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Scientific Investigations Report 2017–5122

U.S. Department of the Interior
U.S. Geological Survey

Cover photographs. Cyanobacterial bloom on Lake Richie, Isle Royale National Park. Upper left (2010) by Rick Damstra, National Park Service. Upper right and lower (2007) by Mark Edlund, St. Croix Watershed Research Station.

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U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

ELISA	enzyme-linked immunosorbent assay
ISRO	Isle Royale National Park
LC/MS/MS	liquid chromatography/tandem mass spectrometry
MRL	minimum reporting level
NPS	National Park Service
ORGL	Organic Geochemistry Research Laboratory
PIRO	Pictured Rocks National Lakeshore
SLBE	Sleeping Bear Dunes National Lakeshore
TN	total nitrogen
TN:TP	total nitrogen to total phosphorus ratio
TP	total phosphorus
EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WHO	World Health Organization

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Detection of Microcystin and Other Cyanotoxins in Lakes at Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes Lakeshore, Northern Michigan, 2012–13

By Lori M. Fuller, Angela K. Brennan, Lisa R. Fogarty, Keith A. Loftin, Heather E. Johnson, David D. VanderMeulen[1], and Brenda Moraska Lafrancois[1]

Abstract

Although cyanotoxins released during algal blooms have become an increasing concern in surface waters across the United States, the presence of cyanotoxins in northern Michigan lakes had not been evaluated in detail. The U.S. Geological Survey and National Park Service (NPS) led a 2-year study (2012 and 2013) to determine the presence of microcystin and other algal toxins in several inland lakes at Isle Royale National Park (hereafter referred to as ISRO, Pictured Rocks National Lakeshore (hereafter referred to as PIRO), and Sleeping Bear Dunes National Lakeshore (hereafter referred to as SLBE). Samples also were collected at four sites in Lake Michigan within the SLBE. The two analytical techniques used in the study were enzyme-linked immunosorbent assays (ELISA) for microcystin, cylindrospermopsin, and saxitoxin; and liquid chromatography/tandem mass spectrometry (LC/MS/MS) for a larger suite of algal toxins. Neither cylindrospermopsin nor saxitoxin were detected in the 211 samples. Microcystin was detected in 31 percent of samples (65 of 211 samples) analyzed by the ELISA method, but no sample results exceeded the World Health Organization recreational health advisory standard for microcystin (10 micrograms per liter [µg/L]). However, about 10 percent of the samples (21 of 211 samples) that were collected from PIRO and SLBE and were analyzed by ELISA for microcystin had concentrations greater than the U.S. Environmental Protection Agency (EPA) drinking water 10-day health advisory of 0.3 µg/L for children preschool age and younger (less than 6-years old). One sample collected in 2012 from SLBE exceeded the EPA drinking water 10-day health advisory of 1.6 µg/L for school-age children through adults (6-years old and older). In 2012, the highest concentration of 2.7 µg/L was detected in Florence Lake within SLBE. Many visitors enjoy recreation in or on the water and camp in the backcountry at these national parks where the most common source of drinking water is filtered surface water.

Approximately 18 percent of the samples (39 of 211 samples) were analyzed by LC/MS/MS to confirm the ELISA results and to evaluate the samples for a larger suite of algal toxins. In general, the microcystin results between the ELISA and LC/MS/MS methods were similar; although, the ELISA results tended to be slightly higher than the summation of LC/MS/MS microcystin congeners. The slightly higher ELISA results might be because the ELISA microcystin method is reactive with the ADDA functional group common to all microcystins, and because not all microcystin congeners are included in the LC/MS/MS method. The LC/MS/MS method indicated that the congener microcystin-LR was the most frequently detected, followed by microcystin-WR and microcystin-YR.

Sixteen of the lakes included in this study also were monitored by the NPS for nutrients. Total phosphorus (TP) concentrations were, on average, highest at the ISRO lakes, whereas total nitrogen (TN) concentrations were highest at SLBE. The average annual TN:TP ratios for the 16 lakes within the national park and national lakeshores ranged from ratios of 20 to 89. Overall, results indicated a slight increase in percentage of microcystin detections with an increase in the TN:TP ratio (R-squared 0.269 and 0.340, respectively [2012 and 2013 combined dataset] derived from linear regression).

This study also indicated that even in the absence of visible algal blooms, microcystin may be present. Most microcystin concentrations did not exceed the EPA's 10-day health advisory drinking-water benchmark. In general, these results provide a useful baseline with which to evaluate potential future changes in algal toxin concentrations.

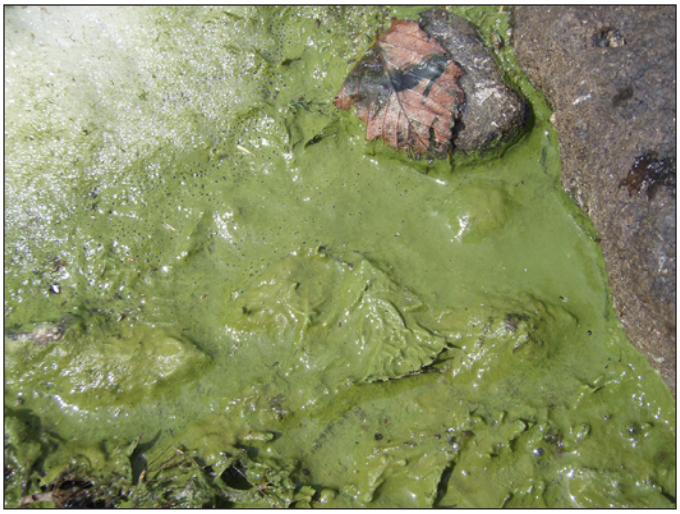
[1]National Park Service.

Introduction

The presence of cyanotoxins in surface water is an emerging lacustrine water-quality issue, not only in northern Michigan but also throughout the United States (fig. 1) (Loftin and others, 2017). Cyanotoxins are toxins produced by cyanobacteria (also commonly referred to as blue-green algae), which are naturally occurring organisms. At high concentrations, cyanotoxins can cause illness or even death in humans, domestic animals, and wildlife, as well as aquatic plants and animals. Combined, the Isle Royale National Park (hereafter referred to as ISRO), Pictured Rocks National Lakeshore (hereafter referred to as PIRO), and Sleeping Bear Dunes National Lakeshore (hereafter referred to as SLBE) (fig. 1) serve more than 2.4 million visitors annually (National Park Service, 2016). Many of the visitors enjoy recreation in or on the water and camp in the backcountry where the most common source of drinking water is filtered surface water, mainly from lakes (personal communication with National Park Service, 2014). There are several benchmarks with which to compare algal toxin concentrations, ranging from most protective (for drinking water) to lesser protective (for recreational water usage). Thus, identifying whether or not cyanotoxins are present in ISRO, PIRO, and SLBE lakes at concentrations that could pose a threat to visitor health by means of contact recreation (swimming, fishing, and boating) or drinking water is important.

Most reported cases of elevated microcystin concentrations were detected in locations with visible algal blooms, in part because cyanotoxins are not routinely monitored and samples are typically collected once a bloom occurs (Graham and others, 2009). The relation of cyanobacteria abundance to toxin occurrence is influenced by environmental conditions (lake hydrology, geomorphology, water chemistry, and physical water characteristics), biological processes (cellular toxin production, and cell proliferation and lysis), and biological community structure (Glibert and others, 2005).

The most commonly detected cyanotoxins in the United States are microcystins (U.S. Environmental Protection Agency, 2015a), which at high enough concentrations can cause acute or chronic toxicity in plants, wildlife, and humans (Chorus and Bartram, 1999). Microcystins are hepatotoxins capable of causing a range of symptoms that include acute and chronic liver ailments in wildlife and humans. Hepatotoxins can be produced by several cyanobacterial genera including *Microcystis sp., Oscillatoria sp.,* and *Anabaena sp.* when their densities intensify (Sivonen, 1996; Yoo and others, 1995). These hepatotoxins act as inhibitors of protein phosphatases and are potential tumor promoters (Sivonen, 1996). Toxic effects of microcystins on zooplankton (*Daphnia sp.*) through ingestion of the algal cells were noted in Lampert (1981) and Nizan and others (1986). The cascading effects of trophic disruption in freshwater environments during severe cyanobacterial blooms was highlighted in Lampert (1981) and Nizan and others (1986). As reported by the U.S. Environmental Protection Agency (EPA), several other algal toxins commonly detected in freshwaters of the United States that also pose a threat to human and animal health include cylindrospermopsin, anatoxins, and saxitoxins (U.S. Environmental Protection Agency, 2015a).



Cyanobacterial bloom on Lake Richie, Isle Royale National Park, 2010. Photographs by Rick Damstra, National Park Service

Currently (2017), neither the United States nor State of Michigan have issued cyanotoxin guidelines for recreational waters. The World Health Organization (WHO) has a series of recommended guidelines for freshwater recreational exposure, the most protective being microcystin-LR concentrations less than 10 micrograms per liter (µg/L), for a low probability of acute effects (World Health Organization, 2003b). The EPA recently (2015) developed a 10-day health advisory in drinking water for concentrations of microcystins (0.3 µg/L) and cylindrospermopsins (0.7 µg/L) for children preschool age and younger (less than 6-years old). For school-age children through adults (6-years old and older), the health advisory concentrations of microcystins and cylindrospermopsins are higher at 1.6 µg/L and 3.0 µg/L, respectively (U.S. Environmental Protection Agency, 2015b).

