake Erie, 1970-1991. *Journal of Great Lakes Research* 19:224-236.

Bingham, M., S. K. Sinha, and F. Lupi. October 2015. Economic benefits of reducing harmful algal blooms in lake erie. International Joint Commission: Environmental Consulting & Technology, Inc.

Bridgeman, T. B., J. D. Chaffin, D. D. Kane, J. D. Conroy, S. E. Panek, and P. M. Armenio. 2012. From River to Lake: Phosphorus partitioning and algal community compositional changes in Western Lake Erie. *Journal of Great Lakes Research* 38 (1):90-97.

Bury, N. R., G. A. Codd, S. E. Wendelaar Bonga, and G. Flik. 1998. Fatty acids from the cyanobacterium *Microcystis* aeruginosa with potent inhibitory. *The Journal of Experimental Biology* 201:81-89.

Carmichael, W. W. 2001. Health Effects of Toxin-Producing Cyanobacteria: “The CyanoHABs”. *Human and Ecological Risk Assessment: An International Journal* 7 (5):1393-1407.

Carmichael, W. W., S. M. F. O. Azevedo, J. S. An, R. J. R. Molica, E. M. Jochimsen, S. Lau, K. L. Rinehart, G. R. Shaw, and G. K. Eaglesham. 2001. Human fatalities from cyanobacteria: Chemical and biological evidence for cyanotoxins. *Environmental Health Perspectives* 109 (7):663-668.

Chaffin, J. D., T. B. Bridgeman, S. A. Heckathorn, and S. Mishra. 2011. Assessment of *Microcystis* growth rate potential and nutrient status across a trophic gradient in western Lake Erie. *Journal of Great Lakes Research* 37 (1):92-100.

Charmaz, K. 2015. Teaching theory construction with initial grounded theory tools: a reflection on lessons and learning. *Qualitative Health Research* 25 (12):1610-22.

Cires, S., L. Wormer, D. Carrasco, and A. Quesada. 2013. Sedimentation patterns of toxin-producing *Microcystis* morphospecies in freshwater reservoirs. *Toxins (Basel)* 5 (5):939-57.

Cui, Y. J., D. F. Liu, J. L. Zhang, Z. J. Yang, S. T. Khu, D. B. Ji, L. X. Song, and L. H. Long. 2016. Diel migration of *Microcystis* during an algal bloom event in the Three Gorges Reservoir, China. *Environmental Earth Sciences* 75 (7).

Davis, T. W., D. L. Berry, G. L. Boyer, and C. J. Gobler. 2009. The effects of temperature and nutrients on the growth and dynamics of toxic and non-toxic strains of *Microcystis* during cyanobacteria blooms. *Harmful Algae* 8 (5):715-725.

Dedual, M., O. Sague Pla, R. Arlinghaus, A. Clarke, K. Ferter, P. Geertz Hansen, D. Gerdeaux, F. Hames, S. J. Kennelly, A. R. Kleiven, A. Meraner, and B. Ueberschär. 2013. Communication between scientists, fishery managers and recreational fishers: lessons learned from a comparative analysis of international case studies. *Fisheries Management and Ecology* 20 (2-3):234-246.

Denzin, N. K., and Y. S. Lincoln. 1994. Handbook of Qualitative Research: Sage publications, inc.

Dodds, W. K., W. W. Bouska, J. L. Eitzmann, T. J. Pilger, K. L. Pitts, A. J. Riley, J. T. Schloesser, and D. J. Thornbrugh. 2008. Eutrophication of U.S. Freshwaters:

Analysis of potential economic damages. *Environmental Science & Technology* 43 (1):12-19.

Drosdowsky, W., and H. Huang. 2003. Verification of Spatial Fields. In *Forecast Verification: A Practioner's Guide in Atmospheric Science*, edited by Ian T. Jolliffe and D. B. Stephenson. West Sussex, England: John Wiley & Sons Ltd.121-136.

Eder, T., and M. Doss. March 2014. Great Lakes Restoration at Work in Ohio. Edited by G. L. Commission. www.glc.org/policy/glc-legislative-priorities.

Fahnenstiel, G. L., R. A. Stone, M. J. McCormick, C. L. Schelske, and S. E. Lohrenz. 2000. Spring isothermal mixing in the Great Lakes: evidence of nutrient limitation and nutrient-light interactions in a suboptimal light environment. *Canadian Journal of Fisheries and Aquatic Sciences* 57 (9):1901-1910.

