

# FINAL REPORT

## LAKE ERIE PROTECTION FUND PROJECT LEPF-TG-09-01

Connecting Phosphorus Load, Transport, and Biological Use: How Does  
*Microcystis* Use Phosphorus and Where is the Bloom Trigger Point?

Dr. David A. Culver<sup>1</sup>, Project Director

Dr. Joseph D. Conroy<sup>1,2</sup>, Co-Project Director

<sup>1</sup>Department of Evolution, Ecology, and Organismal Biology

The Ohio State University

Columbus, OH 43212

<sup>2</sup>Current Address: Inland Fisheries Research Unit

Ohio Department of Natural Resources

Division of Wildlife

Hebron, Ohio 43025

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Final Report to the Ohio Lake Erie Committee for Project LEPF-TG-09-01.  
*Connecting Phosphorus Load, Transport, and Biological Use: How Does Microcystis Use Phosphorus and Where is the Bloom Trigger Point?*  
David A. Culver and Joseph D. Conroy, Principal Investigators

**Abstract.** We determined the sources of *Microcystis* blooms entering Lake Erie via the Maumee and Sandusky rivers, where and when they began, and the role of phosphorus in their growth. *Microcystis* blooms began in the smallest tributaries, and were found at all sites by April, whereas Lake Erie's blooms typically begin in July.

Soluble reactive phosphorus was abundant in both systems, ranging from 6 to 174 micrograms P/L, whereas Lake Erie open water is usually  $< 2 \mu\text{g P/L}$ . Laboratory tests showed that P available to algae and *Microcystis* exceeded that needed for maximal growth. Phytoplankton in the rivers discharged to Lake Erie included huge amounts of *Microcystis* ( $\sim 10^{13}$  kg wet weight/mo in June and August 2009), equivalent to the capacity of 110 million railroad coal cars (at 100 tons each). Greater discharges of phytoplankton occurred in 2010. While other research tests whether this *Microcystis* continues to grow in Lake Erie after discharge, the tons of organic matter from phytoplankton loading to the lake each month has a large impact on the ecology of the lake. The best way to control *Microcystis* is to decrease the nonpoint P input from the watershed to the tributaries.

## Introduction

Since the mid-1990s, Lake Erie has shown clear signs of re-eutrophication. Although recent total phosphorus loads have remained generally at the mandated target of 11,000 metric tons since the mid-1980s (Dolan and Richards 2008), the dissolved portion of the tributary load has increased since the mid-1990s (Richards et al. 2007) likely making phosphorus more bioavailable (Baker et al. 2007). Also, large blooms of *Microcystis* and other Cyanobacteria (including *Lyngbya* in the nearshore area) have increased since the mid-1990s as has seasonal total phytoplankton biomass (Conroy et al. 2005, Bridgeman et al. 2011). These observations combined with other recurring problems including the invasion of the potentially toxic cyanobacterium *Cylindrospermopsis* (Conroy et al. 2007) and potentially detrimental hypolimnetic hypoxia (Conroy 2005) indicate that Lake Erie ecosystem health has continued to decline in recent years (Conroy et al. 2008). Accordingly, determining the role of increased bioavailable phosphorus, how the phytoplankton and cyanobacterial (including *Microcystis*) communities use that phosphorus to initiate blooms, and the initial sites of those blooms have been the focus of this research project. The Maumee and Sandusky rivers typically contribute the largest sources of nonpoint dissolved phosphorus to the lake from agricultural, sewage, and storm water inputs, and represent the lake's most agriculturally influenced watersheds, so we have performed intense sampling of these rivers, both temporally and spatially.

In this research project, we seek to evaluate the role of increased tributary dissolved reactive phosphorus delivery in initiating Harmful Algal Blooms in Lake Erie's two most agriculturally influenced watersheds. Outcomes from our project will directly assist lake and watershed managers who seek to reverse increasing phosphorus load and who seek to remediate harmful algal blooms, two of the 2008 Lake Erie Protection and Restoration Plan's Strategic Objectives.

Because we must also understand how phytoplanktonic (including *Microcystis* and other Cyanobacteria) and heterotrophic bacterial communities affect the other's dynamics through their use of phosphorus, carbon, and nitrogen (Heath et al. 2003, DeBruyn et al. 2004, Gao and Heath 2005), especially in riverine systems where light and nutrient availability vary dramatically, we have also sought to determine the competitive balance between these groups (Clevinger et al. 2007). Our research builds on our previous work to test the Algal Loading Hypothesis (Conroy 2007) which focused on the balance of light versus nutrient limitation of phytoplankton growth in the coupled Sandusky Ecosystem, including the Sandusky River, bay, and subbasin (LEPF Project No. 04-16). In that project, we found *Microcystis* upstream in the Sandusky River, even during spring and at times of phosphorus limitation. During times of low *Microcystis* abundance, the upstream community showed phosphorus limitation. However, only after P availability exceeded demand did *Microcystis* bloom, indicating the importance of phosphorus availability in triggering blooms.

**Project Goals and Objectives:** In this project, we sought to directly assess the role of bioavailable phosphorus in facilitating harmful algal blooms by determining (1) how *Microcystis* uses the bioavailable portion of the total phosphorus pool to form blooms in the Maumee and Sandusky systems of Lake Erie to determine (2) where in these blooms are "triggered" (i.e., far upstream, in the main tributary, not until the river discharges into the nearshore, or not until offshore). Ultimately, accomplishing these two goals allows us to inform ecosystem managers on how any future decreases in the bioavailable portion of loaded phosphorus may lead to decreases in harmful algal blooms in Lake Erie.

To achieve these goals we established four **Project Objectives**:

**(1) to determine temporal and spatial changes in phytoplankton community composition**, with particular emphasis on *Microcystis*, moving from small, low-order streams high in the watershed, into the main tributary, and out into the near- and offshore zones of Lake Erie in the coupled Maumee River-bay-western basin and Sandusky River-bay-subbasin systems;

**(2) to determine how phosphorus, nitrogen, and carbon (e.g., nutrient) concentrations, light attenuation, and temperature co-vary with alterations in phytoplankton community composition** and *Microcystis* abundance in these systems both spatially (i.e., up- to downstream and/or near- to offshore) and temporally (i.e., spring to summer and/or low flow to high flow);

**(3) to determine how *Microcystis*, the rest of the phytoplankton, and heterotrophic bacterial communities uptake and use phosphorus** in these systems both spatially and temporally; and,

**(4) to determine water flow connectivity between sites in these coupled systems** during various times of the year.

## Methods

Field Sampling: To quantify spatial and temporal variation in phytoplankton community composition, nutrient concentration, light attenuation, temperatures, nutrient use, and hydrodynamic connectivity, we sampled four sites in each of the Maumee and Sandusky coupled systems in 2009 (Table 1). In the Maumee system, these sites included (1) Lost Creek, a tributary to the Tiffin River which is a tributary of the Maumee River; (2) Maumee River at the Farnsworth Metro Park, Waterville, OH; (3) Maumee Bay, near the river mouth; and (4) at the historically important 7M station in the western basin east of the Maumee River discharge (Figure 1). In the Sandusky system, these sites included (1) Honey Creek near Melmore, OH, a site studied since 1975 by Heidelberg University; (2) Sandusky River where Wolf Creek joins the river near Fremont, OH; (3) Sandusky Bay east of the railway causeway; and (4) Lake Erie, in the Sandusky subbasin, east of the Sandusky River discharge (Figure 2). On the other hand, sampling in 2010 involved seven tributary sites for each river, including four sites previously sampled in 2009 (Figures 1 and 2, Table 1), to better characterize the role of the different portions of the watershed on physics, chemistry, and phytoplankton blooms. We sampled each site six times in 2009 (~once per month) during the months May–October 2009. Sampling trips coincided with both high- and low-flow events during the spring and summer months, but much of the year’s tributary discharge occurred in the March through June period, so sampling in 2010 began in March and extended again into October for a total of 11 sampling events (Figure 3).

For each sampling date and site, we used a multiparameter survey instrument (sonde) (Model 6600, YSI, Inc., Yellow Springs, Ohio) to measure temperature, dissolved oxygen concentration, *in situ* fluorescence (as a surrogate for chlorophyll concentration), *in situ* cyanobacterial phycocyanin concentration, and turbidity at depth. We also collected whole-water samples to analyze for chlorophyll *a*, phycocyanin, phytoplankton community composition, nutrient concentrations, and phosphorus uptake, plus phytoplankton and heterotrophic bacterial productivity measurements. Whole-water samples were held on ice until returned to The Ohio State University (OSU; chlorophyll and nutrients) or Kent State University (KSU; uptake and primary productivity) for further processing. Phytoplankton community samples were preserved with Lugol’s iodine solution for later enumeration using an inverted microscope.

For the four objectives, therefore, we performed a series of field samplings of the stations on the Maumee and Sandusky River systems, followed by laboratory analyses of samples, and quantitative analysis of the field and laboratory results (Table 2).

Table 1. Sample Site Locations, 2009 and 2010. The river miles (Rmi) from Lake Erie are shown in the last column.

<b>Sandusky River Sites</b>	<b>Lat/Long</b>	<b>2009 Station #</b>	<b>2010 Station #, Rmi</b>
Unnamed Tributary to Silver Creek, Melmore, OH	41.022834, -83.067189		SR1, Rmi 55
Silver Creek Tributary to Honey Creek, Melmore, OH	41.035863, -83.073919		SR2, Rmi 53
Honey Creek, Melmore, OH, Heidelberg WQL Sampling Site	41.021806, -83.105854	S1	SR3, Rmi 48
Honey Creek, Tiffin, OH	41.082515, -83.189831		SR4, Rmi 41
Sandusky River, Fort Seneca, OH	41.208929, -83.146744		SR5, Rmi 25
Wolf Creek, Sandusky State Scenic River Access, Fremont, OH	41.274374, -83.167722	S2	SR6, Rmi 20
USGS Gage Site 04198000, Rice Road, Fremont, OH	41.309003, -83.156186		
Sandusky R., Memory Marina	41.421684, -83.062713		SR7, Rmi 2
E. Sandusky Bay	41.47517, -82.76683	S3	
Lake Erie	41.47083, -82.61805	S4	
<b>Maumee River Sites</b>			
Tributary to Lost Creek, Rosedale Road, Hicksville, OH	41.361784, -84.690841	M1	MR1, Rmi 87
Tiffin River, Schick Road, Defiance, OH	41.348593, -84.42431		MR2, Rmi 71
Auglaize River, 2d Street, Defiance, OH	41.305876, -84.383883		MR3, Rmi 63
Maumee River, Independence Dam State Park, Defiance, OH	41.294777, -84.291355		MR4, Rmi 59
Maumee River, Napoleon, OH	41.382138, -84.138767		MR5, Rmi 49
Maumee River, M. J. Thurston State Park, Grand Rapids, OH	41.412705, -83.88701		MR6, Rmi 32
Maumee River, USGS Gage Site 04193500, State Route 64, Waterville, OH	41.500245, -83.714846		
Maumee River, Farnsworth Metro Park, Waterville, OH	41.476617, -83.74883	M2	MR7, Rmi 24
Maumee Bay	41.71667, -83.3667	M3	
Lake Erie	41.73300, -83.29700	M4	

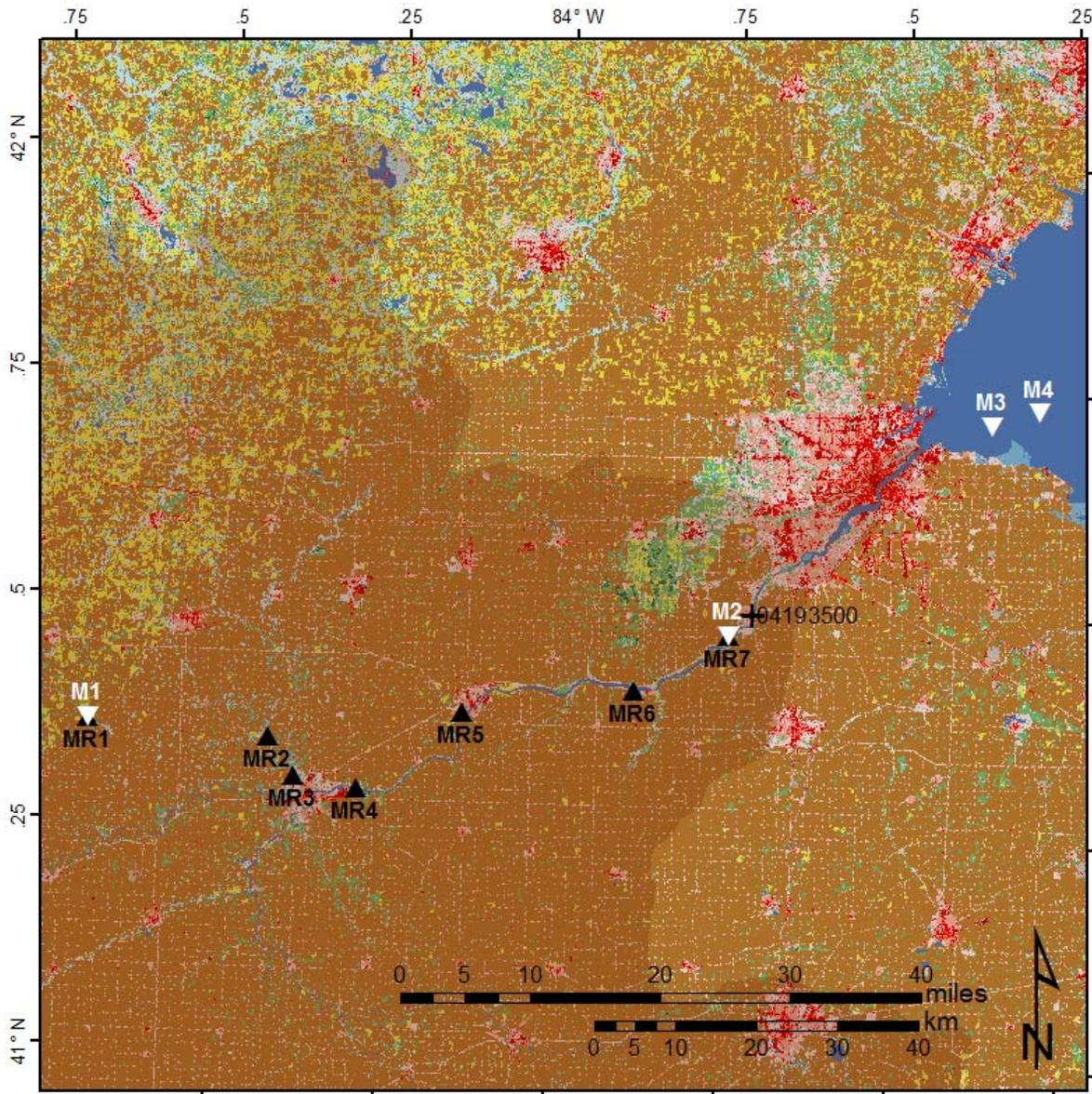


Figure 1. Sampling sites for 2009 (white labels) and 2010 (black labels) in the Maumee River tributaries, main stem, Maumee Bay, and the main sampling site in western Lake Erie. Background maps present land-use data for the drainage basin of each river with brown indicating agricultural land-use, shades of green indicating various forested land uses, and red colors indicating urban land use.