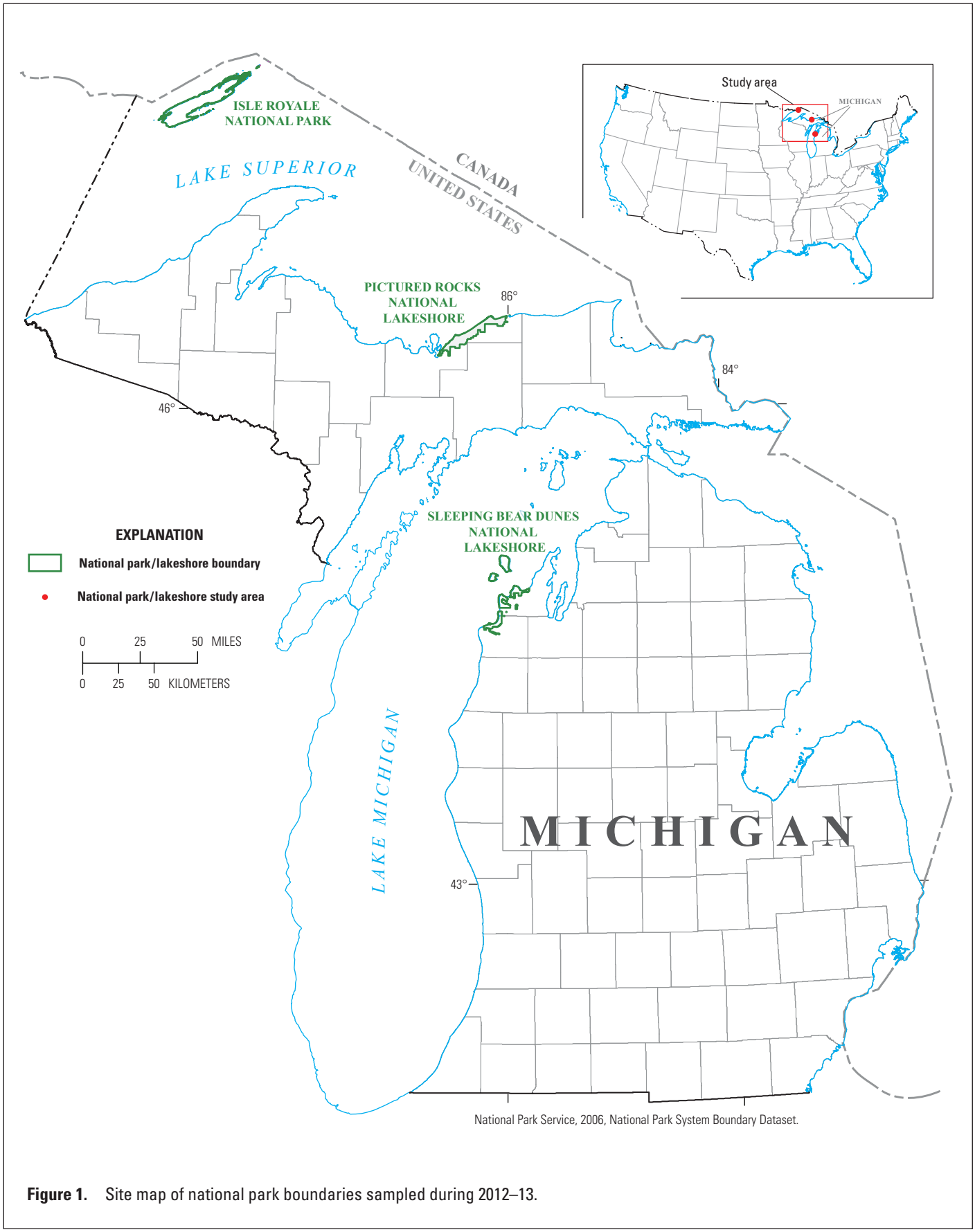


Figure 1. Site map of national park boundaries sampled during 2012–13.

Cyanobacteria often are most abundant in midsummer to early fall, but cyanobacterial harmful algal blooms can occur any time of year (Chorus and Bartram, 1999; Drake and others, 2010). Understanding the controlling factors for cyanobacteria growth, accumulation, and toxin production is critical for managing and preventing algal toxicity issues. Cyanobacteria growth and accumulation is influenced by a diverse range of physical, chemical, and biological factors (Chorus and Bartram, 1999). Nutrient input, solar irradiance, hydrology, and climate may all substantially influence the proliferation of cyanobacteria. The amount of nitrogen and phosphorus in the water is particularly important because these nutrients are necessary for cyanobacterial growth.

Numerous studies discuss the role of nutrient concentrations and ratios in production of algal blooms and toxins (for example, Orihel and others, 2012; Scott and others, 2013; Downing and others, 2001). Orihel and others (2012) reported that high microcystin concentrations were detected only at low total nitrogen (TN) to total phosphorus (TP) ratios (TN:TP) in a study of Canadian lakes from 2001 to 2011. To further understand this concept, large scale mesocosm experiments were led by Harris and others (2014a; 2014b). The experiments were completed in an Oregon reservoir where TN:TP ratios were manipulated by adding ammonium nitrate and aluminum sulfate, where the manipulation of the TN:TP greater than 50 (by mass) shifted the dominant primary producers from cyanobacteria to the more ecologically desirable chlorophytes and cryptophytes. As a consequence of decreased cyanobacteria occurrence, the frequency at which microcystin was detected declined as well.

For this 2-year study, the U.S. Geological Survey (USGS), in partnership with the National Park Service (NPS), monitored surface waters at 17 inland lakes and 4 Great Lake sites across 1 national park and 2 national lakeshores in northern Michigan to (1) assess the presence and concentrations of common algal toxins irrespective of whether or not visible algal blooms were present, (2) to relate the toxins to known EPA and WHO benchmarks for recreation and drinking water, and (3) to explore the possible relation between nutrient conditions and the presence and concentrations of algal toxins.

Purpose and Scope

The purpose of this report is to describe the detection of microcystin and other algal toxins in several inland lakes in ISRO, PIRO, and SLBE. The objectives of this report are to (1) highlight previous studies that have evaluated cyanotoxins within the study area, (2) describe detections of cyanotoxins in lake samples by use of enzyme-linked immunosorbent assays (ELISA) (Abraxis, LLC) and liquid chromatography/tandem mass spectrometry (LC/MS/MS) methods, (3) compare ELISA microcystin results to the WHO recreational guideline for acute health effects (less than 10 µg/L; World Health Organization, 2003a) and to the EPA drinking-water recommendations (U.S. Environmental Protection Agency, 2015b) to provide a context for potential human-health risk, (4) evaluate results to determine if microcystin concentrations differed by lake and if concentrations differed seasonally, and (5) relate cyanotoxin results to nutrient ratios within each lake.

Study Area Description

Northern Michigan is home to one national park and two national lakeshores with significant surface-water resources—ISRO and PIRO on Lake Superior and Sleeping Bear Dunes National Lakeshore (SLBE) on Lake Michigan (fig. 1)—each containing many inland lakes greater than 1 hectare (77, 24, and 24 lakes, respectively) (Elias and others, 2015).

The national park (ISRO) and two national lakeshores (PIRO and SLBE) that were sampled as part of this study are in northern Michigan; ISRO and PIRO are in the upper peninsula, and SLBE is in the northern lower peninsula of Michigan (fig. 1). Forests and wetlands are the predominant land cover for all three study areas (National Park Service, 2016; figs. 2–4, table 1). The SLBE is less than 1 percent agriculture but has about 4 percent urban land cover (National Park Service, 2016; table 1).

Previous Studies

U.S. Environmental Protection Agency National Lakes Assessment (2007)

In 2007, the EPA led a National Lakes Assessment on approximately 1,000 inland lakes throughout the United States. Microcystin was detected in 30 percent of the lakes sampled nationwide and in 23 percent of the lakes sampled in the Upper Midwest (U.S. Environmental Protection Agency, 2009). The EPA noted that these samples were collected in the middle of the lake, in open water, as opposed to the nearshore areas where concentrations of microcystins are typically higher (U.S. Environmental Protection Agency, 2009; Beaver and others, 2014; Lindon and Heiskary, 2009). Results from this 2007 lakes assessment also indicated that cylindrospermopsins and saxitoxins were detected in 4 and 7.7 percent of samples, respectively, but co-occurrence of cylindrospermopsins, microcystins, and saxitoxins was rare (0.3 percent) (Loftin and others, 2016). The method for microcystin analysis was based on the use of an immunoassay kit manufactured by Abraxis.