Federal Water Pollution Control Act Amendments of 1972, 33 U.S.C. §§ 1251 (1972).

Frerichs, L., M. Kim, G. Dave, A. Cheney, K. Hassmiller Lich, J. Jones, T. L. Young, C. W. Cene, D. S. Varma, J. Schaal, A. Black, C. W. Striley, S. Vassar, G. Sullivan, L. B. Cottler, A. Brown, J. G. Burke, and G. Corbie-Smith. 2017. Stakeholder perspectives on creating and maintaining trust in community-academic research partnerships. *Health Education and Behavior* 44 (1):182-191.

Gilroy, D. J., K. W. Kauffman, R. A. Hall, X. Huang, and F. S. Chu. 2000. Assessing potential health risks from microcystin toxins in blue-green algae dietary supplements. *Environmental Health Perspectives* 108 (5):435 - 439.

Glaser, B. G., A. L. Strauss, and S. Beer. 1968. The Discovery of Grounded Theory: na.

Gray, S., R. Shwom, and R. Jordan. 2012. Understanding factors that influence stakeholder trust of natural resource science and institutions. *Environmental Management* 49 (3):663-74.

Great Lakes Water Quality Agreement Amendments of 1972, U.S.-Can., Apr. 15, 1972, 23 U.S.T. 301.

Guest, G., A. Bunce, and L. Johnson. 2006. How many interviews are enough? An experiment with data saturation and varibility. *Field Methods* 18 (1):59-82.

Han, H., J. D. Allan, and N. S. Bosch. 2012. Historical pattern of phosphorus loading to Lake Erie watersheds. *Journal of Great Lakes Research* 38 (2):289-298.

Harke, M. J.; Steffen, M. M.; Gobler, C. J.; Otten, T. G.; Wilhelm, S. W.; Wood, S. 557 A.; Paerl, H. W., A review of the global ecology, genomics, and biogeography of the 558 commonly toxic cyanobacterium, *Microcystis*. *Harmful Algae* 2016**,** *54*, 4-20.

Hartley, T. W., and R. A. Robertson. 2008. Stakeholder collaboration in fisheries research: Integrating knowledge among fishing leaders and science partners in northern New England. *Society & Natural Resources* 22 (1):42-55.

Hecky, R. E., P. Campbell, and L. L. Hendzel. 1993. The stoichiometry of carbon, nitrogen, and phosphorus in particulate matter of lakes and oceans. *Limnology and Oceanography* 38 (4):709-724.

Hogan, R. J., and I. B. Mason. 2012. Deterministic forecasts of binary events. In *Forecast Verification: A Practioner's Guide in Atmospheric Science*, edited by Ian T. Jolliffe and D. B. Stephenson. West Sussex, England: John Wiley & Sons Ltd.31-59.

Holmes, J., and J. Lock. 2010. Generating the evidence for marine fisheries policy and management. *Marine Policy* 34 (1):29-35.

Hsieh, H. F. 2005. Three Aapproaches to qualitative content analysis. *Qualitative Health Research* 15 (9):1277-1288.

Huisman, J., R. R. Jonker, C. Zonneveld, and F. J. Weissing. 1999. Competition for light between phytoplankton species: Experimental tests of mechanistic theory. *Ecology* 80 (1):211–222.

Ibelings, B. W., L. R. Mur, and A. E. Walsby. 1991. Diurnal changes in buoyancy and vertical distribution in populations of *Microcystis* in two shallow lakes.

Jensen, R., and V. Uddameri. 2009. Using communication research to gather stakeholder references to improve groundwater management models: a South Texas case study. *Journal of Science Communication* 8 (1).

Karlsen, J. T., K. Græe, and M. J. Massaoud. 2008. Building trust in project-stakeholder relationships. *Baltic Journal of Management* 3 (1):7-22.

Knudsen, F. G., Sisse. 2010. Making sense of fishermen's risk perception. Policy and Practice in Health and Safety 8 (2):77-94.

Krantzberg, G., I. F. Creed, K. B. Friedman, K. L. Laurent, J. A. Jackson, J. Brammeier, and D. Scavia. 2015. Community engagement is critical to achieve a "thriving and prosperous" future for the Great Lakes–St. Lawrence River basin. Journal of Great Lakes Research 41:188-191.

Kromkamp, J., and A. E. Walsby. 1990. A computer-model of buoyancy and vertical migration in cyanobacteria. *Journal of Plankton Research* 12 (1):161-183.