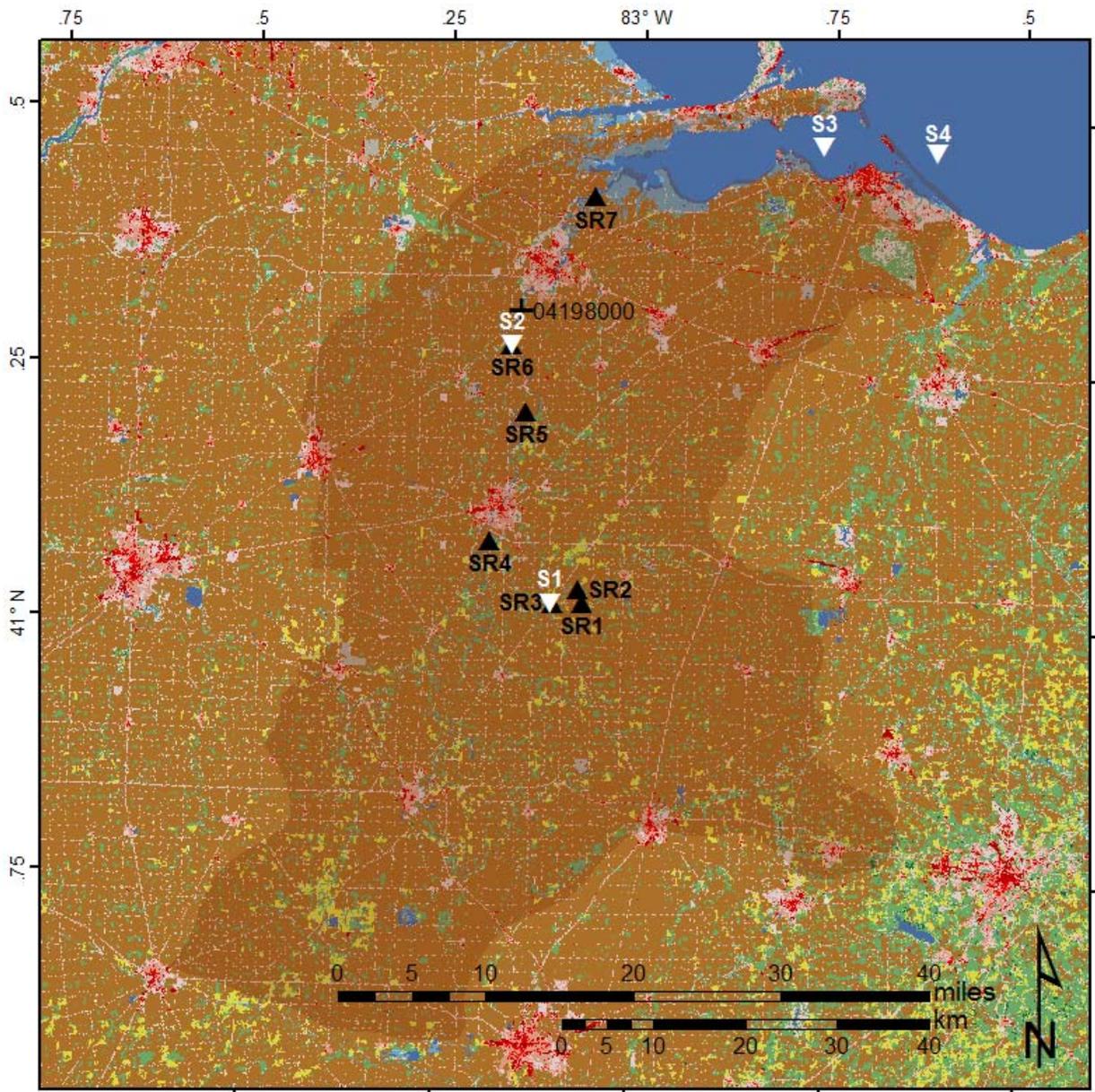
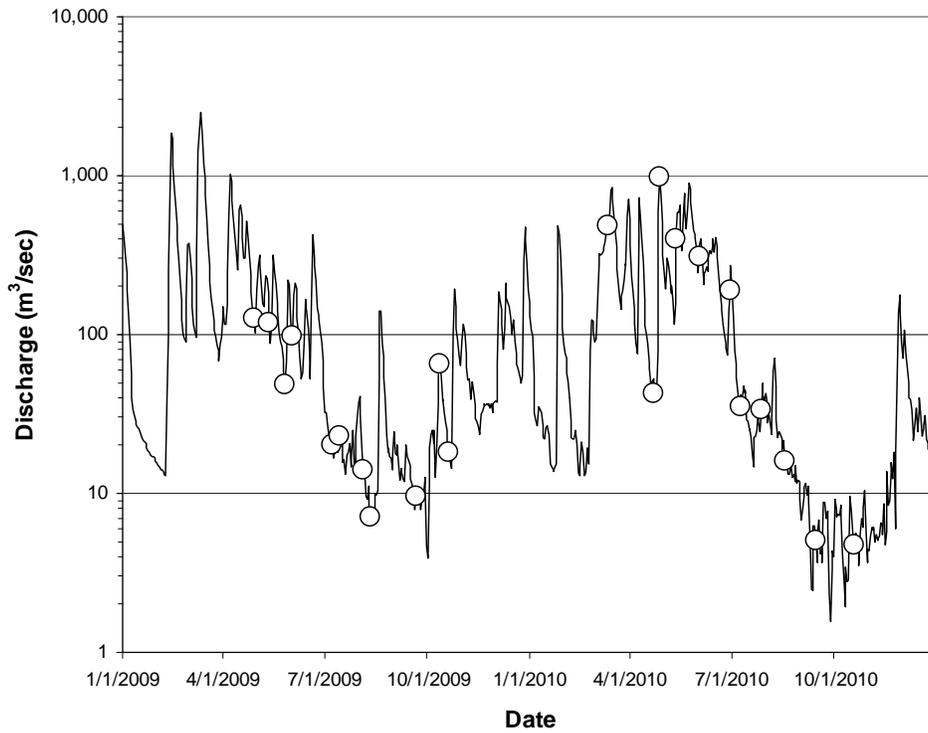


Figure 2. Sampling sites for 2009 (white labels) and 2010 (black labels) in the Sandusky River tributaries, main stem, eastern Sandusky Bay, and offshore in the Sandusky subbasin in the central basin of Lake Erie. Land uses are as above.

### Maumee Discharge and Sampling Dates 2009-2010



### Sandusky Discharge & Sampling Dates 2009-2010

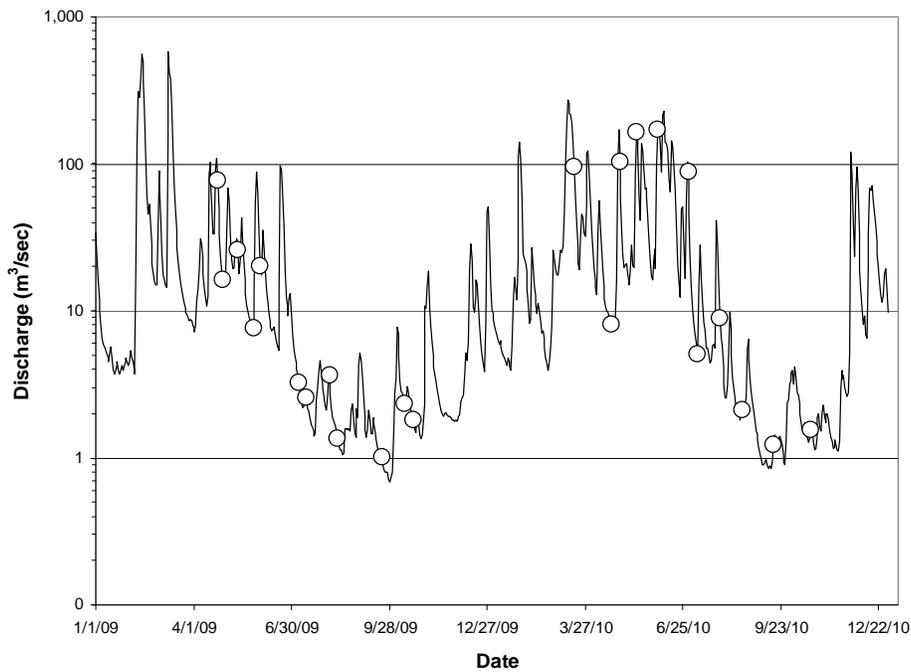


Figure 3. Discharge ( $m^3/sec$ ) at the USGS gauge station at Waterville for the Maumee River and at Fremont for the Sandusky River relative to our sampling dates in 2009 and 2010. Note the larger scales for discharge in the Maumee River. The 2010 sampling began earlier in the spring and achieved better representation of both high and low discharge events in the two rivers.

Table 2. Project Activity Schedule

Activity	2009										
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Field sampling		X	X	X	X	X	X	X			
Nutrient measurements		X	X	X	X	X	X	X			
Phosphorus use measurements		X	X	X	X	X	X	X			
Transport measurements				X		X					
Phytoplankton enumerations					X	X			X	X	
Progress Report delivered									X		

Activity	2010									
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Field sampling			X	X	X	X	X	X	X	X
Nutrient measurements			X	X	X	X	X	X	X	X
Phosphorus use measurements				X	X	X	X	X	X	X
Phytoplankton enumerations	X	X	X			X	X	X	X	X
Progress Report delivered						X				
Presentations		X		X						

Activity	2010		2011							
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Phytoplankton enumerations	X									
Presentations			X	X						

Activity	2011			
	Sep	Oct	Nov	Dec
Final Report delivered				X
Presentations				X

Laboratory analyses: For chlorophyll analysis, a sufficient volume of water to leave a heavy residue was filtered through GF/F (0.7-µm nominal pore diameter; Whatman) filters and frozen for later analysis by spectrophotometry. Phycocyanin samples were filtered similarly, followed by sonication of the filters in a phosphate buffer, filtration, and analysis by fluorescence relative to known concentrations of phycocyanin using a Turner 10-AU fluorometer. Nutrient analyses (total, particulate, and soluble reactive phosphorus, total Kjeldahl, particulate, nitrate, nitrite, and ammonium nitrogen, silicate, chloride, and particulate and dissolved carbon ) were performed at Heidelberg University’s National Center for Water Quality Research using 250-mL samples of the filtrate and whole water held on ice in the field and then frozen. At KSU, phytoplankton productivity was measured by incorporation of <sup>14</sup>C-sodium bicarbonate, bacterial productivity was measured by incorporation of <sup>3</sup>H-leucine, and phosphorus uptake rates and phosphorus debt

were measured by  $^{32}\text{P}$  incorporation in the dark into the particulate fractions  $> 1.0 \mu\text{m}$  (the phytoplankton) and between  $0.2\text{--}1.0 \mu\text{m}$  (the bacteria). Further description of algal and bacterial growth methods may be found in Conroy (2007) and Gao and Heath (2005).

Phytoplankters in preserved whole-water samples were quantitatively concentrated by settling. We used inverted microscopes at 400x to identify them to genus and enumerate them to generate estimates of numbers/ml, size frequency ( $\mu\text{m}$ ), wet weight biomass ( $\mu\text{m}^3/\text{individual}$ , and  $\text{ml}/\text{m}^3$ ), and their summations by phylum. Biomass determinations (cell volume based on geometric formulae) required measurements of representative cell dimensions (20 specimens) for each taxon.

## Results

### Objective 1. Determine temporal and spatial changes in phytoplankton community composition, with particular attention to *Microcystis*.

Estimates of seasonal and spatial variation in total phytoplankton biomass (algae plus Cyanobacteria) in 2009 show that biomass was high in all samples, but especially in the 4 August Maumee River station (36.5 mg/L wet weight), in the 11 August Maumee Bay station (26.5 mg/L), and in all samples from the Sandusky system, but especially on 20 October when the Sandusky Bay site biomass was 40.1 mg/L (Figure 4). These are remarkably high biomass values. For example, typical open lake samples do not exceed 3 mg/L, except during late summer *Microcystis* blooms. Note that these figures present biomass data from the small tributary stations at the bottom of the graph, followed by the main stem river stations, the bay stations, followed by the lake stations at the top. Biomass is represented by a series of colored contour plots. Similar graphs are used throughout this report to represent the temporal and spatial variation in state variables. Note that differences in concentration between the two river systems often requires that different scales be adopted for a given variable (e.g., Figure 4).

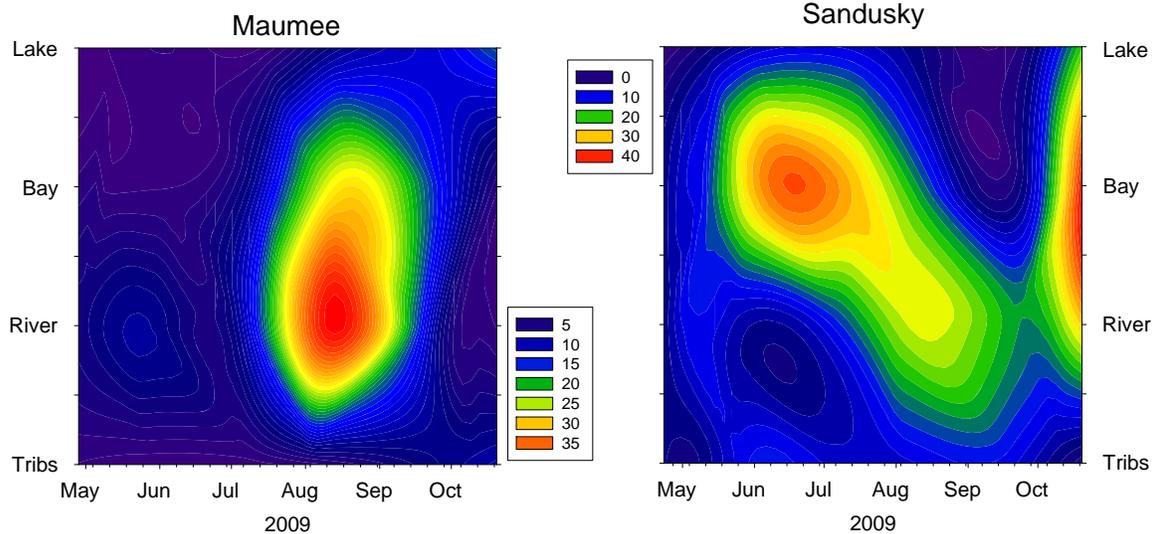


Figure 4. Comparison of total phytoplankton biomass (mg/L wet weight) in the Maumee and Sandusky River systems, 2009. Stations sampled included small, upstream tributaries, the main stem of each river, bays at the river mouths, and Lake Erie offshore stations for each river.

Chlorophyll *a* concentrations (Figure 5) are often used as a substitute for the algal counts and biomass estimates presented here (Figure 4). Both figures indicate that while significant blooms

occurred at all sites and dates, phytoplankton were most abundant in the Maumee River and Bay sites in July–September 2009, with lower concentrations in the Lake Erie and small tributary sites. Blooms occurred earlier in the year in the Sandusky River system, with the highest concentrations occurring in Sandusky Bay in late June and late October. Analysis of phytoplankton abundance and taxonomic composition helps characterize the dynamics of the phytoplankton community. The two river systems have a taxonomically diverse community (Table 3).

Table 3: Algal and cyanobacterial genera found in Sandusky and Maumee River and Lake Erie stations, 2009-2010. Genera marked with M or S were found only in the Maumee or Sandusky systems, respectively, but most taxa were common to both systems.

<b>Chlorophyta</b>	<b>Chrysophyta</b>	<b>Cyanobacteria</b>
<i>Actinastrum</i>	<i>Asterionella</i>	<i>Anabaena</i>
<i>Ankistrodesmus</i>	<i>Cyclotella</i>	<i>Aphanizomenon</i>
<i>Carteria</i>	<i>Cymbella</i>	<i>Chroococcus</i>
<i>Chlamydomonas</i>	<i>Dinobryon</i>	<i>Cylindrospermopsis</i>
<i>Closteriopsis</i>	<i>Fragilaria</i>	<i>Lyngbya</i>
<i>Closterium</i>	<i>Gomphonema</i>	<i>Merismopedia</i>
<i>Coelastrum</i>	<i>Gyrosigma</i>	<i>Microcystis</i>
<i>Cosmarium</i>	<i>Melosira</i>	<i>Planktothrix</i>
<i>Crucigenia</i>	<i>Navicula</i>	<i>Spirulina</i>
<i>Dictyosphaerium</i>	<i>Nitzschia</i>	
<i>Eudorina</i>	<i>Opephora</i> S	
<i>Franceia</i> M	<i>Rhizosolenia</i>	<b><u>Euglenophyta</u></b>
<i>Golenkinia</i>	<i>Rhoicosphenia</i>	<i>Euglena</i>
<i>Gonium</i>	<i>Stephanodiscus</i>	<i>Phacus</i>
<i>Lagerheimia</i>	<i>Surirella</i>	
<i>Micractinium</i>	<i>Synedra</i>	
<i>Oocystis</i>	<i>Synura</i>	
<i>Pandorina</i>		
<i>Pediastrum</i>	<b><u>Cryptophyta</u></b>	<b><u>Pyrrhophyta</u></b>
<i>Scenedesmus</i>	<i>Chroomonas</i>	<i>Ceratium</i>
<i>Schroederia</i>	<i>Cryptomonas</i>	<i>Gymnodinium</i>
<i>Sphaerocystis</i> S	<i>Rhodomonas</i>	<i>Peridinium</i>
<i>Spirogyra</i> S		
<i>Staurastrum</i>		
<i>Tetraedron</i>		
<i>Treubaria</i>		

*Microcystis* blooms and their initiation are an important focus of this project, and indeed, *Microcystis* was present in every phytoplankton sample collected in 2009, and often was a predominant taxon (Figure 6), exceeding 5 mg/L (wet weight) in the Maumee River on 7 July 2009, and in the Sandusky River on 7 July and 4 August 2009, and in Lake Erie at the Maumee site on 1 October and 20 October 2009, and in Sandusky Bay on 14 July, and the Sandusky

subbasin of Lake Erie 20 October 2009. Its biomass often exceeded 50% of the total phytoplankton present (Figure 7). However, the distribution of the cyanobacterial pigment phycocyanin (Figure 8) does not match the distribution of *Microcystis*, suggesting that other cyanobacteria were present and abundant. Indeed, the filamentous cyanobacterium *Planktothrix* exceeded 20 mg/L in Sandusky Bay on three dates (1 June, 14 July, and 20 October). Various species of this genus can produce the hepatotoxin microcystin and/or the neurotoxin saxitoxin.

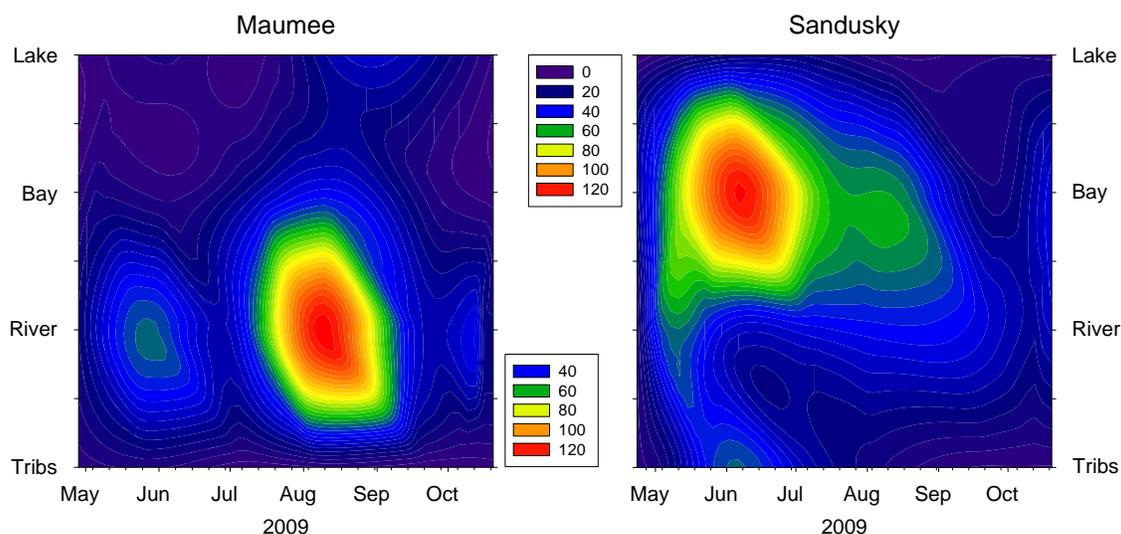


Figure 5. Comparison of chlorophyll *a* concentration ( $\mu\text{g/L}$ ) as an additional indication of the seasonal and spatial variation in the total phytoplankton biomass in the Maumee and Sandusky River systems, 2009.