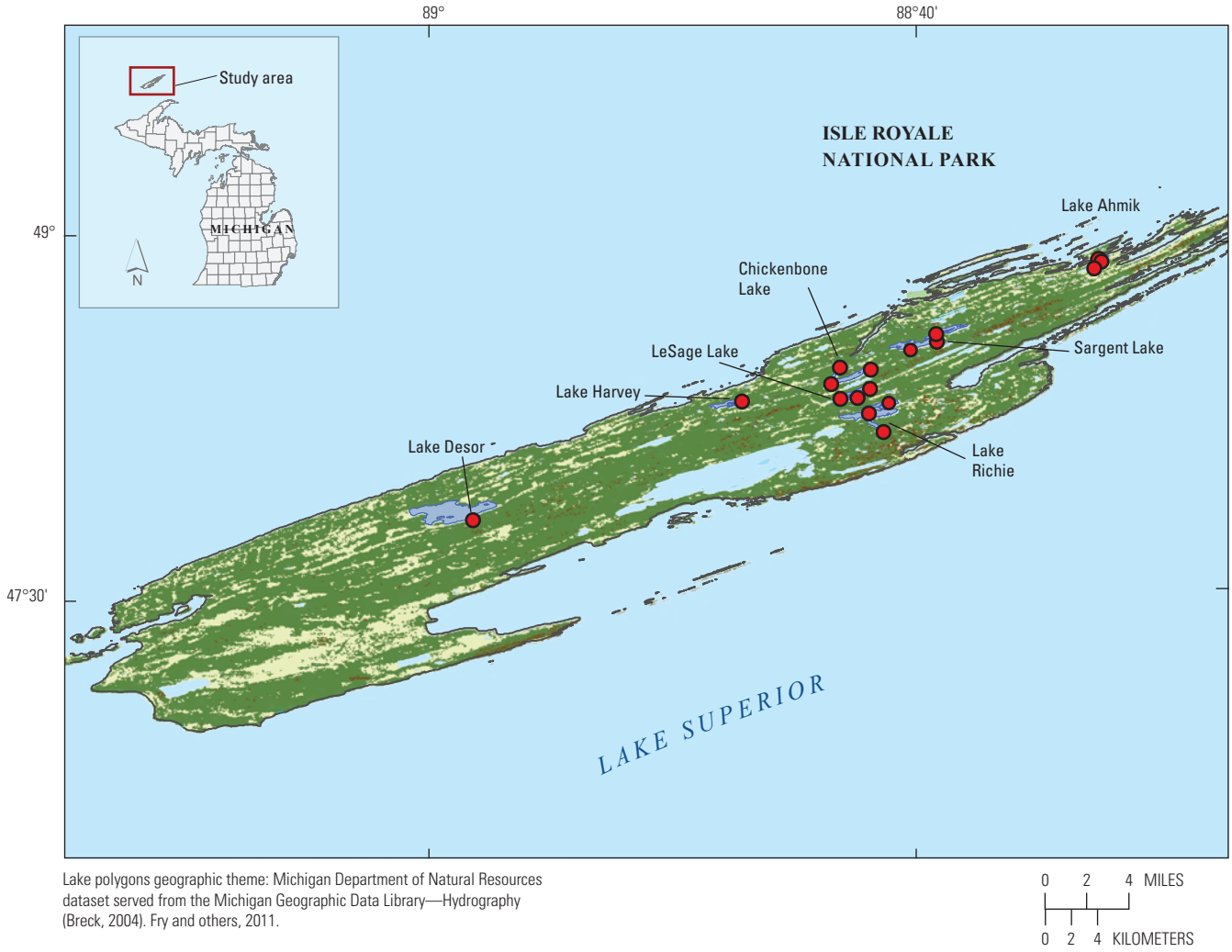


Figure 2. Isle Royale National Park study sites.

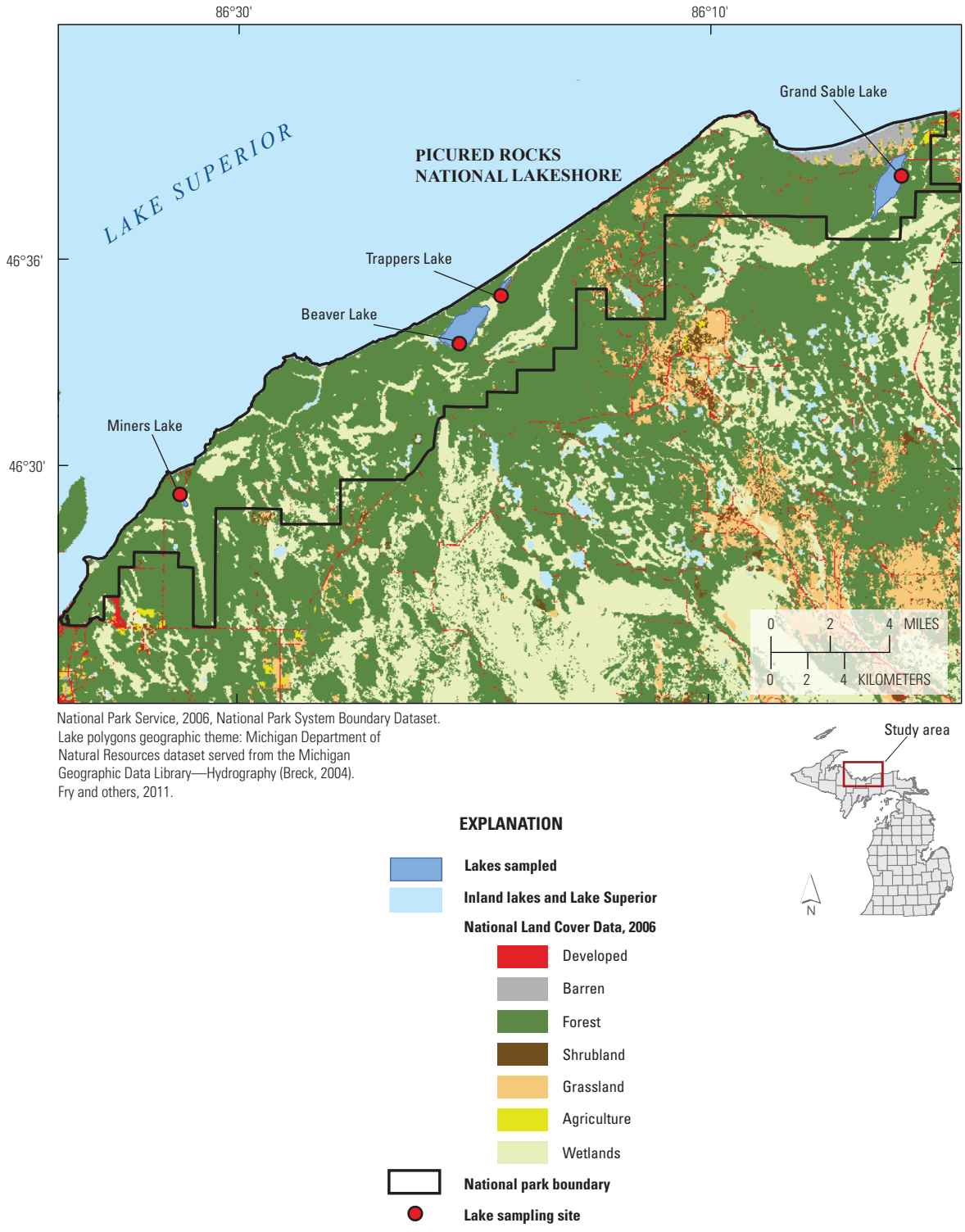


Figure 3. Pictured Rocks National Lakeshore study sites.

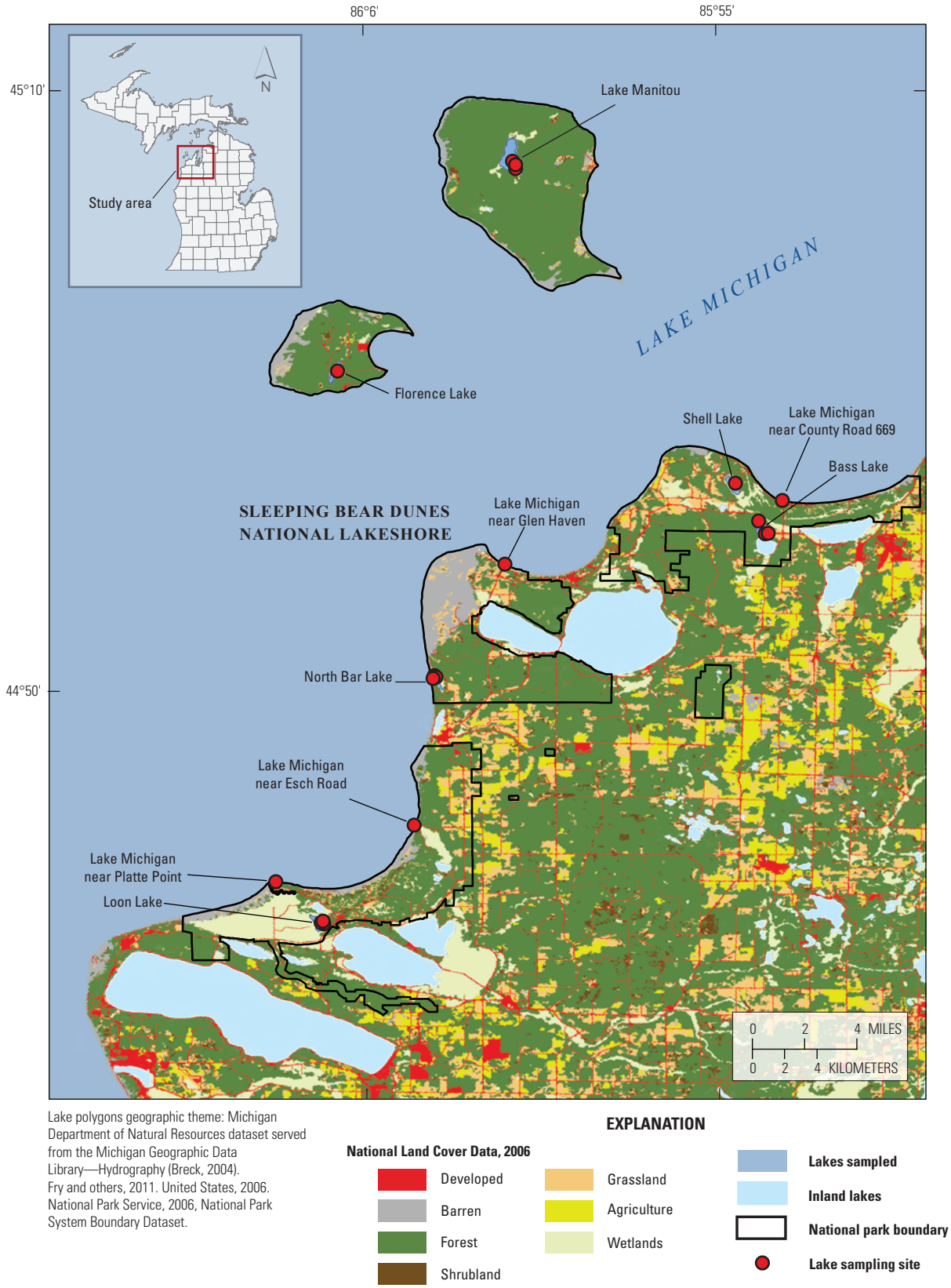


Figure 4. Sleeping Bear Dunes National Shoreline study sites.

Table 1. Land cover at Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore.