Kromkamp, J. C., and L. R. Mur. 1984. Buoyant density changes in the cyanobacterium *Microcystis* aeruginosa due to changes in the cellular carbohydrate content. *FEMS Microbiology Letters* 25:105-109.

Kruger, R. A., and M. A. Casey. 2009. Developing a questioning route. In *Focus Groups* (35-61). Los Angeles, CA: Sage Publications.

Kruger, R. A., and M. A. Casey. 2009. Overview of focus groups. In *Focus Groups* (1-15). Los Angeles, CA: Sage Publications.

Kruger, R. A., and M. A. Casey. 2009. Planning the focus group study. In *Focus Groups* (17-33). Los Angeles, CA: Sage Publications.

Li, L., P. Xie, and J. Chen. 2007. Biochemical and ultrastructural changes of the liver and kidney of the phytoplanktivorous silver carp feeding naturally on toxic *Microcystis* blooms in Taihu Lake, China. *Toxicon* 49 (7):1042-53.

Lin, L., G. Appiah-Sefah, and M. Li. 2014. Using a laser particle analyzer to demonstrate relationships between wind strength and *Microcystis* colony size distribution in Lake Taihu, China. *Journal of Freshwater Ecology* 30 (3):425-433.

Lucente, J. E., T. Gabriel, G. Davis, C. Wellington, and F. Lichtkoppler. 2012. Ohio's 2010 Lake Erie Charter Fishing Industry. *Fisheries* 37 (12):532-541.

Makarewicz, J. C., and P. Bertram. 1993. Evidence of the restoration of the Lake Erie ecosystem. Journal of Great Lakes Research 19 (2):197.

McIntyre, L., D. Cassis, and N. Haigh. 2013. Formation of a volunteer harmful algal bloom network in British Columbia, Canada, following an outbreak of diarrhetic shellfish poisoning. *Marine Drugs* 11 (11):4144-4157.

McNie, E. C. 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. Environmental Science & Policy 10 (1):17-38.

Medrano, A. E., R. E. Uittenbogaard, L. M. Dionisio Pires, B. J. H. van de Wiel, and H. J. H. Clercx. 2013. Coupling hydrodynamics and buoyancy regulation in *Microcystis* aeruginosa for its vertical distribution in lakes. *Ecological Modelling* 248:41-56.

Michalak, A. M., E. Anderson, D. Beletsky, S. Boland, N. Bosch, T. Bridgeman, J. Chaffin, K. Cho, R. Confesor, I. Daloglu, J. V. DePinto, M. A. Evans, G. L. Fahnenstiel, L. He, J. Ho, L. Jenkins, T. H. Johengen, K. Kuo, E. LaPorte, X. Liu, M. McWilliams, M. Moore, D. Posselt, P. Richards, D. Scavia, A. Steiner, E. Verhamme, D. Wright, and M. Zagorski. 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorlogical trends consistent with expected future conditions. *PNAS* 110 (16):6448-6452.

Miles, M. S., A. M. Huberman, and J. Saldana. 2014. Fundamentals of qualitative data analysis. In *Qualitative Data Analysis: A Methods Sourcebook*. Thousand Oaks, California: Sage Publications.69-104.

Mittermaier, M., and N. Roberts. 2010. Intercomparison of spatial forecast verification methods: Identifying skillful spatial scales using the Fractions Skill Score. *Weather and Forecasting* 25 (1):343-354.

Mittermaier, M., N. Roberts, and S. A. Thompson. 2013. A long-term assessment of precipitation forecast skill using the Fractions Skill Score. *Meteorological Applications* 20 (2):176-186.

Morgan, D. L. 1993. Successful Focus Groups: Advancing the State of the Art. edited by R. A. Krueger. Thousand Oaks, California: SAGE Publications, Inc.

Mueller, K. B. 2004. The role of a social network in the functioning of the Grand Haven charter boat fishery, Lake Michigan. Department of Fisheries and Wildlife, Michigan State University.

Mueller, K. B., W. W. Taylor, K. A. Frank, J. M. Robertson, and D. L. Grinold. 2008. Social networks and fisheries: the relationship between a charter fishing network, social capital, and catch dynamics. North American Journal of Fisheries Management 28 (2):447-462.

Nakamura, T., Y. Adachi, and M. Suzuki. 1993. Flotation and sedimentation of a single *Microcystis* floc collected from surface bloom. *Wat. Res.* 27 (6):979-983.