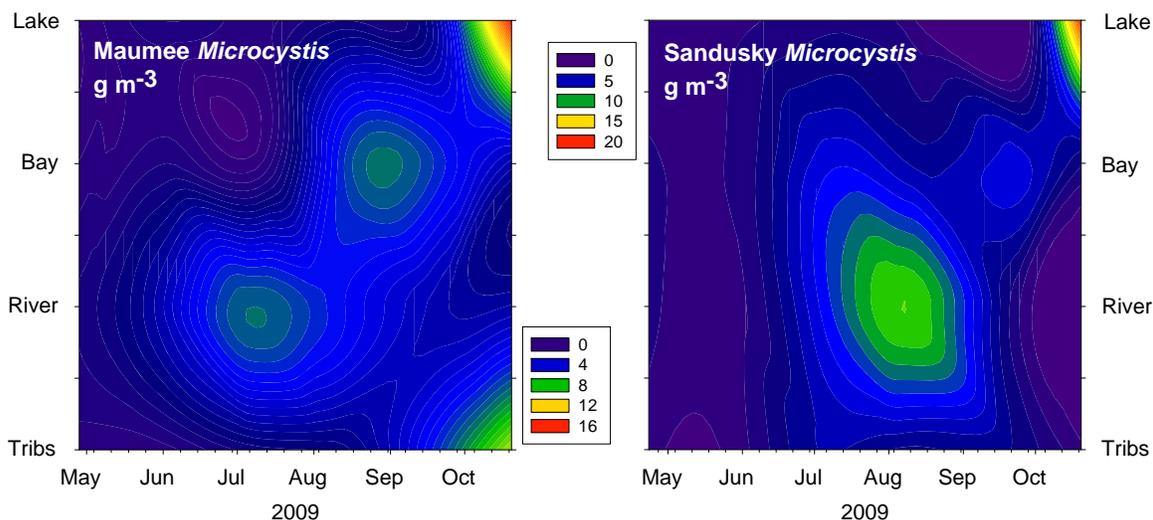


Figure 6. Comparison of spatial and temporal variation in *Microcystis* biomass ( $\text{mg/L}$  wet weight) in the Maumee and Sandusky river tributaries, main stem, Lake Erie bay and offshore locations for 2009.

*Microcystis* was present in all samples at all sites and dates. Peak tributary biomasses were 8.6 in the small tributary to the Maumee River (12 October 2009) and 4.1 mg/L in the Honey Creek

tributary to the Sandusky River on 7 July 2009. The maximum *Microcystis* biomasses found were 16.4 mg/L in the Maumee Lake Erie site and 19.6 mg/L in the Sandusky subbasin of Lake Erie, both on 20 October 2009.

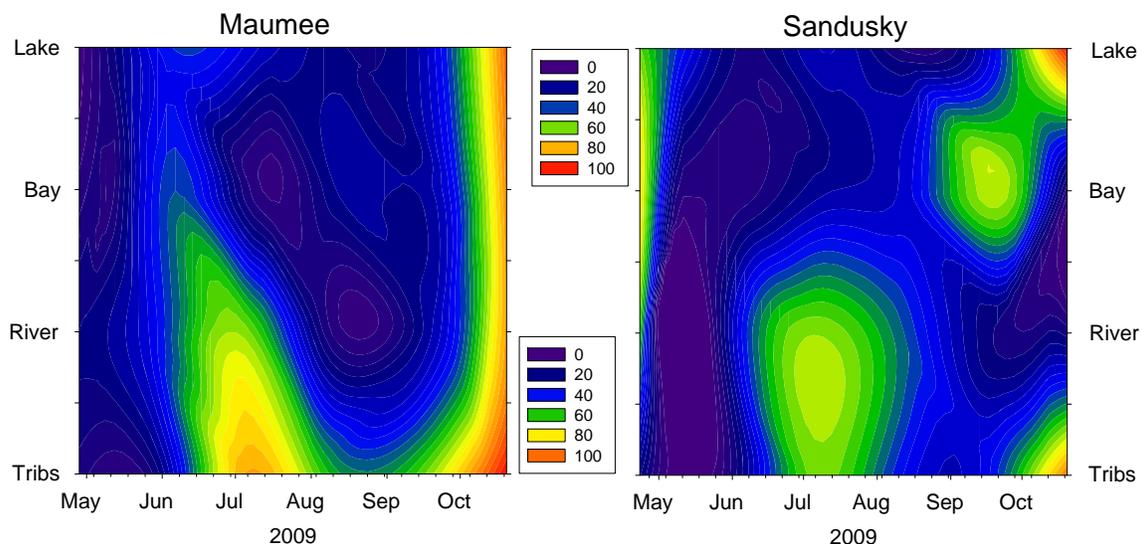


Figure 7. Comparison of the spatial and temporal variation in *Microcystis* as a percentage of the total phytoplankton biomass in the Maumee and Sandusky river tributaries, main stem, Lake Erie bay and offshore locations for 2009.

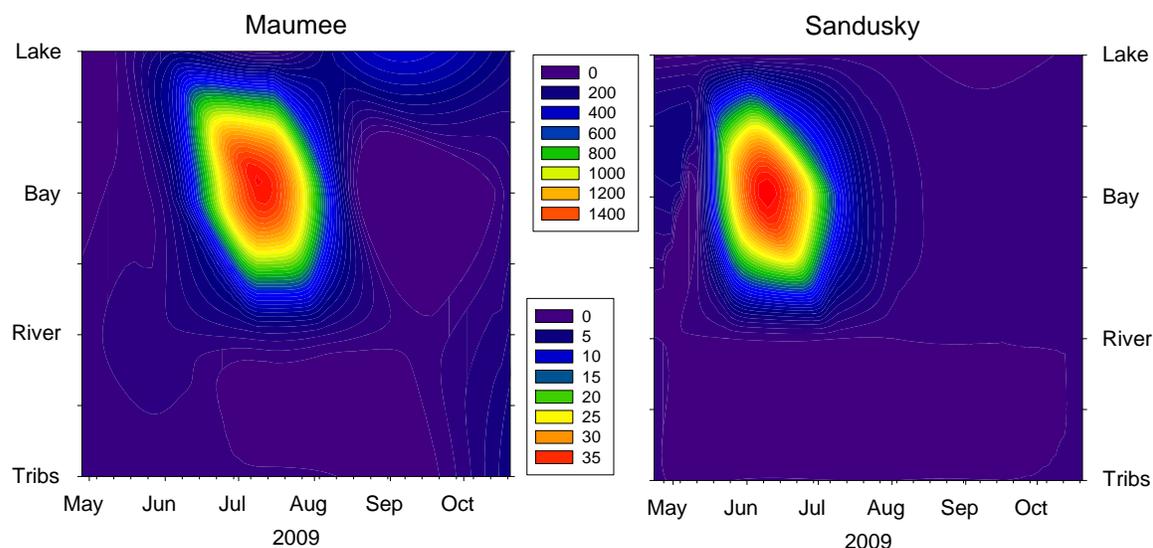


Figure 8. Seasonal and spatial variation in the cyanobacterial pigment phycocyanin ( $\mu\text{g/L}$ ) in the Maumee and Sandusky river tributaries, main stem, Lake Erie bay and offshore locations for 2009. While both systems had the greatest phycocyanin content in the bays in July and August, the much higher (40x) phycocyanin content in Sandusky Bay required a different scale for the isopleths.

Other taxonomic groups also achieved high densities at individual sites, with the dinoflagellate *Gymnodinium* achieving a biomass of 26.1 mg/L on 4 August 2009 in the Maumee River, the filamentous diatom *Melosira* (recently renamed *Aulacoseira*) present at 11.4 mg/L in Sandusky Bay on 20 October, a coccoid colonial green alga reached 11.5 mg/L in Maumee Bay on 11 August, and the flagellated green alga *Carteria* reached 8.4 mg/L in the Sandusky River on 21 September 2009.

**Modifying our approach: Sampling in 2010.** Because *Microcystis* occurred much earlier in the year at small tributaries to both rivers than we anticipated, and because Lake Erie sampling was the focus of many other research groups, we modified our strategies for 2010 to begin sampling earlier in the year, to sample an additional five tributary and river stations, and to intentionally sample both high flow and low events throughout the year (Table 1, Figure 3). The phytoplankton biomass distribution thus appears much different (Figure 9) from those seen in 2009 (Figure 4). The contouring program can perform more intricate interpolations through the numerous stations and dates.

The biomass of phytoplankton in 2010 exceeded that seen in 2009, in part because we sampled the early spring blooms occurring in the Maumee and Sandusky Rivers in March 2010, but primarily because summer blooms in the rivers in 2009 greatly exceeded those in 2009. Total phytoplankton biomass exceeded 20 mg/L in individual Maumee system sites on 22 April, 12 May, 1 June, 8 July, and on 27 July (three sites), with the highest biomass being 41.8 mg/L wet weight on the Maumee River at Napoleon (MR5) on 27 July 2010. Phytoplankton biomass in the Sandusky system was higher yet, with values above 20 mg/L on 30 June, above 30 on 17 March, 2 June, 30 June, and a maximum value of 53.5 on 17 March on the Sandusky River at Fort Seneca (station SR5).

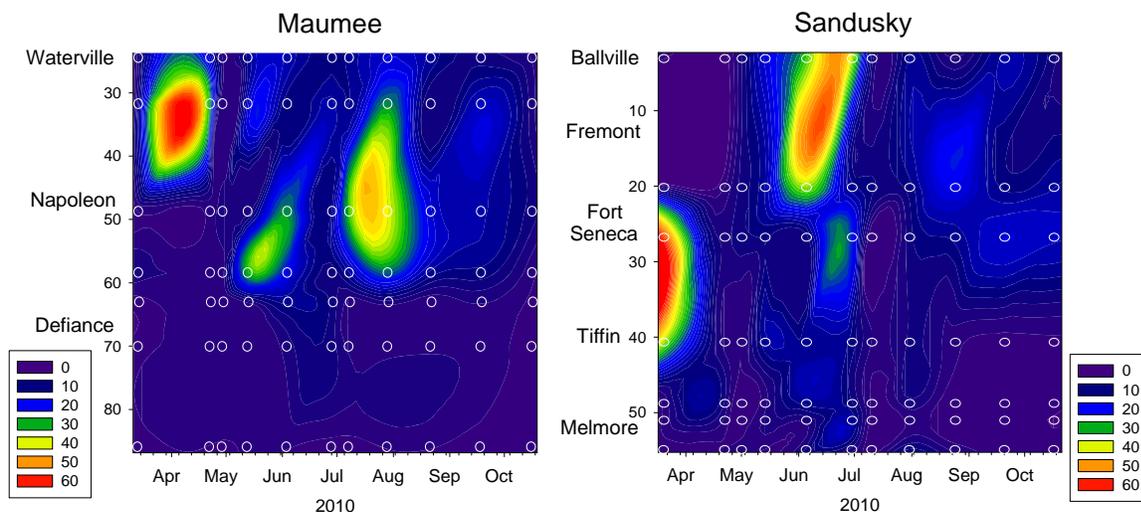


Figure 9. Seasonal and spatial variation in total phytoplankton biomass (algae plus Cyanobacteria, mg wet weight /L) for seven tributary and main stem stations on both the Maumee and Sandusky river systems, 2010. Numbers on the y-axis reflect the number of river-miles from the confluence with Lake Erie, plus the position of major towns. White circles mark the date and river-mile of each sample taken.

High biomass values were usually associated with *Microcystis* blooms ranging from 5 to 23 mg/L at many Maumee stations on 12 May, 1 June, and 29 June, but other taxa were also abundant, including 9 mg/L for the cyanobacterium *Anabaena* on 27 July on the Maumee River at Grand

Rapids (MR6). Other abundant algae included centric diatoms at main stem Maumee River sites on 22 April (15.0 mg/L at MR6), 27 July (8.4, 6.0, and 8.8 at MR5, MR6, and MR7, respectively), and 14 September (7.9 mg/L at MR6). Various green algae (*Eudorina*, *Carteria*, *Chlamydomonas*, and *Oocystis*) formed blooms on the Maumee River on 8 July (26.1 mg/L), 27 July (12.8, 22.9, and 6.0 at MR4, MR5, MR6), and 17 August (5.4, 10.4 at MR4 and MR5).

Total phytoplankton biomass in the Sandusky River was higher yet, with values exceeding 10 mg/L wet weight on 13 May (3 sites), 2 June (2 sites), 30 June (3 sites), 9 July (1 site), 19 August (2 sites), 16 September (3 sites), and 21 October (2 sites). Biomass exceeded 20 mg/L at one site on both 2 and 30 June, but exceeded 30 mg/L on 3 occasions, with the maximum biomass of 53.5 mg/L occurring on the Sandusky River at Fort Seneca on 17 March. *Microcystis* was a principal contributor to these blooms (i.e., > 5 mg/L, maximum = 41.4 mg/L) in 17 samples, but other taxa were abundant as well, including the same taxa listed above. However, diatoms exceeded 10 mg/L in only 3 samples, while greens exceeded 5 mg/L in 5 samples.

Although the biomass was higher in the Sandusky system, spring and summer chlorophyll *a* was much higher in the Maumee River stations in 2010 (Figure 10) than in the single main river station sampled in 2009. The Sandusky River station was again high, but not as high as the Maumee River. Both Figures 8 and 9 indicate the remarkable phytoplankton abundance in the Maumee and Sandusky systems, and that the biomass changed rapidly from station to station and date to date.

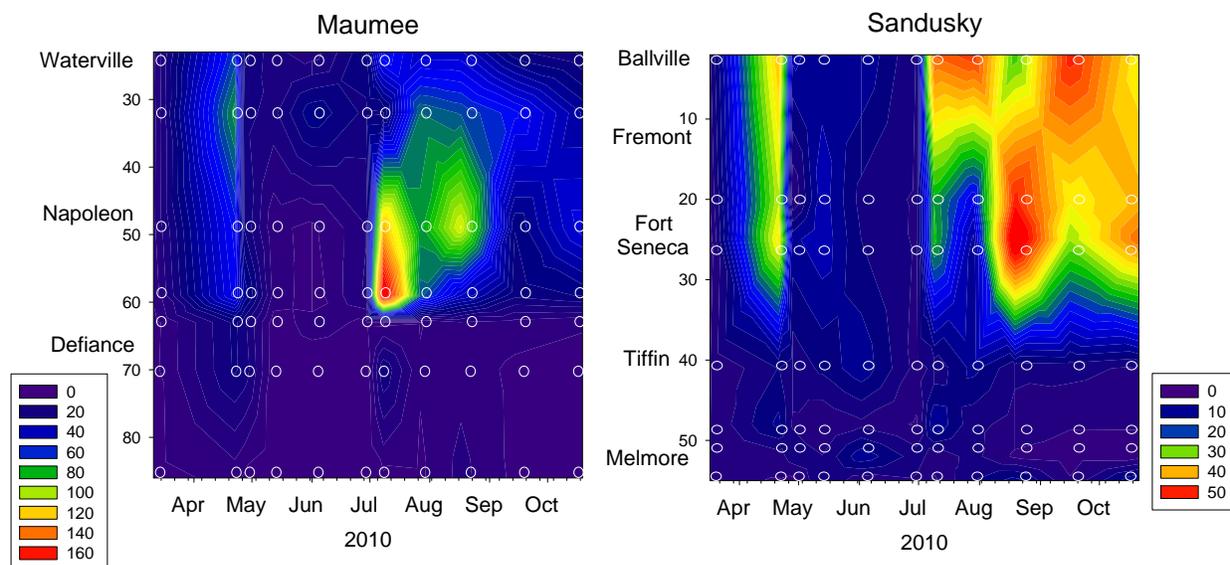


Figure 10. Seasonal and spatial variation in chlorophyll *a* ( $\mu\text{g/L}$ ) as an additional indication of total phytoplankton biomass for seven tributary and main stem stations on both the Maumee and Sandusky river systems, 2010. Note that the maximum scale for the Maumee isopleths is 3.2 times that of the Sandusky isopleths.

Because *Microcystis* dynamics are of particular importance to this study, we have again prepared isopleths showing its spatial and temporal variation at the same stations (Figure 11). The figures are very similar to those of total phytoplankton biomass (Figure 9), so we have again calculated the percentage of the total biomass that consists of *Microcystis* (Figure 12). For many stations and dates, the *Microcystis* biomass approached 100% of the total phytoplankton biomass, and for most of the year in both river systems, it exceeded 50%. The distribution of the cyanobacterial pigment phycocyanin again does not match the *Microcystis* distribution precisely, due to the

presence of other cyanobacterial taxa in the rivers and their tributaries. Nevertheless, Cyanobacteria were extremely abundant in 2010, particularly in the Sandusky system.