[National land cover percentage by national park, national lakeshore, and National Park Service lakeshed, from National Park Service, 2006; NPS, National Park Service; NHDPlus, National Hydrography Dataset Plus (McKay and others, 2014); —, no data; data presented in bold represent total land cover percentage by park]

Location	Catchment	Deciduous forest	Mixed forest	Wetlands	Evergreen forest	Shrub/herbaceous	Barren	Urban	Agriculture
Isle Royale National Park		**33**	**28**	**22**	**15**	**2**	**1**	**0**	**0**
Lake Ahmik	NPS lakeshed	11	27	34	25	3	0	0	0
Lake Harvey	NPS lakeshed	18	46	18	18	0	0	0	0
LeSage Lake	NPS lakeshed	27	38	14	14	7	0	0	0
Lake Richie	NPS lakeshed	13	44	12	29	2	0	0	0
Sargent Lake	NPS lakeshed	31	41	10	16	1	0	0	0
Chickenbone Lake	No lakeshed or NHDPlus catchment available	—	—	—	—	—	—	—	—
Lake Desor	No lakeshed or NHDPlus catchment available	—	—	—	—	—	—	—	—
Pictured Rocks National Lakeshore		**64**	**3**	**15**	**11**	**3**	**2**	**1**	**0**
Beaver Lake	NHDPlus catchment	41	6	18	33	0	1	1	0
Grand Sable Lake	NHDPlus catchment	75	1	9	4	3	5	2	1
Miners Lake	NHDPlus catchment	75	5	12	7	1	0	1	0
Trappers Lake	NHDPlus catchment	39	6	19	33	0	1	1	0
Sleeping Bear Dunes National Lakeshore		**59**	**4**	**9**	**4**	**9**	**10**	**4**	**1**
Bass Lake	NPS lakeshed	50	3	5	1	16	11	14	0
Florence Lake	NPS lakeshed	92	1	1	0	2	2	3	0
Loon Lake	NPS lakeshed	35	3	36	6	8	0	13	0
Lake Manitou	NPS lakeshed	95	0	4	0	1	0	0	0
North Bar Lake	NPS lakeshed	61	5	8	3	16	2	6	0
Shell Lake	NPS lakeshed	55	3	21	1	6	8	6	0
Lake Michigan County Road 669	No lakeshed or NHDPlus catchment available	—	—	—	—	—	—	—	—
Lake Michigan Esch Road	No lakeshed or NHDPlus catchment available	—	—	—	—	—	—	—	—
Lake Michigan Glen Haven	No lakeshed or NHDPlus catchment available	—	—	—	—	—	—	—	—
Lake Michigan Platte Point	No lakeshed or NHDPlus catchment available	—	—	—	—	—	—	—	—

U.S. Geological Survey Analysis of Inland Lakes in Michigan (Microcystin)

In August 2008, the USGS collected samples at 41 inland lakes in Michigan following similar protocols used in the 2007 EPA National Lakes Assessment, including collection of samples in deep, open waters of inland lakes (U.S. Environmental Protection Agency, 2009). Lake samples were analyzed for microcystin concentrations by immunoassay, and approximately 54 percent of the samples (22 out of 41 samples) collected had detectable (greater than or equal to 0.10 µg/L) concentrations of microcystin, ranging from 0.12 to 0.69 µg/L (U.S. Geological Survey, 2017) (fig. 5). When detected, many of the higher microcystin concentrations were in inland lakes in northwest lower Michigan (near SLBE) and in open waters without visible blooms present.

Isle Royale National Park (ISRO) Algal Blooms

In August 2007, an algal bloom was observed throughout the waters of remote Lake Richie at ISRO (M. Edlund, oral commun., 2016; fig. 2). Samples were collected and the algae were identified as *Lyngbya birgei* (Cyanophyta) (M. Edlund, oral commun., 2016), which can produce microcystins as well as saxitoxin (National Oceanic and Atmospheric Administration, 2017). Another bloom was detected in Lake Richie in 2010, in which *Lyngbya birgei* and two other cyanobacteria, *Anabaena flos-aquae* and *Anabaena planctonica,* were present (M. Edlund, oral commun., 2016). *Anabaena flos-aquae* can produce microcystin and anatoxin-a, whereas *Anabaena planctonica* can produce anatoxin-a (Bruno and others, 1994; MERHAB–LGL, 2017). Algal blooms caused by unidentified algal species were also detected in Sargent Lake at ISRO in 2009 (fig. 2) and Whittlesey (not shown) and Chickenbone Lakes (fig. 2) in 2010 (Rick Damstra, oral commun., 2016).

Cyanobacterial bloom on Lake Richie, Isle Royale National Park, 2007. Photographs by Mark Edlund, St. Croix Watershed Research Station.

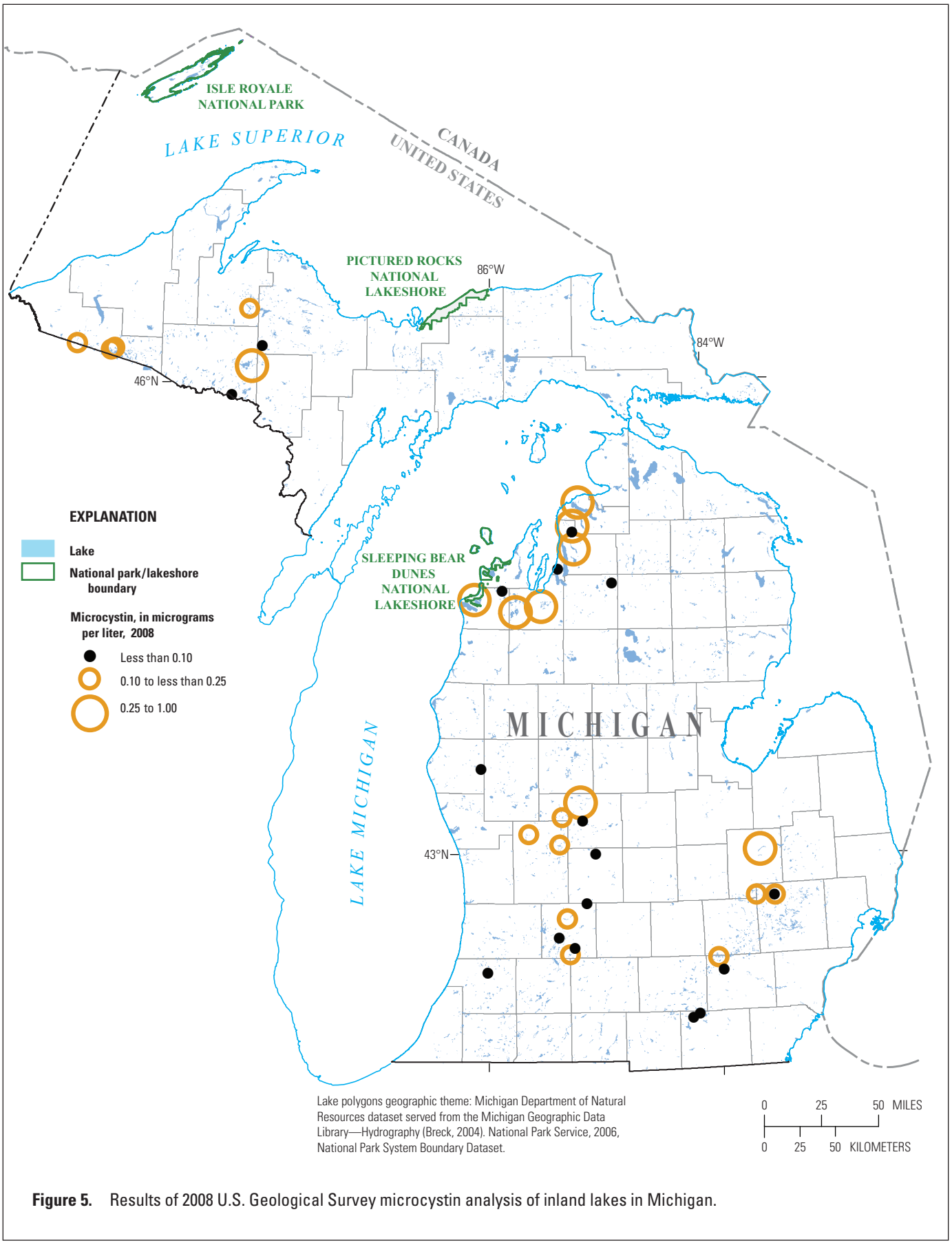


Figure 5. Results of 2008 U.S. Geological Survey microcystin analysis of inland lakes in Michigan.

Cyanobacterial bloom on Sargent Lake, Isle Royale National Park, 2009. Photograph by Rick Damstra, National Park Service.

Methods

Site Selection

A total of 17 inland lakes were selected for monitoring for this study. Fifteen of these 17 lakes are included within a larger long-term monitoring effort (since the middle of the 2000s) by the NPS Great Lakes Inventory and Monitoring Network that annually assesses lake water quality during the summer (Elias and others, 2015). Of the 17 lakes, 7 lakes were at ISRO, 4 lakes at PIRO, and 6 lakes were monitored at SLBE. In addition, four nearshore Lake Michigan beach sites at SLBE (table 2) were sampled as part of this study because of the high recreational usage at these beaches. LeSage Lake was eliminated and replaced with Lake Ahmik (fig. 2) in 2013 because of sampling difficulties at ISRO in 2012.

Field Methods

For most sites, three environmental samples were collected from each lake in nearshore waters on the same day as routine NPS monitoring. These samples were assessed for potential toxins using standard USGS methods (Graham and others, 2008a; 2008b). In addition, multiple lake samples were collected at nine lakes in different locations each year to assess within-lake spatial variability (table 2).

For each lake and Lake Michigan nearshore sites, the primary sampling location for toxin analysis was determined by where each received the most recreational traffic, representing an area of potentially higher risk of exposure to visitors by algal toxins, if present. Monitoring sites were accessed by various methods depending on the location, including by canoe, kayak, boat, and wading. Grab samples were collected in waist deep water near the shoreline from 0.5 to 1.0 meters below the water surface where people would be most likely to enjoy recreation or obtain water for drinking.

Sample bottles were rinsed three times with native lake water from the immediate sampling area. Using the rinsed bottle with the cap in place, the bottle was lowered to the appropriate depth, and the cap was removed to collect the sample at that depth. In order to assess spatial variability at the primary monitoring location, three samples were collected parallel to the shoreline; one at the center location and two at locations approximately 10 meters to the right and to the left of center. In 2012, additional sampling locations were added at Lake Richie at ISRO on two occasions and once at Lake Desor (fig. 2) to capture visible algal blooms in a specific area of the lake.