NCCOS. 2016. Experimental Lake Erie Harmful Algal Bloom Bulletin. edited by N. C. f. C. O. Science.

Oberemm, A., J. Fastner, and C. Steinberg. 1997. Effects of microcystin-LR and cyanobacterial crude extracts on embryo-larval development of zebrafish (Danio rerio). *Wat. Res.* 31 (11):2918-2921.

Oberholster, P. J., J. G. Myburgh, D. Govender, R. Bengis, and A. M. Botha. 2009. Identification of toxigenic *Microcystis* strains after incidents of wild animal mortalities in the Kruger National Park, South Africa. *Ecotoxicol Environ Saf* 72 (4):1177-82.

O'Donnell, D. M., S. W. Effler, C. M. Strait, and G. A. Leshkevich. 2010. Optical characterizations and pursuit of optical closure for the western basin of Lake Erie through in situ measurements. *Journal of Great Lakes Research* 36 (4):736-746.

Ohio EPA. 2012. 2012 *Public Water System Harmful Algal Bloom Summary*. Ohio, US.

O'Leary, Z. 2007. deductive/inductive reasoning. The Social Science Jargon Buster.

Oliver, R. L., and A. E. Walsby. 1984. Direct evidence for the role of light-mediated gas vesicle collapse in the buoyancy regulation of *Anabaena flos-aquae* (cyanobacteria). *Limnology and oceanography* 29(4):879-886.

Patton, M. Q. 2002. Qualitative Analysis & Interpretation. *Qualitative research and evaluation methods*. Thousand Oaks, CA: Sage Publications.431-539.

Patton, M. Q. 2002. Qualitative Interviewing. *Qualitative research and evaluation methods*. Thousand Oaks, CA: Sage Publications.

Phillipson, J., P. Lowe, A. Proctor, and E. Ruto. 2012. Stakeholder engagement and knowledge exchange in environmental research. Journal of Environmental Management 95 (1):56-65.

Pontius, R. G., D. Huffaker, and K. Denman. 2004. Useful techniques of validation for spatially explicit land-change models. *Ecological Modelling* 179 (4):445-461.

Puddick, J., Wood, S. A., Hawes, I., & Hamilton, D. P. 2016. Fine-scale cryogenic sampling of planktonic microbial communities: Application to toxic cyanobacterial blooms. *Limnology and Oceanography-Methods* 14(9), 600-609.

Qin, H., S. Li, and D. Li. 2015. Differential responses of different phenotypes of *Microcystis* (Cyanophyceae) to UV-B radiation. *Phycologia* 54 (2):118-129.

Ramaswamy, S. 2001. Issues in the statistical mechanics of steady sedimentation. *Advances in Physics* 50(3): 297-341.

Rasenat, S., Hartung, G., Winkler, B. L., and Rehberg, I. 1989. The Shadowgraph Method in Convection Experiments. Experiments in Fluids 7(6), 412-420.

Richards, R. P., D. B. Baker, J. P. Crumrine, and A. M. Stearns. 2010. Unusually large loads in 2007 from the Maumee and Sandusky Rivers, tributaries to Lake Erie. *Journal of Soil and Water Conservation* 65 (6):450-462.

Roberts, N. M., and H. W. Lean. 2008. Scale-selective verification of rainfall accumulations from high-resolution forecasts of convective events. *Monthly Weather Review* 136 (1):78-97.

Rochet, M.-J., M. Prigent, J. A. Bertrand, A. Carpentier, F. Coppin, J.-P. Delpech, G. Fontenelle, E. Foucher, K. Mahé, E. Rostiaux, and V. M. Trenkel. 2008. Ecosystem trends: evidence for agreement between fishers' perceptions and scientific information. ICES Journal of Marine Science 65 (6):1057-1068.

Rowe, M. D., E. J. Anderson, T. T. Wynne, R. P. Stumpf, D. L. Fanslow, K. Kijanka, H. A. Vanderploeg, J. R. Strickler, and T. W. Davis. 2016. Vertical distribution of buoyant *Microcystis* blooms in a Lagrangian particle tracking model for short-term forecasts in Lake Erie. *Journal of Geophysical Research: Oceans* 121:1-19.

Rubin, R. 2012. Designing research for the responsive interviewing model. In *Qualitative Interviewing* (41-57). Thousand Oaks, CA: Sage Publications.

Rubin, R. 2012. Listening, hearing, and sharing. In *Qualitative Interviewing* (1 – 11). Thousand Oaks, CA: Sage Publications.