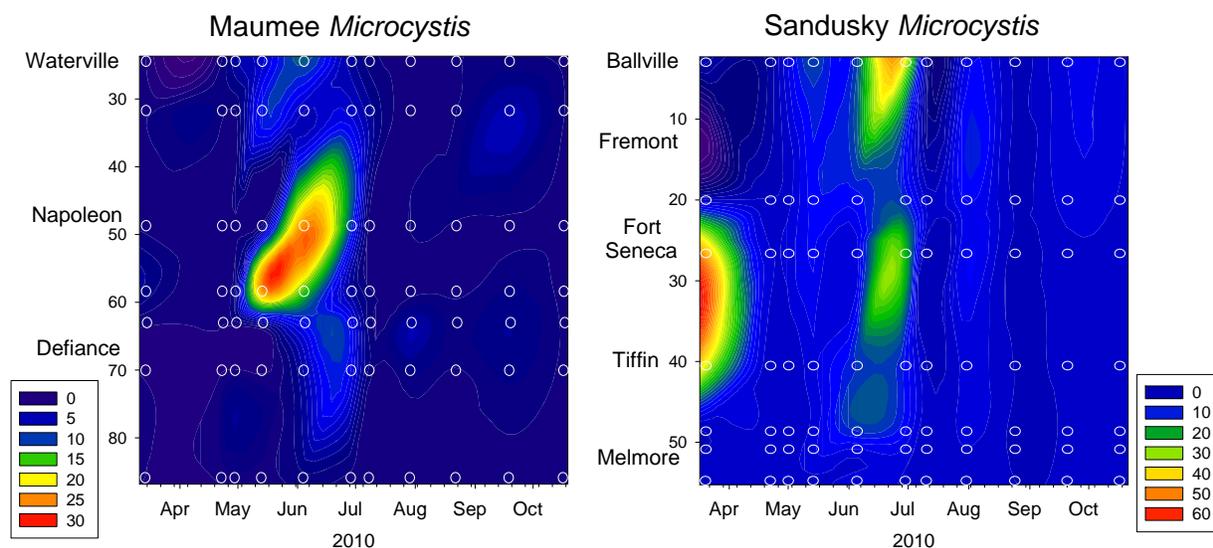


Figure 11. Seasonal and spatial variation *Microcystis* biomass (mg wet weight /L) for seven tributary and main stem stations on both the Maumee and Sandusky river systems, 2010.

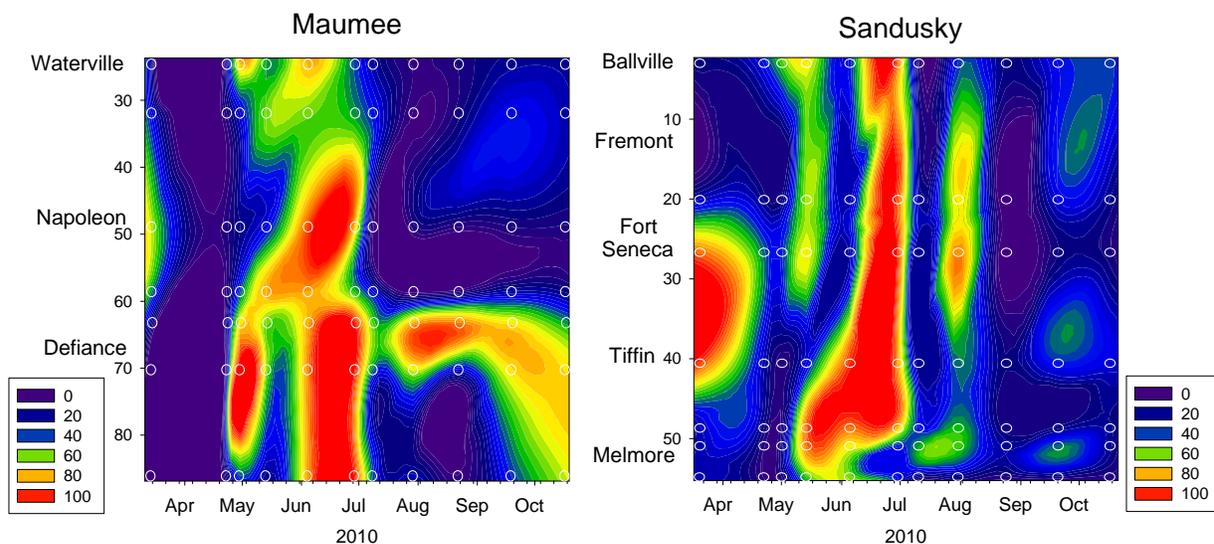


Figure 12. Seasonal and spatial variation *Microcystis* biomass as a percentage of total phytoplankton biomass for seven tributary and main stem stations on both the Maumee and Sandusky river systems, 2010. Note that while the biomass of *Microcystis* was not a constant fraction of the total phytoplankton (compare Figures 10 and 12), this figure shows that it was often the dominant (and approached the only) taxon present.

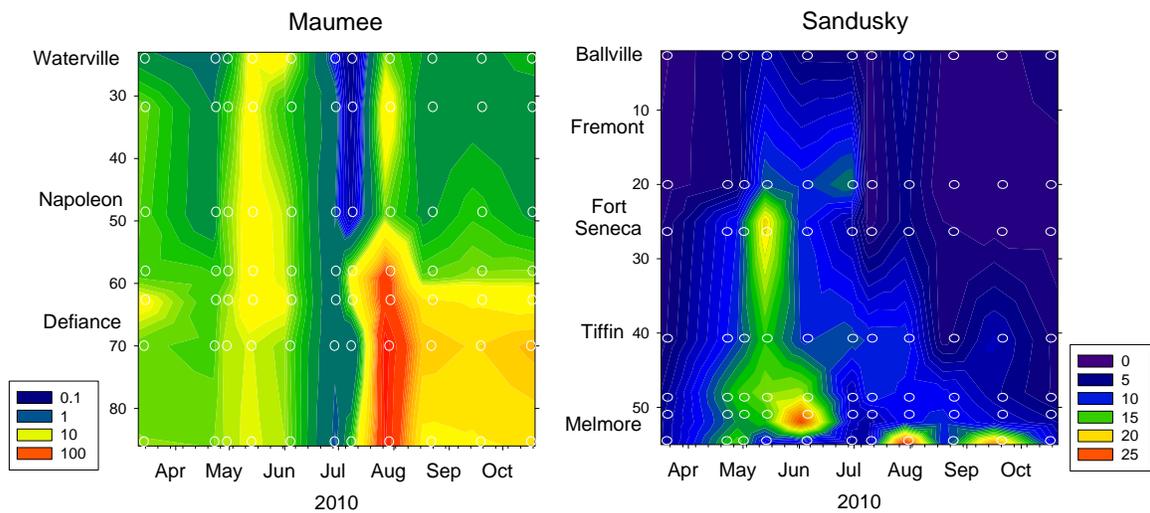


Figure 13. Seasonal and spatial variation in the concentration of the cyanobacterial pigment phycocyanin ( $\mu\text{g/L}$ ), 2010. Note that the extremely high concentrations in the Maumee system require representing the data as the  $\log_{10}$  of the phycocyanin concentration.

**Objective 2. Determine how phosphorus, nitrogen, and carbon (e.g., nutrient) concentrations, light attenuation, and temperature co-vary with alterations in phytoplankton community composition and *Microcystis* abundance in these systems both spatially and temporally (i.e., spring to summer and/or low flow to high flow).**

While it is interesting to contrast the seasonal and spatial abundances of various phytoplankters and their pigments in the Maumee and Sandusky Rivers and the two bays and Lake Erie, a primary goal of this project was to determine the factors important to the initiation and expansion of algal blooms therein, with particular attention to the role of phosphorus in the blooms of *Microcystis*. In this section, we focus on the effects of tributary and river flow on the abundance of suspended solids and phosphorus, and their impact on phytoplankton blooms.

In 2009, total phosphorus concentrations were highest in the Maumee and Sandusky rivers throughout the sampling season, and also in Sandusky Bay in June and July (Figure 14). While soluble reactive phosphorus was high at all stations and on all dates in 2009, it was particularly abundant in May and October in the Maumee River, and was a much higher percentage of total phosphorus in those months, and was a smaller fraction of total phosphorus in the Sandusky system, except on the October sampling date in the Honey Creek tributary (Figure 14).

The total phosphorus and the soluble reactive phosphorus concentrations were much higher in 2010 in both rivers (Figure 15). The highest concentrations occurred in May–July, which were samples taken during very high flow events (Figure 3). The soluble reactive phosphorus (SRP) that is most stimulatory to algal and cyanobacterial growth typically was 40% or more of the total phosphorus in both rivers in 2010 (Figure 15).

Total suspended solids (TSS) (Figure 16) were also strongly influenced by discharge in 2009 (Figure 3). A large fraction of the total suspended solids was inorganic material, so the nonvolatile suspended solids (NVSS) isopleths are very similar to the TSS isopleths. The difference between the TSS and the NVSS is the weight of particulate organic matter, which is presented as a percentage of the TSS in the bottom two panels. The relatively precise correspondence between the top two sets of panels shows that most of the peaks in suspended particulate occurred when inorganic matter (NVSS) was also high, corresponding to high discharge events. The percent of the particulate matter that is organic (to which algae and cyanobacteria contribute) often peaks when TSS and NVSS were lower, i.e., at low flow.

In 2010, the more frequent spatial and temporal sampling of the tributaries and various reaches of the rivers even better illustrates the impact of discharge variation on the total suspended solids (TSS) and nonvolatile suspended solids (NVSS) (Figure 17). As in 2009, the relatively precise correspondence between the top two sets of panels shows that most of the peaks in suspended particulate occurred when inorganic matter (NVSS) was also high, corresponding to high discharge events. However, the particulate matter suspended in the tributaries in 2010 was five to ten times higher than those found in 2009. The percent organic matter (algae and cyanobacteria) often peaks when TSS and NVSS were lower.

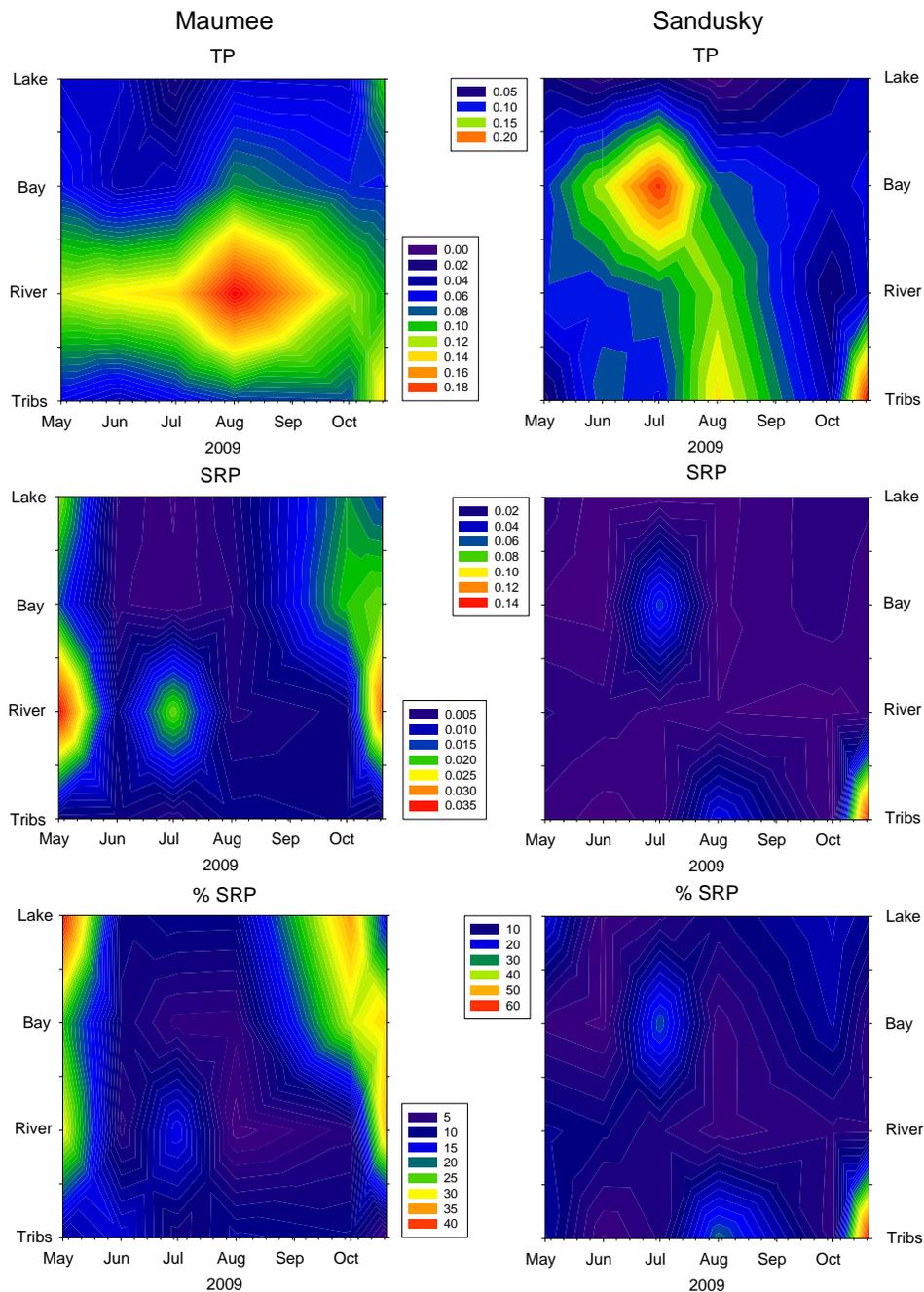


Figure 14. Comparison of the temporal and spatial variation in total phosphorus (TP) and soluble reactive phosphorus (SRP) (mg P/L), and the percentage of the TP that is SRP, in the Maumee and Sandusky river tributaries, main stem, Lake Erie bay and offshore locations for 2009. The higher SRP content of water in the Sandusky system required scales four times higher than those in the Maumee system.

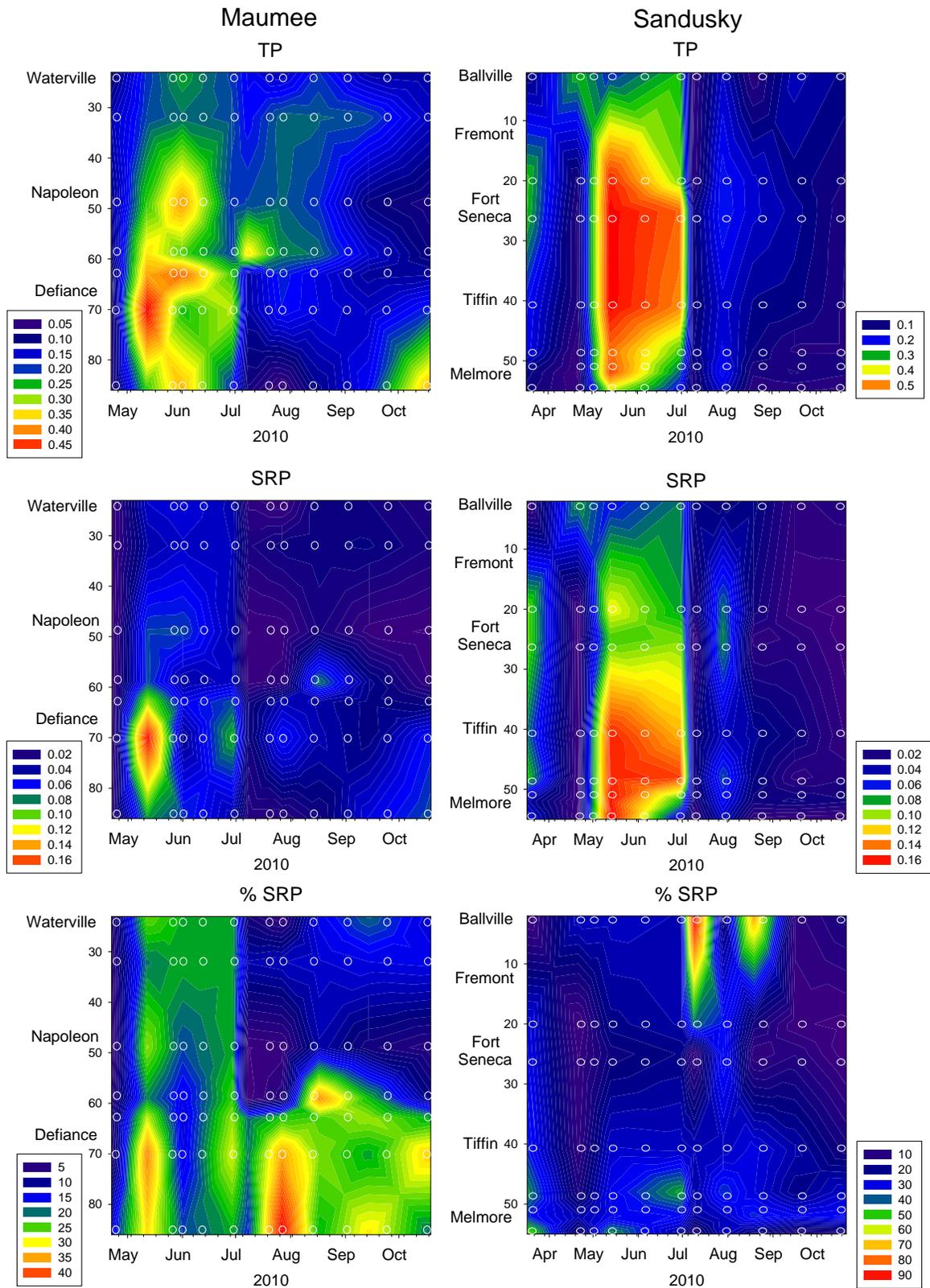


Figure 15. Comparison of the temporal and spatial variation in total phosphorus (TP) and soluble reactive phosphorus (SRP) (mg P/L), and the percentage of the TP that is SRP, in the Maumee and Sandusky watersheds (2010).