Sampling teams frequently recorded whether blooms were visibly present or not present. All samples intended for toxin analysis were stored at -20 degrees Celsius and shipped on ice to the USGS Organic Geochemistry Research Laboratory (OGRL) in Lawrence, Kansas, for analysis.

Also as part of this study, basic water-quality samples were collected by NPS aquatic specialists at ISRO, PIRO, and SLBE during scheduled routine water-quality monitoring visits, generally from June through September in 2012 and 2013. A complete description of the field methods, including typical parameters monitored, can be found in Elias and others (2015). During routine NPS water-quality monitoring, water samples were collected from offshore surface waters at the deepest area of the lake and were analyzed for total TP, TN, and chlorophyll *a* by the St. Croix Watershed Research Station in Marine on St. Croix, Minnesota. A TN:TP ratio was calculated for each sampling event, and sampling events were then averaged to determine the annual TN:TP ratio for that particular location.

Table 2. Location of lake sampling sites in Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore, 2012–13.

[USGS, U.S. Geological Survey; NPS, National Park Service; NAD 83, horizontal coordinate information referenced to North American Datum of 1983; E, east; CB, Chickenbone; ISRO, Isle Royale National Park; MI, Michigan; °, degrees; ', minutes; ", seconds; S, south; NE, northeast; NW, northwest; Tr, Trail; SC, south-central; PIRO, Pictured Rocks National Lakeshore; SW, southwest; SBDNL, Sleeping Bear Dunes National Lakeshore; SLBE, Sleeping Bear Dunes National Lakeshore; SE, southeast; LeSage Lake is referred to as "Lake LeSage" and Lake Manitou is referred to as "Manitou Lake"]

USGS site name	NPS park unit	USGS site number	Latitude (NAD 83)	Longitude (NAD 83)
Chickenbone Lake near E CB Campground at ISRO, MI	ISRO	480350088433001	48°03'50"	-88°43'30"
Chickenbone Lake near Old Portage at Isle Royale, MI	ISRO	480429088431001	48°04'29"	-88°43'10"
Chickenbone Lake near W CB Campground at ISRO, MI	ISRO	480426088415401	48°04'26"	-88°41'54"
Lake Ahmik near Portage at Isle Royale, MI	ISRO	480856088322601	48°08'56"	-88°32'26"
Lake Ahmik near South Shore at Isle Royale, MI	ISRO	480856088322001	48°08'56"	-88°32'20"
Lake Ahmik near West End at Isle Royale, MI	ISRO	480841088323401	48°08'41"	-88°32'34"
Lake Desor near S Desor Campground at Isle Royale, MI	ISRO	475814088582001	47°58'14"	-88°58'20"
Lake Harvey near NE of Lake at Isle Royale, MI	ISRO	480308088471401	48°03'08"	-88°47'14"
Lake LeSage near NE end of Lake at Isle Royale, MI	ISRO	480338088415901	48°03'38"	-88°41'59"
Lake LeSage near NW Portage at Isle Royale, MI	ISRO	480318088430801	48°03'18"	-88°43'08"
Lake LeSage near South Portage at Isle Royale, MI	ISRO	480317088422601	48°03'17"	-88°42'26"
Lake Richie at Moskey Portage Isle Royale, MI	ISRO	48030888410001	48°03'08"	-88°41'00"
Lake Richie near Bedrock Beach at Isle Royale, MI	ISRO	480305088410601	48°03'05"	-88°41'06"
Lake Richie near Canoe Campground at Isle Royale, MI	ISRO	480237088415701	48°02'37"	-88°41'57"
Lake Richie near Indian Portage Tr at Isle Royale, MI	ISRO	480155088412101	48°01'55"	-88°41'21"
Sargent Lake near NE end of Lake at Isle Royale, MI	ISRO	480557088391001	48°05'57"	-88°39'10"
Sargent Lake near NW end of Lake at Isle Royale, MI	ISRO	480518088401401	48°05'18"	-88°40'14"
Sargent Lake near S Basin Portage at Isle Royale, MI	ISRO	480535088390901	48°05'35"	-88°39'09"
Beaver Lake near SC Shore at Pictured Rocks, MI	PIRO	463330086204001	46°33'30"	-86°20'40"
Grand Sable Lake near E Shore at Pictured Rocks, MI	PIRO	463835086015301	46°38'35"	-86°01'53"
Miners Lake near SW Shore at Pictured Rocks, MI	PIRO	462846086321301	46°28'46"	-86°32'13"
Trappers Lake near Campground at Pictured Rocks, MI	PIRO	463516086185201	46°35'16"	-86°18'52"
Bass Lake North near North Shore at SBDNL, MI	SLBE	445543085530801	44°55'43"	-85°53'08"
Bass Lake North near SE Boat Launch at SBDNL, MI	SLBE	445518085525301	44°55'18"	-85°52'53"
Bass Lake North near Glen Lake Benchmark at SBDNL, MI	SLBE	445518085525401	44°55'18"	-85°52'54"
Florence Lake near Boat Launch at SBDNL, MI	SLBE	450037086070801	45°00'37"	-86°07'08"
Lake Michigan near County Road 669 at SBDNL, MI	SLBE	445623085522101	44°56'23"	-85°52'21"
Lake Michigan near Esch Road at SBDNL, MI	SLBE	444546086043501	44°45'46"	-86°04'35"
Lake Michigan near Glen Haven at SBDNL, MI	SLBE	445418086013401	44°54'18"	-86°01'34"
Lake Michigan near Platte Point at SBDNL, MI	SLBE	444355086091101	44°43'55"	-86°09'11"
Loon Lake near Boat Launch at SBDNL, MI	SLBE	444232086073501	44°42'32"	-86°07'35"
Loon Lake near Cove at Sleeping Bear Dunes NL, MI	SLBE	444235086073701	44°42'35"	-86°07'37"
Loon Lake near Platte River Inlet at SBDNL, MI	SLBE	444235086074001	44°42'35"	-86°07'40"
Manitou Lake near Boat Launch at SBDNL, MI	SLBE	450714086011301	45°07'14"	-86°01'13"
Manitou Lake near Midpoint at SBDNL, MI	SLBE	450722086011201	45°07'22"	-86°01'12"
Manitou Lake near Point at Sleeping Bear Dunes NL, MI	SLBE	450729086011901	45°07'29"	-86°01'19"
North Bar Lake near Boat Launch at SBDNL, MI	SLBE	445037086035301	44°50'37"	-86°03'53"
North Bar Lake near North Shore at SBDNL, MI	SLBE	445039086035501	44°50'39"	-86°03'55"
North Bar Lake near Outlet at SBDNL, MI	SLBE	445034086035701	44°50'34"	-86°03'57"
Shell Lake near East Shore Boat Launch at SBDNL, MI	SLBE	445657085535501	44°56'57"	-85°53'55"

Cyanotoxin Analysis

Samples were analyzed for cyanotoxins using ELISA (Abraxis, LLC) (0.10 µg/L detection limit for microcystin) and LC/MS/MS (0.10 µg/L detection limit for microcystin) by the USGS OGRL. The ELISA techniques have commonly been used as a cost effective and quick screening approach for the determination of algal toxins in surface waters (U.S. Environmental Protection Agency, 2009; Graham and Jones, 2009; Graham and others, 2006) with confirmation by LC/MS/MS. Samples were sequentially frozen/thawed three times to lyse cyanobacteria cells and release potential toxins. Lysed samples were filtered using a 0.7-micron glass-fiber filter and syringe. Filtrates from the field samples collected at left, center, and right for each location were composited volumetrically before analysis.

The ELISA microcystin results also were compared to the WHO recreational guideline for acute health effects (less than 10 µg/L; World Health Organization, 2003a) and the EPA drinking-water recommendations (U.S. Environmental Protection Agency, 2015b) to provide a context for potential human-health risk. Results also were evaluated to determine if microcystin concentrations differed by lake and if concentrations differed throughout the summer.

Select samples from ISRO and SLBE also were tested for saxitoxin and cylindrospermopsin using ELISA methods (Graham and others, 2010). In addition, 16 samples in 2012 and 23 samples in 2013 were selected for more detailed analysis using the LC/MS/MS method to determine concentrations for a larger suite of algal toxins (Loftin and others, 2008; Graham and others, 2010) (table 3). Sample selection was based on the presence and concentration of microcystin in the environmental sample.

Microcystin concentration data are stored in the USGS National Water Information System (https://dx.doi.org/10.5066/F7P55KJN).

Table 3. Algal toxins analyzed at Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore, 2012–13.

[ELISA, enzyme-linked immunosorbent assay; LC/MS/MS, liquid chromatography/tandem mass spectrometry]

Method	Algal toxin
ELISA	Microcystin
ELISA	Saxitoxin
ELISA	Cylindrospermopsin
LC/MS/MS	Microcystin-HtYR
LC/MS/MS	Microcystin-LA
LC/MS/MS	Microcystin-LR
LC/MS/MS	Microcystin-LW
LC/MS/MS	Microcystin-LY
LC/MS/MS	Microcystin-RR
LC/MS/MS	Microcystin-WR
LC/MS/MS	Microcystin-YR

Water-Quality Sample Analysis

Additional samples for nutrient (nitrogen and phosphorus constituents) and chlorophyll *a* analysis were collected from the center of the lake during each sampling event at 16 of the inland lakes. These samples were collected as part of the ongoing NPS lake monitoring, using sampling methods and laboratory methods as described in Elias and others (2015). The laboratories used by the NPS for analysis are state or federally certified for performing the water chemistry analyses in natural waters and are consistent with current EPA procedures (Elias and others, 2015). Data collected for nutrient and chlorophyll *a* analysis are stored in the EPA STORET database (http://www.epa.gov/waterdata/storage-and-retrieval-and-water-quality-exchange).