Rubin, R. 2012. Qualitative data gathering methods & style. In *Qualitative Interviewing* (25-39). Thousand Oaks, CA: Sage Publications

Rubin, R. 2012. Research philosophy & qualitative interviews. In *Qualitative Interviewing* (13-24). Thousand Oaks, CA: Sage Publications.

Ruiz, J., Macias, D., & Peters, F. 2004. Turbulence increases the average settling velocity of phytoplankton cells. *Proc Natl Acad Sci U S A*, 101(51), 17720-17724.

Scavia, D., J. David Allan, K. K. Arend, S. Bartell, D. Beletsky, N. S. Bosch, S. B. Brandt, R. D. Briland, I. Daloğlu, J. V. DePinto, D. M. Dolan, M. A. Evans, T. M. Farmer, D. Goto, H. Han, T. O. Höök, R. Knight, S. A. Ludsin, D. Mason, A. M. Michalak, R. Peter Richards, J. J. Roberts, D. K. Rucinski, E. Rutherford, D. J. Schwab, T. M. Sesterhenn, H. Zhang, and Y. Zhou. 2014. Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. *Journal of Great Lakes Research* 40 (2):226-246.

Sohngen, B., W. Zhang, J. Bruskotter, and B. Sheldon. March 2015. *Results from a 2014 survey of Lake Erie anglers: Final Report Submitted to the Lake Erie Protection Fund*. Ohio State University. Retrieved from http://lakeerie.ohio.gov/Portals/0/LEPF%20Final%20Report%20434-12.pdf

Thomas, R. H., and A. E. Walsby. 1985. Buoyancy regulation in a strain of *Microcystis*. *Journal of General Microbiology* 131:799–809

Tomlinson, M. C., R. P. Stumpf, T. T. Wynne, D. Dupuy, R. Burks, J. Hendrickson, and R. S. Fulton III. 2015. Relating chlorophyll from cyanobacteria-dominated inland waters to a MERIS bloom index. *Remote Sensing Letters* 7 (2):141-149.

Trainoff, S. P. and D. S. Cannell. 2002. Physical optics treatment of the shadowgraph. *Physics of Fluids* 14(4), 1340-1363.

Treasurer, J. W., F. Hannah, and D. Cox. 2003. Impact of a phytoplankton bloom on mortalities and feeding response of farmed Atlantic salmon, Salmo salar, in west Scotland. *Aquaculture* 218 (1-4):103-113.

Tushman, M., and R. Katz. 1980. External communication and project performance: An investigation into the role of gatekeepers. *Management Science* 26 (11).

US EPA. 2015. *Drinking Water Health Advisory for the Cyanobacterial Microcystin Toxins.* Washington, DC.

US EPA. *Great Lakes - Lake Erie* 2016. https://www.epa.gov/greatlakes/lake-erie.

Vanderploeg, H. A., J. R. Liebig, W. W. Carmichael, M. A. Agy, T. H. Johengen, G. L. Fahnenstiel, and T. F. Nalepa. 2001. Zebra mussel (Dreissena polymorpha) selective filtration promoted toxic *Microcystis* blooms in Saginaw Bay (Lake Huron) and Lake Erie. *Canadian Journal of Fisheries and Aquatic Sciences* 58 (6):1208-1221.

Vanderploeg, H. A., Sarnelle, O., Liebig, J. R., Morehead, N. R., Robinson, S. D., Johengen, T. H., & Horst, G. P. 2017. Seston quality drives feeding, stoichiometry and excretion of zebra mussels. *Freshwater Biology*, 62(4), 664-680.

Vellucci, M. 2007. *Fishing for the Truth: Achieving the "Best Available Science" by Forging a Middle Ground between Mainstream Scientists and Fishermen*. Doctoral dissertation, Roger Williams University School of Law, Boston University.

Vincent, R. K., X. M. Qin, R. M. L. McKay, J. Miner, K. Czajkowski, J. Savino and T. Bridgeman 2004. Phycocyanin detection from LANDSAT TM data for mapping cyanobacterial blooms in Lake Erie. *Remote Sensing of Environment* 89(3): 381-392.

Visser, P. M., J. Passarge, and L. R. Mur. 1997. Modelling vertical migration of the cyanobacterium *Microcystis*. *Hydrobiologia* 349:99-109.

Walker, D., and F. Myrick. 2006. Grounded theory: an exploration of process and procedure. Qualitative Health Research 16 (4):547-59.