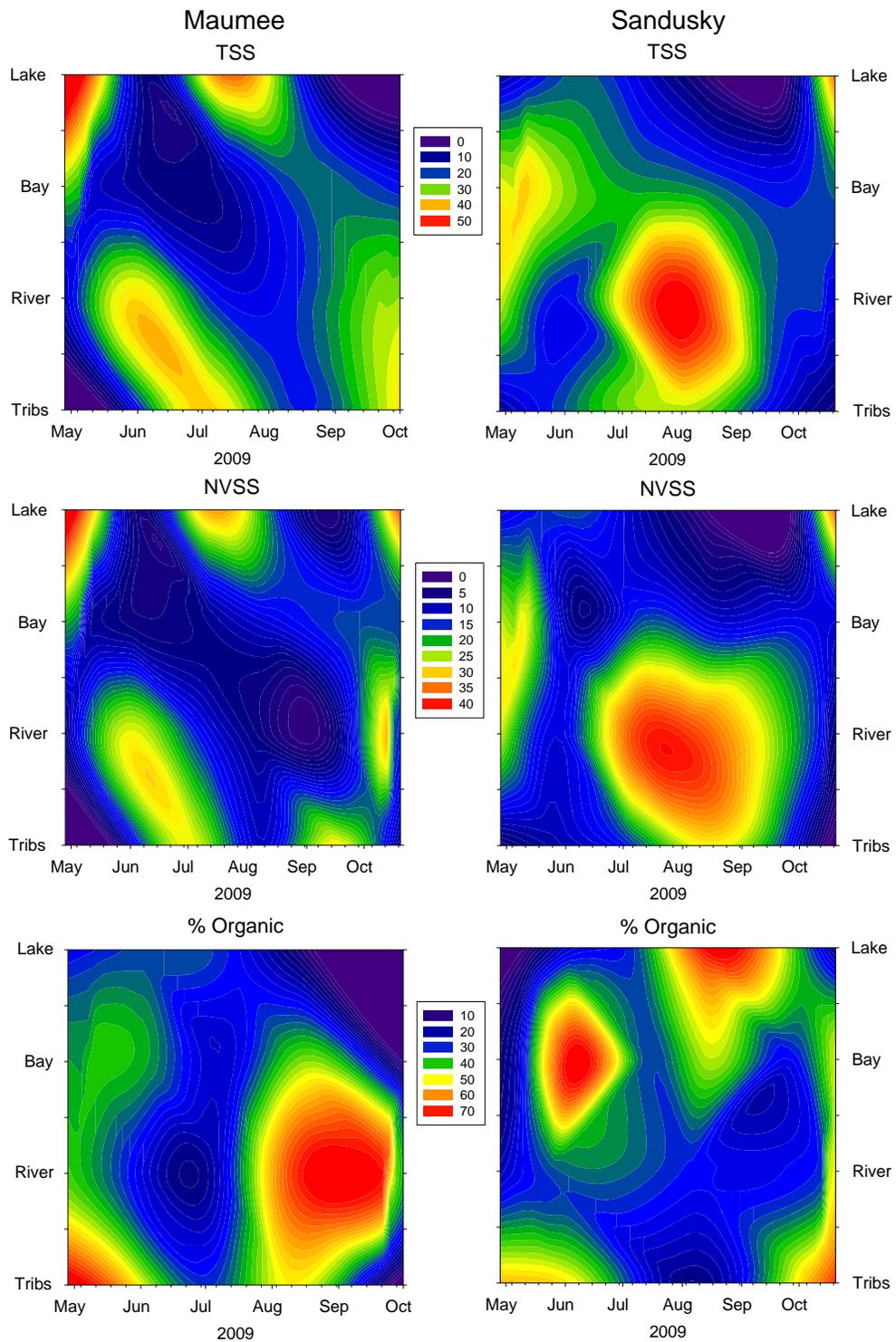


Figure 16. Comparison of the temporal and spatial variation in total suspended solids (TSS) (mg/L) and the non-volatile suspended solids (NVSS) (mg/L) in the Maumee and Sandusky river tributaries, main stem, Lake Erie bay and offshore locations, and the percent particulate organic matter from the same samples, 2009.

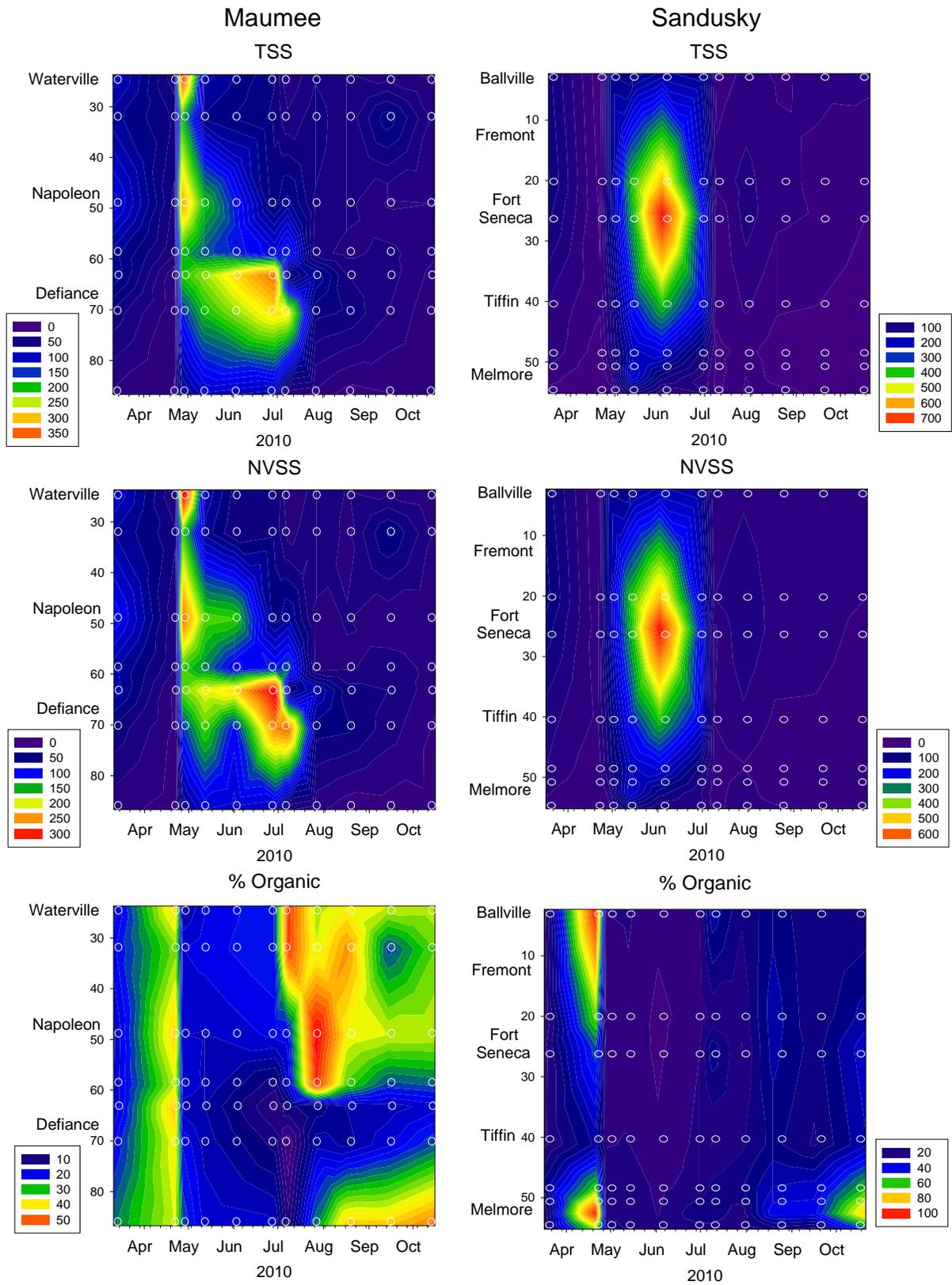


Figure 17. Comparison of the temporal and spatial variation in total suspended solids (TSS) and the non-volatile suspended solids (VSS) in the Maumee and Sandusky watersheds, and the percent particulate organic matter from the same samples (2010). Note that the Sandusky scales are twice those of the Maumee River system.

**Objective 3. Determine how *Microcystis* and the rest of the phytoplankton and heterotrophic bacterial communities take up and use phosphorus in these systems, both spatially and temporally.**

Because the phosphorus concentration in the water tells us little about the availability of phosphate inside the algal and bacterial cells, one cannot determine the relative impact of a high or low phosphate concentration on their growth rate. Therefore, we measured the rate of uptake of radioactive phosphate (P use) from phytoplankton community samples from both rivers as an indication of whether the dissolved phosphate was adequate for algal and bacterial growth. When P limitation occurred, phosphorus concentrations were too low to meet the demand of the phytoplankton. Conversely, when P limitation did NOT occur, phosphate in the system exceeded demand, so algal and cyanobacterial growth was likely limited by light or inorganic N availability.

We measured two physiological indicators of P use in the Maumee and Sandusky systems (at a tributary and at a main stem site in each river and at two sites offshore of each river) at monthly intervals May through October 2009. In 2010 we measured these indicators at the same two river sites in each system, April through October. Phosphorus debt (P-debt) determines the amount of P taken up by phytoplankton over 24 hrs in the dark per unit of chlorophyll *a*, and is an indicator of the level of deficiency in internal P for the phytoplankton (Healey and Hendzel 1980). P-debt levels at approximately  $0.075 \mu\text{mol P } (\mu\text{g chlorophyll } a)^{-1}$  or above are indicative of algae that are deficient in P to a point that it may limit their growth. The only examples of P limitation based on P-debt are from the Maumee system in 2009 (compare Figures 18 and 19). At station M1, there is evidence for P limitation at all dates except May. Limitation is also observed at site M3 in October 2009 and site M4 in July 2009. On the other hand, there was so much phosphate available in 2010 that there was no evidence of phosphorus limitation at either station on any date in 2010 (Figure 19).

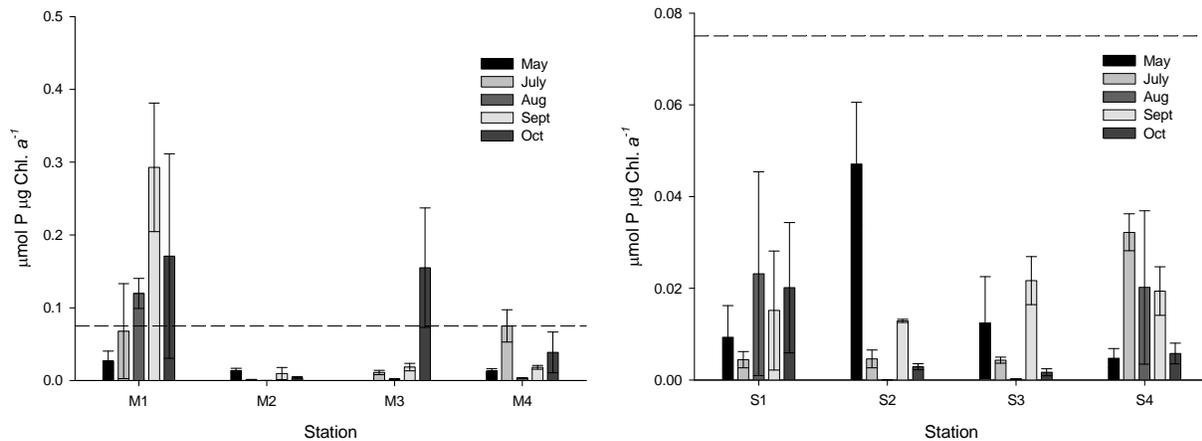


Figure 18. Phosphorus debt assay results for the Maumee River system, left panel, and the Sandusky system, right panel, 2009. A value above  $0.075 \mu\text{mol P } (\mu\text{g chlorophyll } a)^{-1}$  (dashed line) is indicative of P limitation. An anomalous (negative) value at station M3 in May is not plotted. Other values that appear missing are not distinguishable from the axis line. Error bars are  $\pm$  one standard deviation.

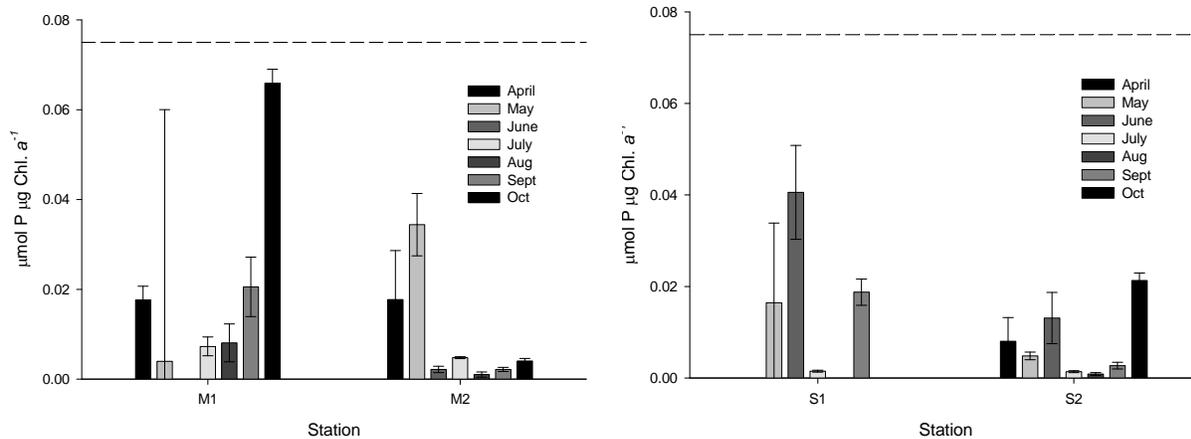


Figure 19. Phosphorus debt assay results for the Maumee River system, left panel, and the Sandusky system, right panel, 2010. A value above  $0.075 \mu\text{mol P } \mu\text{g (chlorophyll } a)^{-1}$  (dashed line) is indicative of P limitation. Negative values at station M1 in June and S1 in April, August, and October are not plotted. Note: Site M2 in this figure corresponds with the same site in 2009. However this site was renamed MR7 for the 2010 sampling campaign. Similarly, S1 = SR3 and S2 = SR6 (see Figures 1 and 2). This same notation will be used for other figures from 2010. Error bars are  $\pm$  one standard deviation.

Phosphorus turnover time (TT) provides another method to determine whether phosphorus availability is adequate for growth. TT is the time required for an amount of phosphorus equal to the pool of biologically available P to be taken up by phytoplankton or bacteria. A turnover time of less than 60 min is considered to be evidence that the phytoplankton and bacteria in the sample are P limited. The TT decreases as SRP pool sizes decrease or as biological uptake increases. This turnover can be partitioned to either phytoplankton or bacteria by filtering different size fractions of the incubated sample. In our plots we combine these by only displaying the faster of the two turnover times to show when P is likely to be limiting overall. In 2009, all sites showed evidence for P limitation except for the Maumee River main stem site M2 (Figure 20). Samples collected in May and August from both systems often showed P limitation or turnover times that were close to the benchmark time of 60 min.

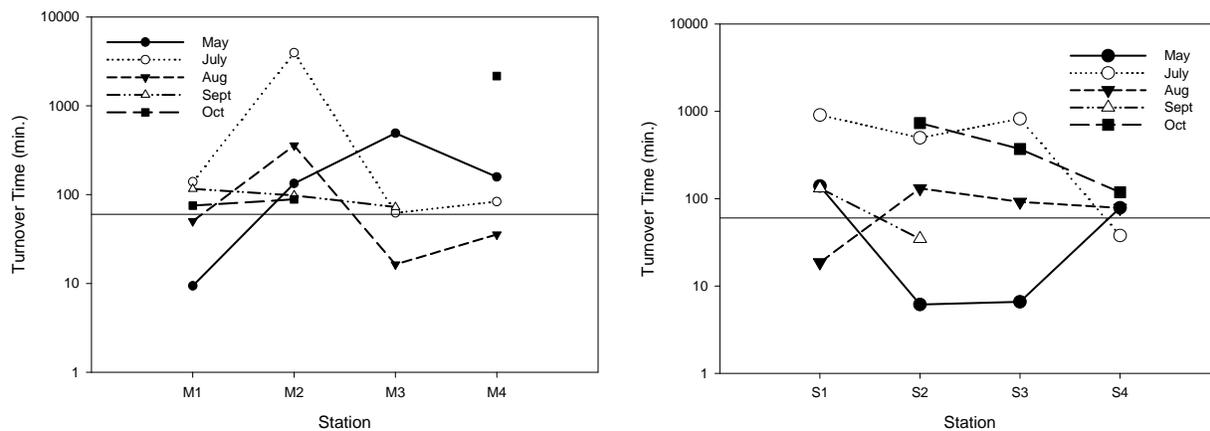


Figure 20. Phosphorus turnover times for samples collected in 2009. A value below 60 minutes is indicative of P limiting conditions (solid line). Missing data points occurred when the assay yielded results that could not be interpreted. This mostly occurs when radio-labeled P is not taken up significantly above background levels or does not increase significantly during the duration of the assay.

In 2010, however, turnover time assays produced few interpretable results. Presumably this was because phosphorus was so abundant that the turnover times were so slow that the short duration of these assays was not able to adequately detect significant turnover. The few samples that could be interpreted showed long turnover times and no indication of P limitation.

We estimated the rate of photosynthesis by algae and cyanobacteria directly at different light levels by measuring uptake of  $\text{H}^{14}\text{CO}_3^-$  to produce photosynthesis-irradiance curves. We examined the maximum photosynthetic rate ( $P_{\text{max}}^b$ ) (corrected for biomass by dividing by the chlorophyll *a* concentration) to determine at which light level the potential productivity could be the greatest. In 2009, maximum productivity was exceptionally low at most sites and times. Productivity in October 2009 was elevated in all the lakes sites in both the Maumee and Sandusky systems (Figure 21). The extremely high value at Maumee River site M1 in September 2009 appears to be heavily influenced by an extremely low chlorophyll *a* concentration measured at that time.