Quality Control Methods

Field Quality Control

In 2012, six field blanks and six replicate samples were collected, whereas in 2013, five field blanks and five replicates were collected. Field blanks consisted of sterile deionized water (provided by USGS OGRL) that was used to fill sample bottles while wading in the water or in the boat after all other samples had been collected at the site.

In order to account for possible spatial variability in the distribution of cyanobacteria within the water column, sequential field replicates were collected following the same sampling protocol for environmental samples. Field replicate data were reported as relative percent difference (RPD) and were calculated for detections for individual sequential replicate pairs using equation 1.

$$RPD_{\text{mean}} = [sample\ 1 - sample\ 2)/Mean]*100, \quad (1)$$

where

RPD_{mean} is the mean relative percent difference;
sample 1 is the concentration of sequential replicate 1, in micrograms per liter;
sample 2 is the concentration of sequential replicate 2, in micrograms per liter; and
Mean is the mean of concentration of the two sequential replicates, in micrograms per liter.

Laboratory Quality Control

Laboratory replicates (ELISA and LC/MS/MS) and spiked replicates (LC/MS/MS only) were measured on a subset of samples. For the laboratory replicates, six samples were collected for ELISA and three samples were collected for LC/MS/MS. For the spiked replicates, two samples were collected for LC/MS/MS. Laboratory replicate data were reported as mean relative percent standard deviation (RPSD), and RPSD was calculated for detections using equation 2.

$$RPSD_{mean} = [SD_{mean}/Mean]*100, \quad (2)$$

where

$RPSD_{mean}$ is the mean relative percent standard deviation;
SDmean is the mean standard deviation of replicate sample concentrations, in micrograms per liter; and
Mean is the grand mean of concentration of all replicate pairs for detected concentrations, in micrograms per liter.

Spiked replicates were amended with the equivalent of a 1.0 µg/L toxin standard mixture. Mean spiked sample recovery was calculated using equation 3.

$$\text{Percent } Spiked\ Recovery_{mean} = \{1 + [(C_{measured} - C_{expected})/C_{expected}]\} \times 100 \quad (3)$$

where

$C_{measured}$ is the mean measured concentration, in micrograms per liter, of all toxins and
$C_{expected}$ is the mean expected concentration, in micrograms per liter, of all toxins.

Cyanotoxin Results Using the Enzyme-Linked Immunosorbent Assay Method

The ELISA method was used to test all samples (n = 211) in order to obtain a baseline assessment for the common freshwater cyanotoxins including microcystin, saxitoxin, and cylindrospermopsin (table 4). Cylindrospermopsin and saxitoxin were not detected by ELISA in any of the samples collected as part of this study.

Summary of Microcystin Results by National Park and National Lakeshore

The ELISA method was used to measure the concentration of microcystin (minimum reporting levels [MRL] of 0.10 µg/L) from samples collected at 21 lake sites throughout 1 national park and 2 national lakeshores. Individual lake summary results are presented in table 5. The ELISA summary statistics by national park and national lakeshore for microcystin concentrations are presented in table 6 and figures 6–8 for each study area.

Microcystin was detected (concentrations above the MRL of 0.1 µg/L) by the ELISA method in 31 percent of the samples (65 of 211 samples), with a higher percentage of samples indicating detectable microcystins in 2012 versus 2013 (35 percent and 26 percent, respectively). Maximum microcystin concentrations ranged from 0.88 µg/L (2013) to 2.7 µg/L (2012), but most samples (approximately 80 percent) were near or less than the MRL of 0.1 µg/L. Microcystin was detected at least once at more than one-half of the sites (13 out of 21) during the study period (tables 5-6). Maximum microcystin concentrations were detected in lakes from SLBE that included Florence Lake (2.7 µg/L) in 2012 and Loon Lake (0.88 µg/L) in 2013 (table 5, fig. 4). Using the ELISA method, SLBE also had the highest percentage (57 percent) of samples with detectable concentrations of microcystin in 2012 (table 6).

Table 4. Number of lake water samples analyzed for each algal toxin assay (by year and location) at Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore, 2012–13.

[ELISA, enzyme-linked immunosorbent assay; LC/MS/MS, liquid chromatography/tandem mass spectrometry]

Location	Number of monitoring locations per lake	Microcystin (ELISA)		Saxitoxin (ELISA)		Cylindrospermopsin (ELISA)		Suite of toxins (LC/MS/MS)	
		2012	2013	2012	2013	2012	2013	2012	2013
Isle Royale National Park									
Chickenbone Lake	3	9	9	4	3	4	3	0	2
Lake Desor	1	4	2	3	2	3	2	0	0
Lake Ahmik[1]	3	0	9	0	3	0	3	0	3
Lake Harvey	1	3	3	3	3	3	3	0	1
LeSage Lake[2]	3	9	0	4	0	4	0	0	0
Lake Richie	4	12	9	3	3	3	3	0	5
Sargent Lake	3	8	9	4	3	5	3	0	0
Pictured Rocks National Lakeshore									
Beaver Lake	1	3	3	0	0	0	0	0	0
Grand Sable Lake	1	3	3	0	0	0	0	0	0
Miners Lake	1	3	3	0	0	0	0	0	0
Trappers Lake	1	3	3	0	0	0	0	3	1
Sleeping Bear Dunes National Lakeshore									
Bass Lake (North)	3	9	9	3	2	3	3	0	2
Florence Lake	1	3	3	3	2	3	3	2	1
Lake Michigan County Road 669	1	3	3	3	3	3	3	0	0
Lake Michigan Esch Road	1	3	3	3	3	3	3	0	0
Lake Michigan Glen Haven	1	3	3	3	3	3	3	0	0
Lake Michigan Platte Point	1	3	3	3	3	3	3	1	1
Loon Lake	3	9	6	3	2	3	2	3	4
Lake Manitou	3	9	8	3	3	3	3	3	1
North Bar Lake	3	9	6	4	2	3	2	3	1
Shell Lake	1	3	3	3	3	3	3	1	1

[1]2013 only.

[2]2012 only.

Table 5. Summary of enzyme-linked immunosorbent assay microcystin results at Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore, 2012–13.

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; >, greater than; µg/L, microgram per liter; MRL, minimum report level; <, less than; NS, no sample analysis]

USGS site name	Number of samples analyzed		Percentage of samples with detectable microcystin by ELISA		Percentage of samples with microcystin > 0.3 (µg/L)		Percentage of samples with microcystin > 1.6 (µg/L)		ELISA microcystin concentration or range of concentrations if above 0.10 (MRL) (µg/L)		ELISA microcystin median concentration (µg/L)	
	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
Isle Royale National Park												
Chickenbone Lake	9	9	22	0	0	0	0	0	<0.10–0.10	<0.10	<0.10	<0.10
Lake Desor	4	2	0	0	0	0	0	0	<0.10	<0.10	<0.10	<0.10
Lake Ahmik[1]	NS	9	NS	0	NS	0	NS	0	NS	<0.10	NS	<0.10
Lake Harvey	3	3	0	33	0	0	0	0	<0.10	<0.10–0.20	<0.10	<0.10
LeSage Lake[2]	9	NS	0	NS	0	NS	0	NS	<0.10	NS	<0.10	NS
Lake Richie	12	9	8	33	0	0	0	0	<0.10–0.12	<0.10–0.19	<0.10	<0.10
Sargent Lake	8	9	13	11	0	0	0	0	<0.10–0.11	<0.10–0.10	<0.10	<0.10
Pictured Rocks National Lakeshore												
Beaver Lake	3	3	0	0	0	0	0	0	<0.10	<0.10	<0.10	<0.10
Grand Sable Lake	3	3	0	0	0	0	0	0	<0.10	<0.10	<0.10	<0.10
Miners Lake	3	3	0	0	0	0	0	0	<0.10	<0.10	<0.10	<0.10
Trappers Lake	3	3	100	67	100	33	0	0	0.35–1.10	<0.10–0.59	0.84	0.12
Sleeping Bear Dunes National Lakeshore												
Bass Lake (North)	9	9	100	67	0	0	0	0	0.12–0.25	<0.10–0.18	0.17	0.11
Florence Lake	3	3	100	67	67	0	33	0	0.11–2.70	<0.10–0.25	0.95	0.23
Loon Lake	9	6	67	50	33	50	0	0	<0.10–0.41	<0.10–0.88	0.12	0.22
Lake Manitou	9	8	67	50	33	0	0	0	<0.10–0.47	<0.01–0.11	0.14	0.10
North Bar Lake	9	6	33	0	33	0	0	0	<0.10–0.73	<0.10	<0.10	<0.10
Shell Lake	3	3	67	33	33	0	0	0	<0.10–0.31	<0.10–0.21	0.10	0.17
Lake Michigan Esch Road	3	3	33	0	0	0	0	0	<0.10–0.14	<0.10	<0.10	<0.10
Lake Michigan Glen Haven	3	3	0	0	0	0	0	0	<0.10	<0.10	<0.10	<0.10
Lake Michigan Platte Point	3	3	33	67	33	33	0	0	<0.10–0.33	<0.10–0.43	<0.10	0.22
Lake Michigan County Road 669	3	3	0	0	0	0	0	0	<0.10	<0.10	<0.10	<0.10

[1]2013 only.

[2]2012 only.

Table 6. Summary statistics of enzyme-linked immunosorbent assay microcystin results in 2012 and 2013 at Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore.