Walsby, A. E. 1972. Structure and function of gas vacuoles. *Bacteriological Reviews* 36 (1):1 - 32.

Walsby. A. E and Booker. M. J, 1980, Changes in buoyancy of a planktomc blue-green alga in response to light intensity. Br. Phycol. J, 15, 311-319.

Wang, H., C. L. Gruden, T. B. Bridgeman, and J. D. Chaffin. 2009. Detection and quantification of *Microcystis* spp. and microcystin-LR in Western Lake Erie during the summer of 2007. *Water Sci Technol* 60 (7):1837-46.

Watson, S. B., C. Miller, G. Arhonditsis, G. L. Boyer, W. Carmichael, M. N. Charlton, R. Confesor, D. C. Depew, T. O. Hook, S. A. Ludsin, G. Matisoff, S. P. McElmurry, M. W. Murray, R. Peter Richards, Y. R. Rao, M. M. Steffen, and S. W. Wilhelm. 2016. The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia. Harmful Algae 56:44-66.

Weiss, R. S. 1994. Interviewing. In *Learning from strangers: The art and method of qualitative interview studies* (61-119). New York, NY: The Free Press.

White, S. H., L. J. Duivenvoorden, and L. D. Fabbro. 2005. Impacts of a toxic *Microcystis* bloom on the macroinvertebrate fauna of lake elphinstone, Central Queensland, Australia. *Hydrobiologia* 548 (1):117-126.

Whitton, B. A. 2012. *Ecology of Cyanobacteria II: Their Diversity in Space and Time*. United Kingdom: Springer.

WHO (World Health Organization). 1999. *Toxic Cyanobacteria in Water: A guide to their public health consequences, monitoring, and management*. London and New York: World Health Organization.

WHO. 1999. *Toxic Cyanobacteria in Water: A Guide to their Public Health Consequences, Monitoring, and Management.* edited by I. Chorus and J. Bartram. London, UK: E&FN Spon.

WHO. 2003. Cyanobacterial toxins: Microcystin-LR in drinking water. In *Background document for development of WHO Guidelines for Drinking-water Quality*. Geneva, Switzerland: World Health Organization.

Wicks, R. J. and Thiel, P. G. 1990. Environmental-Factors Affecting the Production of Peptide Toxins in Floating Scums of the Cyanobacterium *Microcystis-Aeruginosa* in a Hypertrophic African Reservoir. *Environmental Science & Technology* 24(9), 1413-1418.

Wilson, A. E., D. C. Gossiaux, T. O. Hook, J. P. Berry, P. F. Landrum, J. Dyble, and S. J. Guildford. 2008. Evaluation of the human health threat associated with the hepatotoxin microcystin in the muscle and liver

Wynne, T. T., R. P. Stumpf, M. C. Tomlinson, and J. Dyble. 2010. Characterizing a cyanobacterial bloom in Western Lake Erie using satellite imagery and meteorological data. *Limnology and Oceanography* 55 (5):2025-2036.

Wynne, T. T., R. P. Stumpf, M. C. Tomlinson, G. L. Fahnenstiel, J. Dyble, D. J. Schwab, and S. J. Joshi. 2013. Evolution of a cyanobacterial bloom forecast system in western Lake Erie: Development and initial evaluation. *Journal of Great Lakes Research* 39:90-99.

Wynne, T. T., R. P. Stumpf, M. C. Tomlinson, D. J. Schwab, G. Y. Watabayashi, and J. D. Christensen. 2011. Estimating cyanobacterial bloom transport by coupling remotely sensed imagery and a hydrodynamic model. *Ecological Applications* 21 (7):2709-2721.

Wynne, T. T., R. P. Stumpf, M. C. Tomlinson, R. A. Warner, P. A. Tester, J. Dyble, and G. L. Fahnenstiel. 2008. Relating spectral shape to cyanobacterial blooms in the Laurentian Great Lakes. *International Journal of Remote Sensing* 29 (12):3665-3672.

Xiao, Y., N. Gan, J. Liu, L. Zheng, and L. Song. 2011. Heterogeneity of buoyancy in response to light between two buoyant types of cyanobacterium *Microcystis*. *Hydrobiologia* 679 (1):297-311.

Yochum, N., R. M. Starr, and D. E. Wendt. 2011. Utilizing fishermen knowledge and expertise: keys to success for collaborative fisheries research. *Fisheries* 36 (12):593-605.