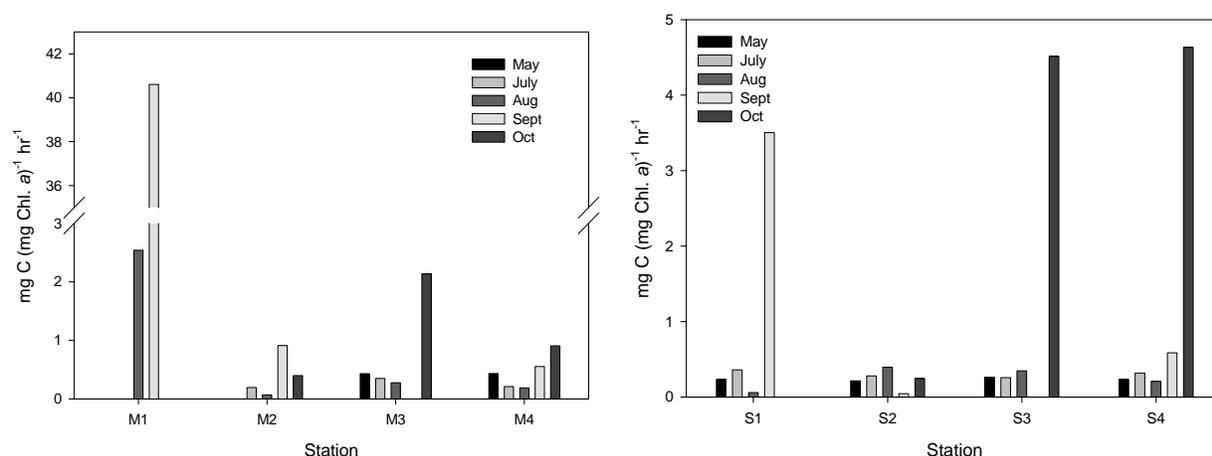


Figure 21. Biomass-corrected maximum photosynthetic rates ( $P_{\text{max}}^b$ ) in the Maumee system (left panel) and Sandusky system (right panel), 2009. Note the break in the y-axis in the Maumee figure. The anomalously high value at site M1 appears due to an extremely low chlorophyll *a* value on that date.

In 2010,  $P_{\text{max}}^b$  was much higher than in 2009 and more similar to earlier measurements of  $P_{\text{max}}^b$  performed by Conroy (2007) for the Sandusky system. At the small tributary site to the Maumee River system (M1) productivity was usually the lowest of all the sites, except in May 2010. Although the May M1 site was relatively low in chlorophyll *a*, it did show high rates of productivity before division by the chlorophyll *a* concentration as a correction for biomass. At site M2, productivity peaks in the late June/early July samples. In the Sandusky system in 2010 productivity was highest at both sites in the late April sample. Site S2 productivity then drops to a minimum in early May, but increases throughout most of the remainder of the season (Figure 22).

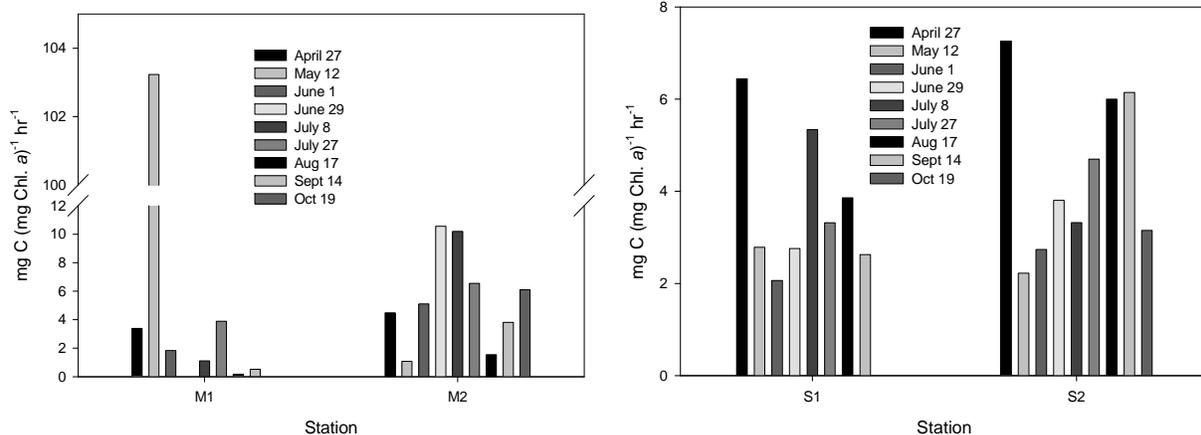


Figure 22. Biomass-corrected maximum photosynthetic rate ( $P_{max}^b$ ) in 2010.

Productivity of heterotrophic bacteria was measured by the rate of assimilation of  $^3\text{H}$ -leucine to assess its potential association with P limitation or phytoplankton productivity. No spatial or temporal patterns were obvious (Figures 23 and 24). However, like the phytoplankton productivity results above, bacterial productivity was generally lower in 2009 than in 2010.

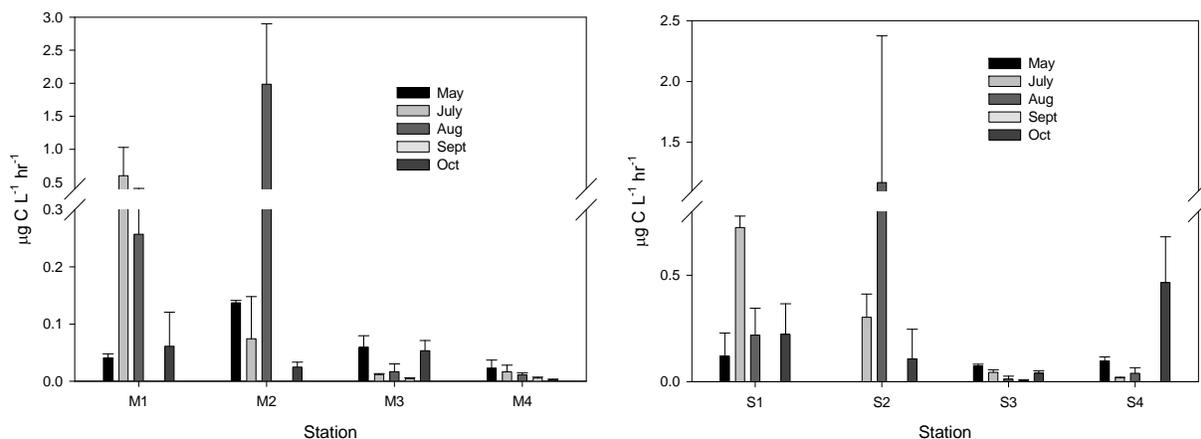


Figure 23. Bacterial productivity determined from  $^3\text{H}$ -leucine incorporation assays in 2009. Note break in scales. Error bars are  $\pm$  one standard deviation.

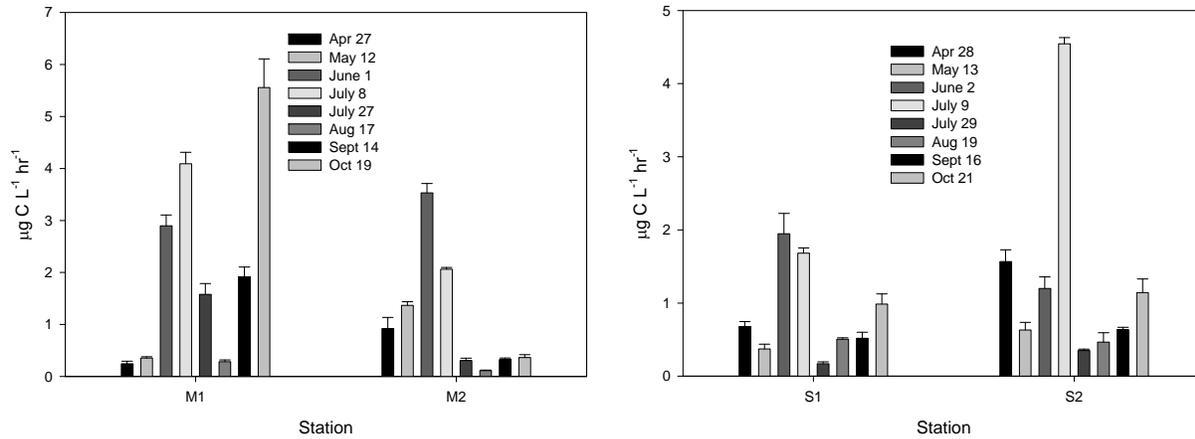


Figure 24. Bacterial productivity determined from <sup>3</sup>H-leucine incorporation assays in 2010. Error bars are ± one standard deviation.

**Objective 4. Determine water flow connectivity between sites in these coupled systems during various times of the year.**

The seasonal variation in phytoplankton, chlorophyll, phycocyanin, phosphorus, and seston concentrations in the 14 sites sampled between the two rivers in 2009 and 2010 reflects results for the specific times at which the samples were taken. Although sampling was designed to reflect both high and low discharge events, the potential impact of tributary contribution of algae and phosphorus to Lake Erie depends not only on the flow from the watershed to the lake, but of reverse flows that occur from the lake into Maumee Bay and Sandusky Bay. The USGS gauging stations at Waterville and Fremont (Table 1) were selected to be far enough upstream that flows are always unidirectional toward the lake. For Objective 4, we measured net flows at each of the four 2009 sampling sites. By multiplying the flow (L/sec) by concentrations (mg or  $\mu\text{g/L}$ ) we can generate fluxes flowing from each site in mass/sec.

Flow sampling for Objective 4 was conducted during June and August of 2009. We measured stream discharge in the headwaters of each system using a Flowtracker Acoustic Doppler Velocimeter (ADV), manufactured by Yellow Springs Instruments/Sontek. Downstream measurements at Maumee Bay were taken using a YSI/Sontek Acoustic Doppler Profiler (ADP), deployed via canoe. Bay and offshore measurements in both systems were taken using the ADP deployed via a small boat. We found that Maumee River locations had significantly higher flow rates than those in comparable locations in the Sandusky drainage system, both in June (Figure 25) and August 2009 (Figure 26). On the other hand, chlorophyll measurements were typically higher in the Sandusky system. Hence multiplying the flows by the concentrations yielded similar loads of chlorophyll to the lake (mg/sec), (i.e., on the same order) in June (Figure 27) in both systems.

Comparing this load with the concentration of chlorophyll in the lake allows estimation of chlorophyll turnover rates as a proportion of the western basin chlorophyll *a* content from Maumee Bay and Sandusky Bay which were 0.022 and 0.015/mo, respectively. At peak flow, these increase to 0.212/mo and 0.175/mo. These values indicate that during high flow events, the larger input of chlorophyll into the lakes can account for a significant portion of the western basin phytoplankton. However, during more typical flows, such as those we measured, the input of chlorophyll into the lake was small relative to the standing crop in the lake. Note that the calculated load at the lake sites M4 and S4 are likely underestimates because there is additional bay-lake exchange not accounted for in discharge calculations. These figures are therefore a lower bound. A 3-dimensional Lake Erie hydrodynamic model with nested embayment models will be useful in better quantifying these exchange rates.

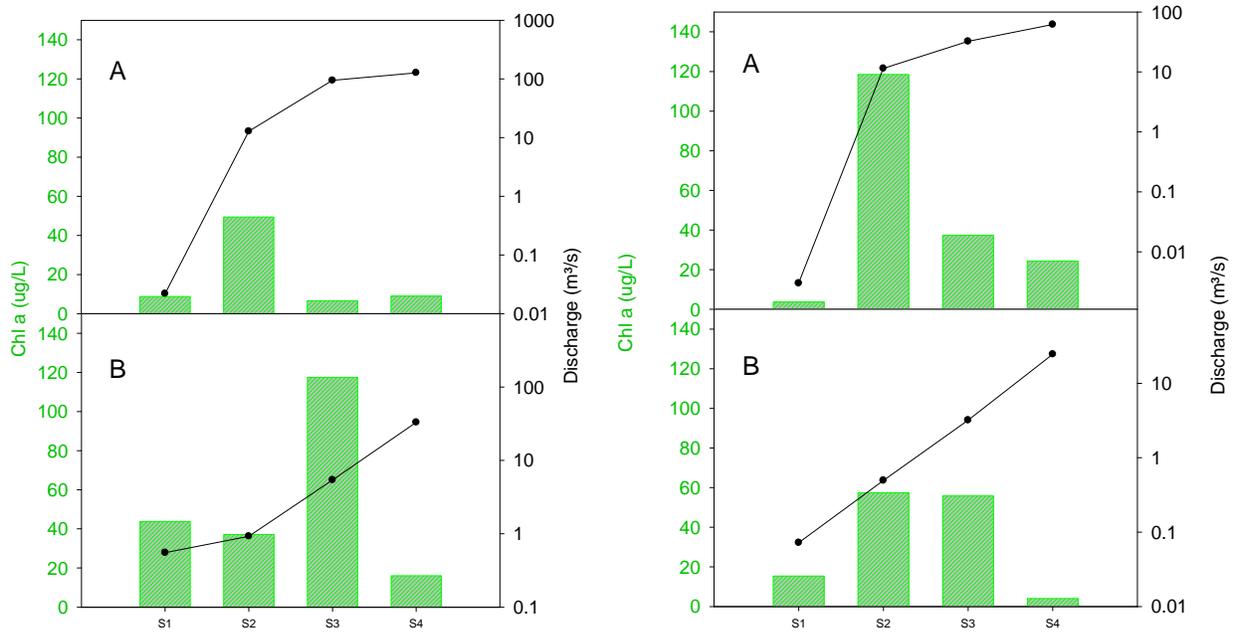


Figure 25. Measured chlorophyll *a* and discharge of water at the sample sites on the Maume River (A) and Sandusky River (B) in June 2009 (left) and August (right). Note the larger discharge scales for June and the Maume River figures for both months. See figures 1 and 2 for sampling locations.

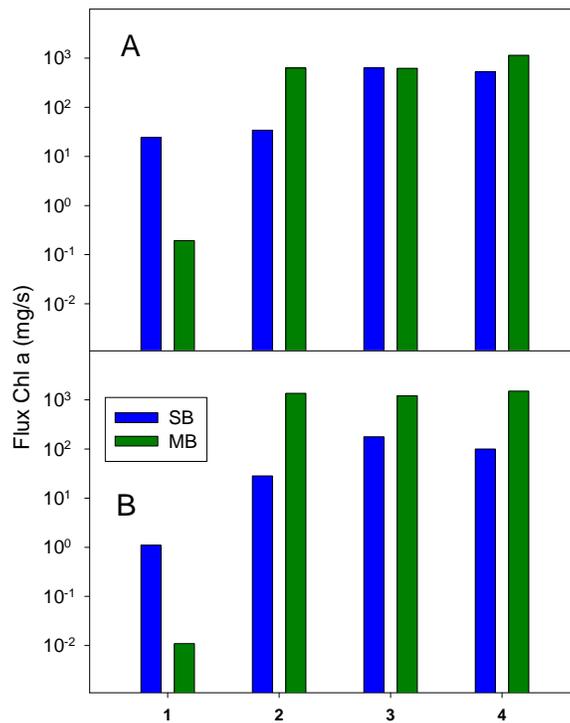


Figure 26. Loading of chlorophyll *a* ( $\text{mg/s}$ ) at the sample sites in each system in June (A) and August (B) 2009.

Similar calculations were performed for the loading of cyanobacteria and total phytoplankton into the lake during June and August (Figure 27). There were very large inputs of algae into the lake from both systems. This included large amounts of cyanobacterial biomass discharged into the lake during June 2009, a period when the *Microcystis* biomass in the lake was small (Figures 6 and 7). During August, loading of total phytoplankton into the lake by the Maumee River was lower, but a larger fraction of the biomass loaded was cyanobacteria. This resulted in higher loading values from the Maumee Bay into the lake, though both systems had very large fluxes of algae. The next step in using these data, both the flow measurements and the ADP measurements within the lake, and the combination of dense nutrient and phytoplankton data, is to couple these data as ground truthing measurements for calibrating a coupled bay-lake hydrodynamic model.

A hydrodynamic model will allow more accurate predictions of loading in high and low flow events (provided accurate field data are available to parameterize it such as those collected in this project), because the density of the model predictions is higher than is possible with field collected data. The data presented here provide a lower bound of the loading to the lake, because the actions of higher flow events could not be captured with episodic sampling (and the fact that small boat work during storms is dangerous). In addition, seiche action into and out of the embayments, which could be accurately calculated via hydrodynamic modeling, may serve to flush algae into the lake as a large mass episodically rather than in continual discharge. A 3-dimensional Lake Erie hydrodynamic model with nested embayment models will also be useful in quantifying this exchange rate.