[>, greater than; µg/L, microgram per liter; <, less than]

National Park System park unit	Number of samples collected	Percentage of samples with detectable microcystin (> 0.1 µg/L)	Percentage of samples with microcystin (> 0.3 µg/L)	Percentage of samples with microcystin (> 1.6 µg/L)	Minimum	25th percentile	Median	75th percentile	Maximum
2012									
Isle Royale National Park	45	11	0	0	<0.1	<0.1	<0.1	<0.1	0.12
Pictured Rocks National Lakeshore	12	25	25	0	<0.1	<0.1	<0.1	<0.1	1.1
Sleeping Bear Dunes National Lakeshore	54	57	22	2	<0.1	<0.1	0.12	0.25	2.7
2013									
Isle Royale National Park	41	12	0	0	<0.1	<0.1	<0.1	<0.1	0.2
Pictured Rocks National Lakeshore	12	17	8	0	<0.1	<0.1	<0.1	<0.1	0.59
Sleeping Bear Dunes National Lakeshore	47	40	9	0	<0.1	<0.1	<0.1	0.12	0.88

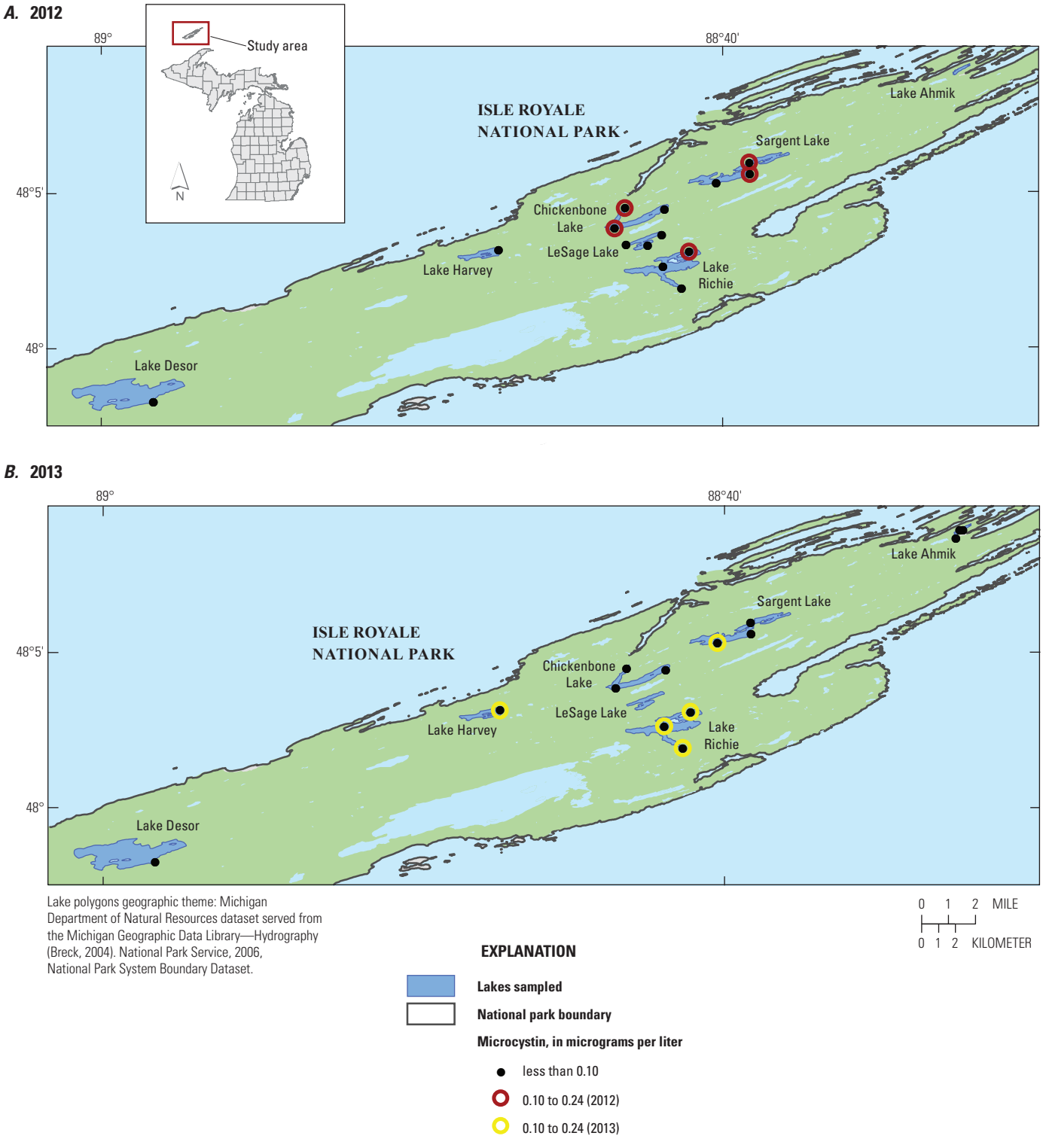


Figure 6. Enzyme-linked immunosorbent assay microcystin results for lakes at Isle Royale National Park, 2012–13.

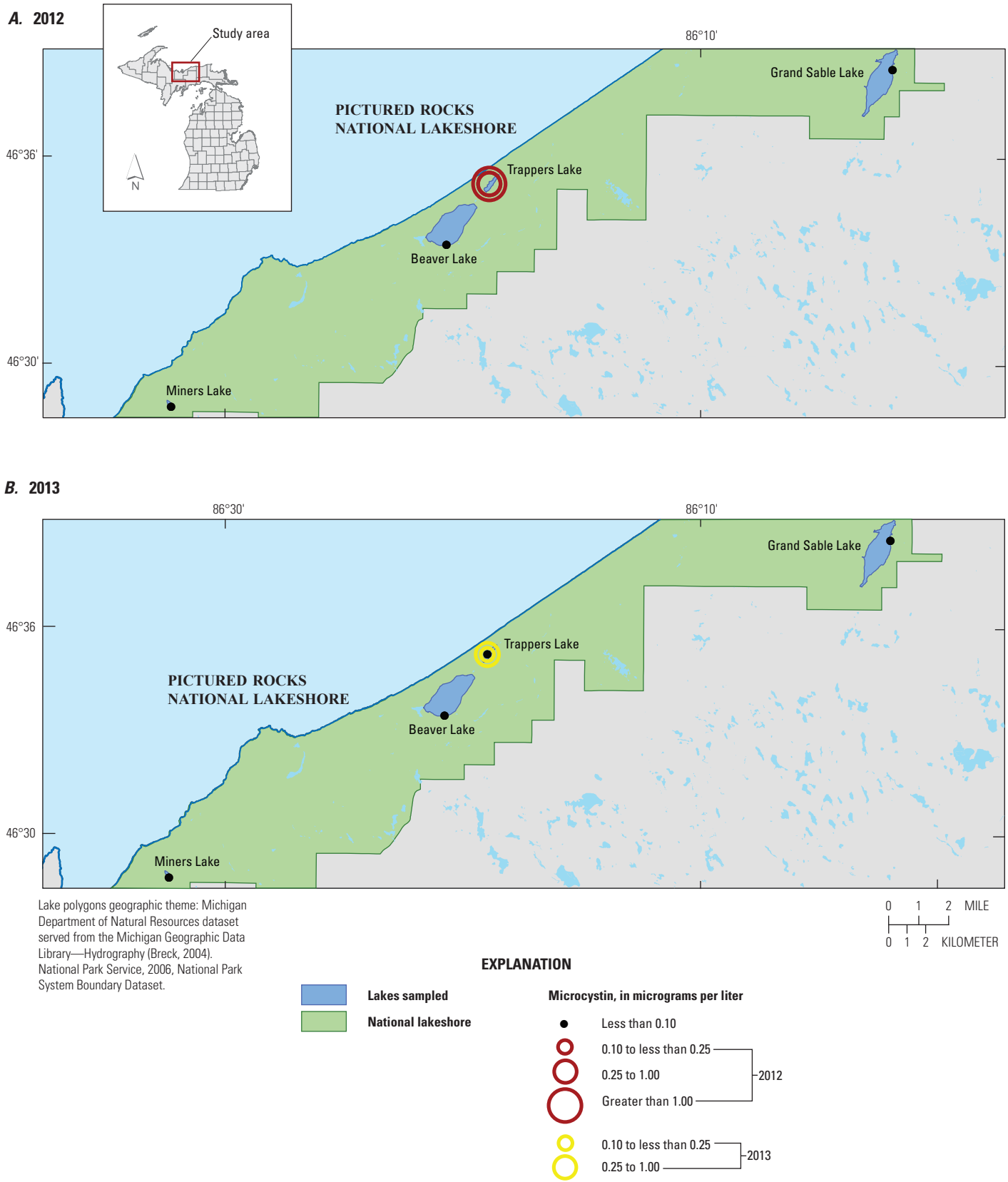


Figure 7. Enzyme-linked immunosorbent assay microcystin results for lakes at Pictured Rocks National Lakeshore, 2012–13.