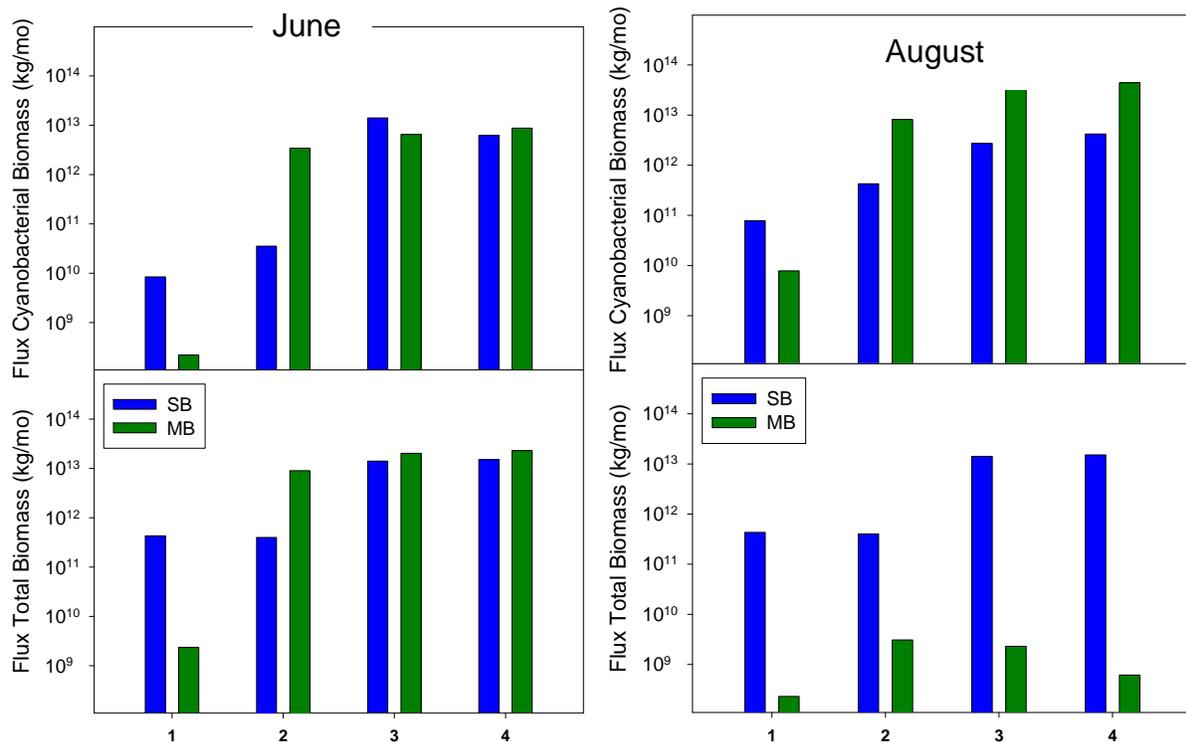


Figure 28. Loading of Total and Cyanobacterial Phytoplankton Biomass (kg/mo) at the sample sites in each system in June and August 2009. Note that the calculated load at site 4 (the open lake) is likely an underestimate as there is additional bay-lake exchange not accounted for in discharge calculations. Therefore these figures show lower bound estimates.

## Discussion

In this research project, we seek to evaluate the role of increased tributary dissolved reactive phosphorus delivery in initiating Harmful Algal Blooms in Lake Erie's two most agriculturally influenced watersheds. Outcomes from our project will directly assist lake and watershed managers who seek to reverse increasing phosphorus load and who seek to remediate harmful algal blooms, two of the 2008 Lake Erie Protection and Restoration Plan's Strategic Objectives.

Accordingly, determining the role of increased bioavailable phosphorus, how the phytoplankton and cyanobacterial (including *Microcystis*) communities use that phosphorus to initiate blooms, and the initial sites of those blooms have been the focus of this research project. The Maumee and Sandusky rivers typically contribute the largest sources of nonpoint dissolved phosphorus to the lake, and represent the lakes most agriculturally influenced watersheds, so we have performed intense sampling of these rivers, both temporally and spatially.

To achieve these goals we established four **Project Objectives**:

- (1) to determine temporal and spatial changes in phytoplankton community composition**, with particular emphasis on *Microcystis*, moving from small, low-order streams high in the watershed, into the main tributary, and out into the near- and offshore zones of Lake Erie in the coupled Maumee River-bay-western basin and Sandusky River-bay-subbasin systems;
- (2) to determine how phosphorus, nitrogen, and carbon (e.g., nutrient) concentrations, light attenuation, and temperature co-vary with alterations in phytoplankton community composition** and *Microcystis* abundance in these systems both spatially (i.e., up- to downstream and/or near- to offshore) and temporally (i.e., spring to summer and/or low flow to high flow);
- (3) to determine how *Microcystis*, the rest of the phytoplankton and heterotrophic bacterial communities uptake and use phosphorus** in these systems both spatially and temporally; and,
- (4) to determine water flow connectivity between sites in these coupled systems** during various times of the year.

In this discussion section of our project completion report, we summarize the results of our work on these objectives and discuss how these results contribute to our knowledge of how the phytoplankton and cyanobacterial (including *Microcystis*) communities use that phosphorus to initiate blooms, and the initial sites of those blooms.

Objective 1: Temporal and spatial changes in phytoplankton community composition, with particular emphasis on *Microcystis*. Microscopic analysis of phytoplankton and measurement of chlorophyll concentrations from 2009 stations showed that abundances of phytoplankton were high at all sites (> 10 mg/L wet weight) with the highest biomasses in the tributaries and rivers, especially in the early spring and midsummer, greatly exceeding concentrations in the lake stations. In 2010, sampling of seven tributary sites from each river found total phytoplankton biomass to be twice that found in 2009, associated with higher discharge rates and phosphate concentrations. Analyses showed that while the taxonomic diversity was high in both river systems, only a few taxa achieved dominance. Among these were the cyanobacteria *Microcystis* and *Planktothrix* and, on a few dates, the diatom *Melosira*, the dinoflagellate *Gymnodinium*, and several green algal taxa. While *Microcystis* blooms generally begin in Lake Erie in mid-summer (July or August, ending as days become shorter and temperatures decline in October), *Microcystis* was present in all samples from March through October in the tributaries and rivers studied here. *Microcystis* biomass typically exceeded 40% of total phytoplankton biomass at all

stations and dates and often approached 100%, particularly during high discharge events in May-July 2010.

Objective 2: Determine how phosphorus, nitrogen, and carbon (e.g., nutrient) concentrations, light attenuation, and temperature co-vary with alterations in phytoplankton community composition and *Microcystis* abundance. The total phosphorus and the soluble reactive phosphorus concentrations were high in 2009, especially in the river stations, but they were much higher in 2010 in both rivers. The highest concentrations occurred in May through July 2010, which were samples taken during very high flow events. The soluble reactive phosphorus (SRP), that P form most stimulatory to algal and cyanobacterial growth, typically made up 25% or more of the total phosphorus in 2009, and 40% or more in 2010. Phosphorus content in the tributaries was highest during high flow events, as were the total suspended solids (TSS), with values greater in 2010. Not only does the higher SRP in 2010 support the higher phytoplankton and *Microcystis* biomass found then, but the biomass would likely be higher yet had the high turbidity of the streams reflected in the TSS not decreased light penetration.

Objective 3: Determine how *Microcystis*, the rest of the phytoplankton, and heterotrophic bacterial communities uptake and use phosphorus. Monthly  $^{32}\text{PO}_4$  uptake experiments with samples of the phytoplankton and bacterial communities in 2009 showed that the communities in the small tributary to the Maumee River were P-limited every month except May, despite the high phosphorus content there. P-limitation was also observed in Maumee Bay in October 2009 and in Lake Erie (site M4) in July 2009. On the other hand, there was so much phosphate available in the Sandusky system stations in 2009 and in both the Maumee and Sandusky systems in 2010 that there was no evidence of P-limitation at any station on any date in these systems.

Objective 4: Determine water flow connectivity between sites in these coupled systems. Multiplying the flow (L/sec) by concentrations (mg or  $\mu\text{g/L}$ ) enables one to estimate the loading (mass/sec) to Lake Erie, although this has primarily been done in the past by use of flows and concentrations measured at USGS gage stations at Waterville (Maumee River) and Fremont (Sandusky River) (e.g., Richards et al. 2007). For Objective 4, we measured net flows at each of the four Maumee and Sandusky sampling sites in both June and August 2009. Maumee River locations had significantly higher flow rates than those in comparable locations in the Sandusky drainage system in both months, but chlorophyll measurements were typically higher in the Sandusky system, so the fluxes of chlorophyll at the Sandusky and Maumee river stations were similar. During typical flows, such as those we measured, the input of chlorophyll from Maumee and Sandusky bays into the lake was small relative to the standing crop in the lake, 0.022 and 0.015/mo, respectively. At peak flow, this increases to 0.212/mo and 0.175/mo. Note that the calculated load at the lake sites M4 and S4 are likely underestimates because there is additional bay-lake exchange not accounted for in discharge calculations. These figures are therefore a lower bound. The flux of Cyanobacteria at each of our sample stations was also similar between the two river systems ( $10^{12}$ – $10^{13}$  kg/month). Although we did not measure flows in 2010, discharge data at Waterville and Fremont suggest they were 6–7 times those in 2009, especially in June through August, so the higher phytoplankton, *Microcystis*, and phosphorus concentrations in 2010 clearly indicated these two rivers affected Lake Erie more in 2009.

This project benefits from simultaneous measurements of physical (light, temperature, water transparency, conductivity, stream flow and USGS river discharge rates, total suspended solids, volatile suspended solids), chemical (total phosphorus, soluble reactive phosphorus, total Kjeldahl nitrogen, ammonia, nitrate, nitrite, sulfate, silicate, and chloride) and biological

variables (phytoplankton taxonomic composition, abundance, and biomass, chlorophyll and phycocyanin concentrations, P-debt and P turnover time, and the response of photosynthetic uptake of carbon as a function of light intensity, and heterotrophic bacterial growth rates). However, presenting all these results would increase the length of this report, making it even more complicated than it already is. Of greater significance is that the real advantage of our approach provides for integration of these state variables, fluxes, and process measurements into an analysis of the spatial and temporal variation in the processes involved in production of Cyanobacteria in the Maumee and Sandusky river systems. Publications in preparation will present these integrations in detail.

Our project set out to determine the source of *Microcystis* blooms entering Lake Erie, where and when they were initiated, and the role of phosphorus in the process. We found that *Microcystis* blooms began high in the watershed in even the smallest tributaries (e.g., a tributary to Lost Creek near Hicksville, OH, 87 miles from the lake in the Maumee system and a tributary to Silver Creek near Melmore, OH, 55 miles from the lake in the Sandusky system. *Microcystis* was found at all sites on the first dates sampled (23 April 2009 and 11 March 2010). It first bloomed (> 1.0 mg/L wet weight) at one or more sites in the Maumee system on 26 May 2009 and 11 March 2010, and on 23 April 2009 and 17 March 2010 in the Sandusky system. Additional blooms occurred throughout both seasons, particularly in summer 2010.

Soluble reactive phosphorus (SRP) was high in both systems, 6.5 and 35.8  $\mu\text{g P/L}$  at M1 and M2, respectively on 28 April 2009, and 50.1 and 45.8  $\mu\text{g P/L}$  at S1 and S2 on 23 April 2009. For 2010, SRP M1 ranged from 7.4  $\mu\text{g P/L}$  on 22 April to 81.5  $\mu\text{g P/L}$  on 12 May, and remained high at all sites through the year, with a maximum of 173.7 on 12 May at station M2 followed by 86.9  $\mu\text{g P/L}$  on 29 June at the same site. These high SRP values were responsible for the recurrent *Microcystis* blooms in the rivers and streams, providing enough phosphorus that P was seldom limiting to the phytoplankton. The tributary to Lost Creek was limited by P in August, September, and October, 2009, as was Maumee Bay in October 2009 (Figure 18). All Sandusky system sites had excess P available for their growth throughout 2009 (Figure 18), and all sites in both rivers had excess P available throughout 2010 (Figure 19).

The algal biomass produced in the Maumee and Sandusky river systems is discharged to Lake Erie (e.g., in 2009, Figure 26), including huge amount of *Microcystis* ( $\sim 10^{13}$  kg wet weight/mo in both June and August 2009, Figure 27), equivalent to the capacity of 110 million railroad steel coal cars (at 100 tons each) per month. Given the higher phytoplankton abundance and greater discharge rates in 2010, even greater discharges of phytoplankton occurred in that year. While other research seeks to determine whether this *Microcystis* successfully grows in Lake Erie after discharge, the large amount of organic matter represented by the phytoplankton loading to the lake each month surely has a large impact on the ecology and biogeochemistry of the lake.

This project addresses priorities identified by the Lake Erie Phosphorus Task Force and the actions recommended by the Ohio Lake Erie Commission's (2008) Lake Erie Protection and Restoration Plan, namely to "Support research on causes and potential solutions to Harmful Algal Blooms including *Microcystis* and *Lyngbya wollei*." Our finding of the tight relationships between SRP and *Microcystis* blooms early in the spring at the uppermost regions of the watershed underscores the importance of reducing nonpoint sources of phosphorus in the Lake Erie basin.

## Acknowledgements

Many people have helped us with the extensive field and laboratory work associated with this project. We appreciate the careful chemical analyses performed by the staff at the Heidelberg University National Center for Water Quality Research. At OSU, postgraduate research staff performing field sample collection, laboratory analyses, and data presentation included Theodore Gover, Joshua Graham, Kyla Hershey, Amanda Martyn, Maria Takahashi, Ruth Briland, and Cathleen Doyle. At Kent State University, Moumita Moitra worked on her doctoral research program on this project, assisted by fellow grad students Curtis Clevinger and Heather Kirkpatrick and undergraduate student Joshua Smith. Ashley Bantelman, a student from Niagara University worked on this project during the summer of 2009 as part of her undergraduate thesis project.

This project was supported by the Ohio Lake Erie Protection Fund, Project LEPF-TG-09-01, administered by the Ohio Lake Erie Commission ([www.lakeerie.ohio.gov](http://www.lakeerie.ohio.gov)). The LEPF is supported by the voluntary contributions of Ohioans who purchase the *Erie...Our Great Lake* license plate featuring the Marblehead lighthouse.

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## Benefits from This Project:

### Research Results

This research program has expanded our knowledge about the temporal and spatial distributions of: (1) Cyanobacteria and other phytoplankton throughout the coupled systems of the Sandusky and Maumee rivers, their watersheds, and Lake Erie; (2) phosphorus use throughout the coupled systems; (3) hydrodynamic connections and water flow between sites during periods of low and high discharge; (4) nutrient concentration dynamics as a function of phytoplankton community changes and phosphorus use by that community; and, most importantly, (5) a synthesis of the previous issues that demonstrates how phytoplankters, especially *Microcystis*, use the bioavailable phosphorus pool throughout these coupled systems and where the “trigger” point for bloom initiation is located in space and time, allowing managers to understand how future decreases in bioavailable phosphorus may lead to reductions in harmful algal blooms in tributaries and near- and offshore portions of Lake Erie and other systems.

We have determined a number of static (i.e., nutrient concentration, light attenuation, temperature, and phytoplankton community structure measurements) and process-based (i.e., nutrient flux, phosphorus uptake due to phytoplankton and heterotrophic bacteria, primary productivity and bacterial productivity) measurements from four tributary and 4 lake sites in 2009 and 14 tributary sites in 2010, an evaluation of the use of phosphorus by *Microcystis* and the remainder of the phytoplankton community, an analysis of the connection between locations in the coupled watershed-river-nearshore-offshore systems, and a determination of how decreasing bioavailable phosphorus from the watershed can be expected to decrease the abundance of *Microcystis* and other harmful algal species (e.g., *Planktothrix*, *Lyngbya*, *Cylindrospermopsis*), while improving the health of the phytoplankton community.

### Other Agency or Institution Involvement

Our project involved collaboration among five institutions: The Ohio State University (OSU), Defiance College (DC), Kent State University (KSU), Niagara University (NU), and Heidelberg University (HU). At OSU, Dr. David Culver served as overall Project Leader, coordinating all aspects of the project and Dr. Joseph Conroy served as Co-Project Leader and was responsible for the oversight of day-to-day operations including field sampling, laboratory sample processing, project reporting, and manuscript preparation. Dr. Douglas Kane (DC) served as Co-Investigator and led extensive field sampling. He was our project’s liaison to activities conducted as part of F.T. Stone Laboratory’s Research Experience for Undergraduates (REU) Program, which involves up to 15 undergraduate students annually in novel research on projects in conjunction with professors at Stone Laboratory. Both Drs. Kane and Conroy have led numerous students since the program’s inception in 2005. At KSU, Dr. Darren Bade served as Co-Investigator and led laboratory determinations of phosphorus uptake and productivity rates by the phytoplankton (including *Microcystis*) and heterotrophic bacterial communities. Dr. William Edwards at NU served as Co-Investigator and measured water transport rates from high in the watersheds out to the offshore regions for estimate of loads to Lake Erie. Our project also used

contractual services from Heidelberg University's National Center for Water Quality Research to determine soluble and particulate nutrient concentrations.

We are also collaborating directly with other researchers in a diversity of projects involving Lake Erie and its tributaries. Our project builds on a long-term project (from 1995–present) sponsored by the Ohio Division of Wildlife (ODW), in which Dr. Culver's laboratory has analyzed zooplankton, phytoplankton and chlorophyll samples collected biweekly by the Ohio Division of Wildlife from a series of 16 to 40 Lake Erie western and central basin stations. Drs. Conroy, Bade, and Kane from our program serve as Co-PIs studying near- and offshore nutrient fluxes, and western basin algal blooms for two the U. S. Environmental Protection Agency (USEPA), Great Lakes National Program Office-sponsored Lake Erie projects: Lake Erie Algal Sources and Transport (LEAST) and the Nearshore-Offshore Lake Erie Nutrient Study (NOLENS). Many of the sample analyses were performed in Dr. Culver's laboratory. Dr. Kane and his students are participating in the Great Lakes Innovative Stewardship through Education Network (GLISTEN) program, sponsored by the Learn and Serve America Higher Education program of the U.S. Corporation for National and Community Service. It involves collaboration among undergraduate students and faculty at 2- and 4-year universities, all working on environmental problems in the Great Lakes. Dr. Kane directed sampling of a series of five Maumee River sites, three of which correspond to our own sites. Additional sampling of Lake Erie and its tributaries by the Ohio EPA and the Ohio Division of Wildlife is being sponsored by the Great Lakes Restoration Initiative (USEPA), and the Culver lab will be analyzing hundreds of phytoplankton and zooplankton samples for those studies during 2012-2014. Eventually, all of the data will be incorporated into the ODW's OPHIS data management program, and a doctoral student, Ms. Ruth Briland, will perform a retrospective analysis of the causes and consequences of Lake Erie ecosystem change. The overall objective is to utilize extant datasets and models to quantify changes in the structure and dynamics of Lake Erie's food webs and fish communities and to better understand the mechanisms underlying these changes.

### **Students Supported by the Project**

Several undergraduate and graduate students worked actively on this project, including one whose doctoral dissertation projects were directly supported by the project, while others assisted with various portions of the laboratory and data analyses (Appendix Table 1).

### **Information Dissemination as Part of This Project**

Although further data analysis and preparation of publications from the project is ongoing, we have published several peer-reviewed publications, abstracts, and reports to date (Appendix Tables 2 and 3) and delivered numerous presentations from this project at scientific conferences (Appendix Table 4).

We are also generating materials for undergraduate and graduate level courses at institutions involved on this project (similar to those generated for Projects LEPF 04–16 and SG233–04, see these projects' completion reports. Finally, we have contributed all abiotic and biotic data generated in this project to the ongoing Ohio Department of Natural Resources, Division of Wildlife-sponsored project ("Lower Trophic Level Monitoring on Lake Erie", Dr. David A.

Culver, PI) as part of the Federal Aid in Sport Fish Restoration Program (F-69-P, Fish Management in Ohio) of the United States Fish and Wildlife Service.

**Appendix Table 1. Students whose research projects were supported by this project, either directly or indirectly.**

**Doctoral Students:**

Supported by the LEPF grant: Moumita Moitra (Ph.D. candidate, Kent State University, expected graduation May 2012)

Collaborator: Curtis Clevinger (Ph.D. candidate, Kent State University)

**Master's Students:**

Collaborator: Heather Kirkpatrick, M.S., Kent State University

Collaborator: Ruth Briland, M.S., Ohio State University

**Undergraduate Research Projects (Honors students):**

Ashley Bantelman, an undergraduate student from Niagara University worked on ADP/ADV measurements of flow for this project during the summer of 2009. She incorporated portions of this work into her undergraduate research thesis “Burrow oxygen dynamics of freshwater insect larvae.” She is currently a Predoctoral Student in environmental science/limnology at the Diplomatic Academy of Vienna, Austria.

Shannon Percival. Niagara University Honors thesis, 2006. “Phytoplankton dynamics in Sandusky Bay: influence on Lake Erie harmful algal blooms.” OSU Stone Laboratory REU program participant. Currently Commissioned, United States Navy.

Staci Blecha. Niagara University Departmental Honors Undergraduate Thesis, 2006. “Nitrogen and Phosphorus excretion by the invasive zebra mussel: role in changing phytoplankton dynamics.” OSU Stone Laboratory REU program participant. Received MS from Old Dominion University. Currently Instructor, Tidewater Community College, Virginia.

Joshua Smith, Kent State University.

**Appendix Table 2. Peer-reviewed papers and reports, published or in press that directly resulted from this project.** Graduate or undergraduate authors are denoted with an asterisk.

### Peer-Reviewed Articles and Reports

- Bridgeman, T.B., J.D. Chaffin\*, D.D. Kane, J.D. Conroy, S. Panek\*, and P. Armenio. 2011. From river to lake: Phosphorus partitioning and algal community compositional changes in western Lake Erie. *Journal of Great Lakes Research*. doi:10.1016/j.jglr.2011.09.010.
- Kutovaya, O. A., R. M. L. McKay, B. Beall, S. W. Wilhelm, D. D. Kane, J. D. Chaffin\*, T. B. Bridgeman, and G. S. Bullerjahn. 2011. Evidence against fluvial seeding of recurrent toxic blooms of *Microcystis* spp. in Lake Erie's western basin. *Harmful Algae* Accepted, in revision.
- Reutter, J.M., J. Ciborowski, J. DePinto, D. Bade, D. Baker, T.B. Bridgeman, D.A. Culver, S. Davis, E. Dayton, D. Kane, R.W. Mullen, C.M. Pennuto. 2011. Lake Erie Nutrient Loading and Harmful Algal Blooms: Research Findings and Management Implications. Final Report of the Lake Erie Millennium Network Synthesis Team. <http://go.osu.edu/ts-060>
- Conroy, J. D., L. Boegman, H. Zhang, W. J. Edwards, and D. A. Culver. 2011. “Dead Zone” dynamics in Lake Erie: the importance of weather and sampling intensity for calculated hypolimnetic oxygen depletion rates. *Aquatic Sciences* 73(2): 289-304, DOI: 10.1007/s00027-010-0176-1
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- \*Moitra, M., D.L. Bade, S. Ghosh, J.D. Conroy, R.T. Heath and L.G. Leff. In Prep. Changes in structure and function of bacterial assemblages in Lake Erie during *Microcystis* blooms. To be submitted to the *Journal of Great Lakes Research*.

**Appendix Table 3. Published abstracts of papers reporting research on this project that were presented at scientific conferences.**

\*Kirkpatrick, H. R., C. C. Clevinger\*, M. Moitra\*, D. L. Bade, J. D. Conroy, D. A. Culver, W. J. Edwards D.D. Kane. 2010. Evaluating phosphorus limitation from the Maumee and Sandusky rivers into Lake Erie. *Ohio Journal of Science* 110(1): A-7. MEETING ABSTRACT April 2010

The widely accepted concept of phosphorus (P) limitation in Lake Erie has been a driving force behind management efforts to mitigate cultural eutrophication for over 20 years. The implementation of the Great Lakes Water Quality Agreement led to reductions of 50% or more in P loading and improvements in ecosystem health. Recent increases in the frequency of harmful algal blooms have led us to reexamine the indicators of P limitation. We measured P use in the Maumee and Sandusky systems (two sites in each river and two sites offshore of each river) at monthly intervals June through September 2009. According to P uptake rates, P limitation was more frequent in the Sandusky River, which was limited 50% of the time, than in the Maumee River, which was limited 33% of the time. Sandusky system lake sites were P limited 72% of the time while Maumee system lake sites were P limited 50% of the time. Algal P-debt indicators show that limitation was higher in the Maumee River, which was limited 66% of the time, than the Sandusky River, which was limited 33% of the time. Both river system lake sites were limited 75% of the time. Given the extent to which P is not limiting, nutrient management strategies may need to account for addition P control or management of other nutrients.

Conroy, J. D., D. L. Bade, W. J. Edwards, D. D. Kane, T. R. Gover, K. M. Hershey, and D. A. Culver. 2010. Determining *Microcystis* bloom trigger points in the Maumee and Sandusky ecosystems. *Ohio Journal of Science* 110(1): A-8. MEETING ABSTRACT April 2010

Remediating harmful algal blooms, especially *Microcystis* spp., in Lake Erie is problematic as scientists do not even know whether *Microcystis* blooms initiate in the lake itself, or if they might be “triggered” well upstream and be transported to the lake. To determine the bloom trigger point in both time and space and the co-varying environmental factors, four sites (stream, river, bay, and lake) were sampled in both the Maumee and Sandusky ecosystems during spring, summer, and fall 2009. Vertical profiles of physical factors were sampled with a multiparameter instrument and whole-water grabs were collected from twice the Secchi transparency depth (SD) to quantify nutrient concentrations and phytoplankton community abundance (both wet-weight biomass and chlorophyll *a* concentration) and composition. Although only spring (May–June) data presently are available, chlorophyll concentrations (chl; mg m<sup>-3</sup>) were high in low-order streams (> 44 mg chl m<sup>-3</sup>) in both the Maumee and Sandusky systems, despite low light availability (SD < 0.5 m). Chlorophyll was strongly related to nutrient (total phosphorus, TP and total Kjeldahl nitrogen, TKN) concentrations (mg m<sup>-3</sup>; chl = -24.63 + 0.68 x TP, F<sub>1,14</sub> = 22.2, p < 0.001, r = 0.78; chl = -25.25 + 0.06 x TKN, F<sub>1,14</sub> = 80.7, p < 0.001, r = 0.92), indicating that nutrient concentrations greatly affect phytoplankton abundance. Importantly, *Microcystis* was found in small streams in mid-spring, indicating that bloom trigger points may be well upstream and may begin much earlier than they are observed in the lake.

Kane, D. D., J. D. Conroy, J. D. Chaffin\*, and T. B. Bridgeman. 2010. Lake Erie source tracking of harmful algal blooms. *Ohio Journal of Science* 110(1): A-8. MEETING ABSTRACT April 2010.

Harmful Algal Blooms (HABs) composed of the cyanobacterium *Microcystis* have consistently occurred in the western basin of Lake Erie during the last decade. To determine the source of nutrients and algae that initiates these blooms in the Maumee River-Maumee Bay-Western Lake Erie coupled ecosystems we sampled five sites in the Maumee River (MR), two in Maumee Bay (MB), and four in Western Lake Erie (WLE) during summer of 2009. During three sampling periods (early June, early August, early September), we quantified numerous water quality parameters including Secchi depth (SD; m) and soluble reactive phosphorus (SRP; mg m<sup>-3</sup>) and chlorophyll *a* (chl *a*; mg m<sup>-3</sup>) concentrations. We found that mean SD was typically shallowest in MR (June = 0.26, August = 0.39, September = 0.49), deeper in MB (June = 0.80, August = 0.57, September = 0.45), and deepest in WLE (June = 1.68, August = 1.21, September = 0.84), whereas mean SRP was greatest in MR (June = 96, August = 21), less in MB (June = 20, August = 5), and least in WLE (June = 2, August = 3). Finally, mean chl *a* varied temporally with MR having greatest concentrations in August (MR = 47.5, MB = 38.9, and WLE = 18.2) and September (MR = 26.9, MB = 8.3, and WLE = 13.4) but MB having greatest concentrations in June (MR = 6.9, MB = 26.5, and WLE = 7.0). These results suggest that high MR nutrient levels support algal biomass not only in the river and MB but may also provide a source of algae to the western basin of Lake Erie. Future phytoplankton community composition analysis of samples taken at the same time of SD, SRP, and chl *a* samples described here will elucidate the relative biomass of *Microcystis* in MR, MB, and WLE samples.

**Appendix Table 4. Scientific Conference presentations related to this project.**

(presenting author bolded, student advisee authors denoted with an asterisk, and invited talks indicated)

**2011**

**Culver, D. A.**, J. D. Conroy, D. L. Bade, D. D. Kane, and W. J. Edwards. 2011. *Connections between P load and Microcystis bloom trigger points in the Maumee and Sandusky rivers.* Maumee River Researchers Meeting, University of Toledo, Lake Erie Center, Oregon, OH. 1 December.

**Kane, D.D.** 2011. *Lake Erie re-eutrophication: multiple tributary contributions.* Paper presented at the Ohio State University, Columbus, OH. 4 November

**Bade, D.L.** Should we care about nitrogen in Lake Erie? Stone Laboratory Summer Seminar Series. Put-in-Bay, OH. 10 Aug

**Bade D.L.**, J.D. Conroy, C.M. Pennuto, D.A. Culver, D.D. Kane, L.E. Burlakova, A.Y. Karatayev, 2011. A. Perez-Fuentetaja, J.W. Kramer, G. Matisoff, and W.J. Edwards. *Biological phosphorus uptake in Lake Erie's tributaries and offshore sites.* 54<sup>th</sup> Annual Conference on Great Lakes Research. Duluth, MN. June.

**Kane, D.D.**, J.D. Conroy, D.L. Bade, W.J. Edwards, and D.A. Culver. 2011. *Re-eutrophication of Lake Erie: multiple contributions by two tributaries.* International Association for Great Lakes Research, 54<sup>th</sup> Annual Meeting. Duluth, Minnesota, 1 June.

**Bade, D.L.** *Phosphorus limitation in Lake Erie.* 2<sup>nd</sup> Millennium Meeting to Summarize Phosphorus Research. Lake Erie Center, U. of Toledo. Toledo, OH. 28 March 2011

**Kane, D.D.**, J.D. Conroy, D.A. Culver, T.B. Bridgeman, J.D. Chaffin\*, W.J. Edwards, R.M. McKay, R.P. Richards, and D.B. Baker. 2011. *Re-eutrophication of Lake Erie: insights from the Maumee and Sandusky systems.* American Society of Limnology and Oceanography Aquatic Sciences Meeting. San Juan, Puerto Rico, 18 February.

**Bade, D.L.** *Should we care about nitrogen in Lake Erie?* The Ohio State University. Columbus, OH. 10 Feb 2011

**Culver, D.A.**, J.D. Conroy, D.L. Bade, W. J. Edwards, D. D. Kane, M. Takahashi, and J. R. Graham. 2011. *Connecting P load, transport, and biological use in Lake Erie: How does Microcystis use P and where is the bloom trigger point?* Paper presented at the Lake Erie Phosphorus Research Forum, University of Toledo, Lake Erie Center, Oregon, OH.

**Kane, D.D.** 2011. *Harmful Algal Blooms: from watershed to walleye, why fishermen should care.* Ohio Charter Captains Conference, Huron, Ohio.

## 2010

- \*Moitra, M.**, D.L. Bade, S. Ghosh, R.T. Heath, and L.G. Leff. Composition and nutrient dynamics of bacterial communities associated with *Microcystis* blooms in Lake Erie. 95<sup>th</sup> Annual Conference, Ecological Society of America. Pittsburgh, PA. Aug. 2010.
- Kane, D.D.**, J.D. Conroy, D.L. Bade, W.J. Edwards, and D.A. Culver. *The problem starts earlier and farther upstream than expected: Microcystis upstream in Lake Erie tributaries early in the year.* International Association for Great Lakes Research, Annual Meeting. Toronto, Ontario, Canada, 21 May. Poster.
- Kane, D.D.** *Lake Erie re-eutrophication: evidence from the Maumee and Sandusky systems.* Paper presented at the Franz Theodore Stone Laboratory, Put-In-Bay, Ohio. June
- Kane, D.D.**, Conroy, J.D., Bade, D.L., Edwards, W.J., Culver, D.A., \*Chaffin, J.D., Wambo, K., Gruden, C.L., and Bridgeman, T.B. 2010. *Monitoring mechanisms and macronutrients: Microcystis in the Maumee and Sandusky systems.* Paper presented at Sixth Biennial Lake Erie Millennium Network Conference, Windsor, Ontario.
- \*Kirkpatrick, H.R.**, C. C. Clevinger\*, M. Moitra\*, D. L. Bade, J. D. Conroy, D. A. Culver, Edwards, W.J., and Kane, D.D. 2010. *Evaluating phosphorus limitation from the Maumee and Sandusky Rivers into Lake Erie.* Ohio Academy of Sciences Meeting, .April 2010.
- Kane, D.D.**, J.D. Conroy, J.D. Chaffin\*, K. Wambo, C.L. Gruden, and T.B. Bridgeman. 2010. *The LEAST we can do is study HABs: tracking of harmful algal blooms in the Maumee River.* International Association for Great Lakes Research, Annual Meeting. Toronto, Ontario, Canada, 21 May.
- Bridgeman, T.B.**, C.L. Gruden, J.D. Conroy, D.D. Kane, G.W. Winston, J.D. Chaffin\*, S.E. Panek, and C.M. Mayer. 2010. *Lake Erie Algal Source Tracking (LEAST): contributions of the Maumee River and lake sediments to Microcystis blooms.* International Association for Great Lakes Research, Annual Meeting. Toronto, Ontario, Canada, 21 May.
- Kane, D.D.**, J.D. Conroy, J.D. Chaffin\*, and T.B. Bridgeman. 2010. *Lake Erie source tracking of harmful algal blooms.* Ohio Academy of Science, Annual Meeting. Ada, Ohio, 10 April.
- Conroy, J.D.**, D.L. Bade, W.J. Edwards, D.D. Kane, T.R. Gover, K.M. Hershey, and D.A. Culver. 2010. *Determining Microcystis bloom trigger points in the Maumee and Sandusky ecosystems.* Ohio Academy of Science, Annual Meeting. Ada, Ohio, 10 April.
- Culver, D.A.**, J.D. Conroy, D.L. Bade, D.D. Kane, W.J. Edwards, T. Gover, K. Hershey, and A. Martyn. 2010. *Connecting phosphorus load, transport, and biological use in Lake Erie: how does Microcystis use phosphorus and where is the bloom trigger point?* Progress meeting of the United States EPA and Lake Erie Protection Fund grants on harmful algal blooms in Lake Erie. Toledo, Ohio, 11 February.
- Takahashi, M.**, J. R. Graham, J. D. Conroy, D. L. Bade, W. J. Edwards, D. D. Kane and D. A. Culver. 2010. *Determining the connection between phosphorus load and Microcystis bloom*

*trigger points in the Maumee and Sandusky rivers.* Ohio Division of Wildlife Research Review Conference, January 2010.

## **2009**

**Conroy, J.D.** 2009. *Are we there yet? Over 30 years of rehabilitation but only continued impairment in Lake Erie.* Department of Biological Sciences Seminar Series, Bowling Green State University. Bowling Green, Ohio 2 December 2009.

**Conroy, J.D.** 2009. *Watershed-lake connections in Lake Erie: linking land use to impairments.* Elder College Program, Terra State Community College. Fremont, Ohio, 1 December.  
**Invited.**

**Edwards, W.J.,** J.D. Conroy, and M.A. Thomas. 2009. *Assessment of metabolism in a coupled nearshore-offshore ecosystem in Lake Erie.* International Association for Great Lakes Research, Annual Meeting. Toledo, Ohio, 19 May.

**Kane, D.D.,** J.D. Conroy, R.P. Richards, D.B. Baker, and D.A. Culver. 2009. *Western Lake Erie nuisance algae: correlations between nutrient load and total phytoplankton and cyanobacterial biomass.* International Association for Great Lakes Research, Annual Meeting. Toledo, Ohio, 21 May.