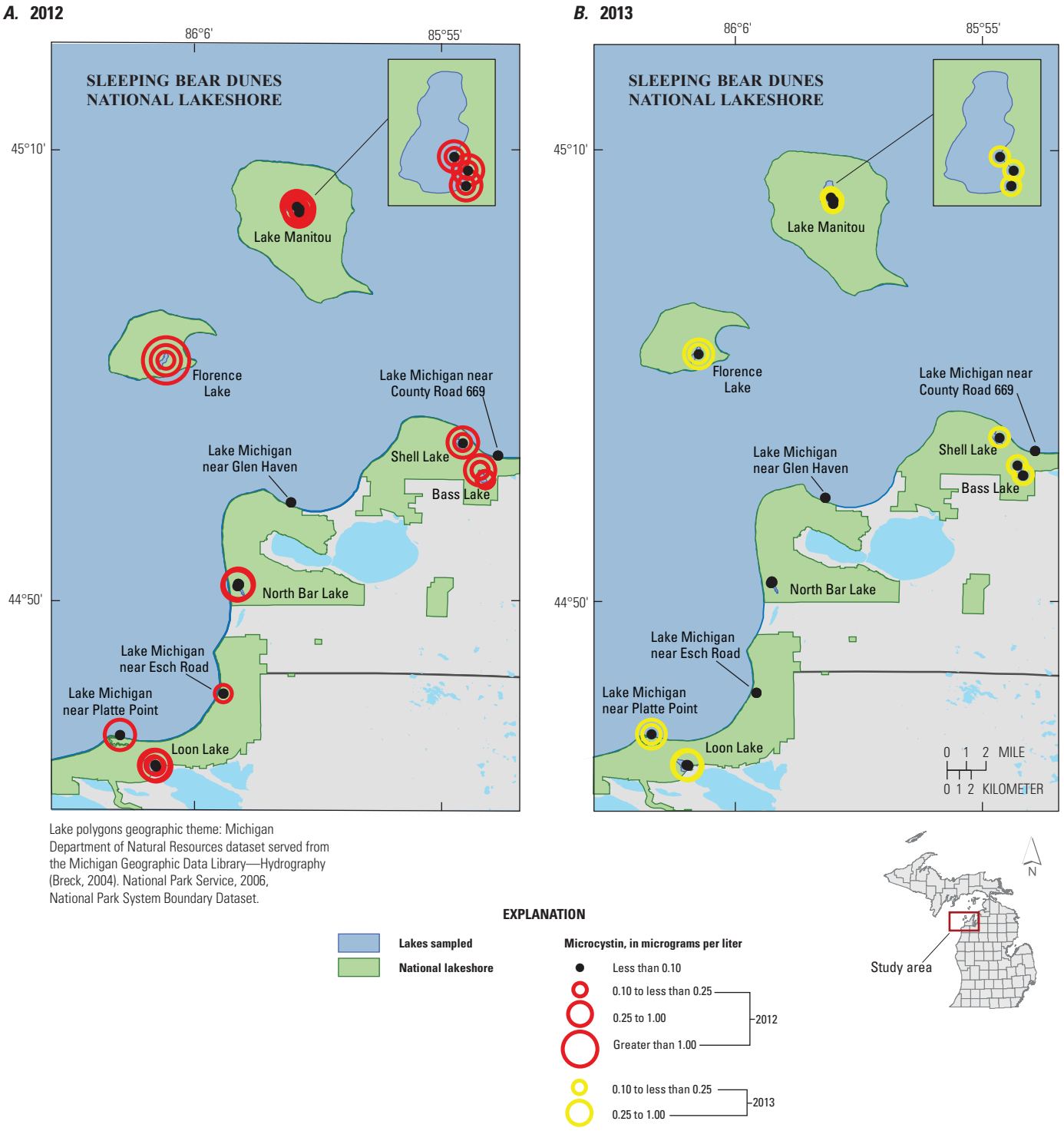


Figure 8. Enzyme-linked immunosorbent assay microcystin results for lakes at Sleeping Bear Dunes National Lakeshore, 2012–13.

To assess if microcystin concentrations varied by study area, water samples were collected at different times throughout the summer (two to three samples). The differences in microcystin concentrations in 2012 and 2013 are shown in figure 9. In 2012 and 2013, the highest microcystin concentrations were detected from July through September. Microcystin concentrations, as well as the number of detections for ISRO and SLBE, were generally higher in 2012 compared to 2013, whereas PIRO had a higher number of microcystin detections in 2013 (table 6).

All the samples analyzed had total microcystin concentrations less than the 10 µg/L WHO recreational water recommendation. The EPA 10-day health advisory for microcystin in drinking water for children less than 6-years old (0.3 µg/L) was exceeded in approximately 10 percent of the samples (21 out of 211 samples). One sample exceeded the EPA drinking water 10-day health advisory of 1.6 µg/L for school-age children through adults (U.S. Environmental Protection Agency, 2015b).

The presence of microcystins was lake specific. Within a single lake on the same date, microcystin concentrations were fairly consistent; however, when comparing concentrations of microcystin among lakes within a park, the presence and concentration of microcystin could be quite variable on a given date, particularly at ISRO and SLBE. The majority of microcystin detections and higher concentrations were detected on inland lakes in SLBE, potentially because of increased nitrogen concentrations at those lakes (Beaver and others, 2014) or because of higher TN:TP ratios.

Although within-season sampling is limited, results indicated a seasonal temporal change toward higher microcystin concentrations and frequency of detection later in the summer. Typically, these results are because of increased sunlight and higher water temperatures that are more optimal for cyanobacterial growth (Beaver and others, 2014).

Visible blooms were not commonly noted during this study; however, when blooms were noted, microcystin concentrations were generally less than or near the MRL. Cyanotoxins are only produced by certain cyanobacteria and only under certain conditions. The factors that control cyanotoxin production are not fully understood and are complicated by movement of the algal bloom or cyanotoxins in the water column and across the lake. This study demonstrated that low level microcystin concentrations could be detected at many of the inland lakes even when blooms were not visible. This detection may be because cyanotoxins can be differentially transported in the dissolved-phase when natural cell senescence occurs, leading to situations where toxins may be present even if harmful algal blooms are not visible (Chorus and Bartram, 1999).

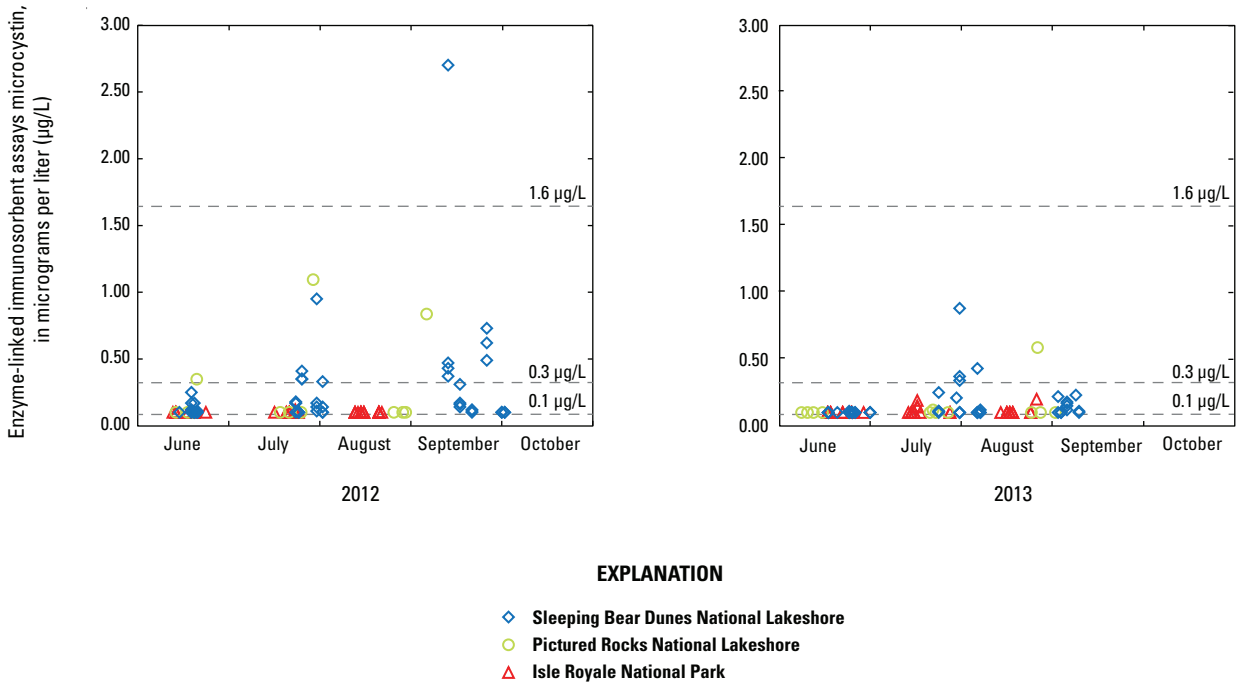


Figure 9. Enzyme-linked immunosorbent assay microcystin results for 2012 and 2013 at Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore.

Isle Royale National Park (ISRO)

ELISA results for microcystin concentrations for the six inland lakes at ISRO are presented in table 7 and figures 6 and 9.

Approximately 12 percent (10 of 86 samples) of the samples collected at ISRO had detectable microcystin concentrations (table 6). The highest microcystin concentrations at ISRO were detected in July 2012 (0.12 µg/L) at Lake Richie and in August 2013 (0.2 µg/L) at Lake Harvey (table 5, fig. 2).

In 2012, 45 samples were analyzed from ISRO and approximately 11 percent (5 samples) had detectable microcystin concentrations. Microcystin concentrations ranged from less than the MRL of 0.10 to 0.12 µg/L. The overall median concentration is less than the MRL of 0.10 µg/L. In 2013, 41 samples were analyzed from ISRO and approximately 12 percent (5 samples) had detectable microcystin concentrations. Concentrations ranged from less than the MRL of 0.10 to 0.20 µg/L. The overall median concentration in 2013 was less than the MRL of 0.10 µg/L (tables 5–6). In 2012 or 2013, no sample concentrations exceeded the EPA 10-day health advisory drinking water level for children preschool age and younger (0.3 µg/L) or for school-age children through adults (1.6 µg/L).

At Lake Richie, field crews visually observed algal blooms during eight sampling events and noted that algal blooms were not present during three events. No notation was made regarding the visual presence of algal blooms for 10 sampling events at Lake Richie. For seven of eight sampling events at Lake Richie in which algal blooms were recorded, microcystin concentrations were all less than the MRL; the concentration for the single microcystin detection was 0.19 µg/L (table 5). Microcystin concentrations were detected during two sampling events (0.14 µg/L and 0.15 µg/L) that algal blooms were noted as not observed (table 7).

Table 7. Microcystin results for samples collected at Isle Royale National Park, 2012–13.

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; µg/L, microgram per liter; E, East; CB, Chickenbone; ISRO, Isle Royale National Park; MI, Michigan; <, less than; NR, not recorded; W, west; S, south; NE, northeast; NW, northwest; Tr, trail; LeSage Lake is referred to as Lake LeSage]

USGS site name	USGS site number	Sample collection date	Sample collection time	ELISA microcystin, in µg/L	Visual presence of algal bloom
Chickenbone Lake near E CB Campground at ISRO, MI	480350088433001	6/21/2012	1245	< 0.10	NR
		7/23/2012	1555	0.10	NR
		8/14/2012	1055	< 0.10	NR
		6/20/2013	1200	< 0.10	NR
		7/20/2013	1215	< 0.10	NR
		8/18/2013	1250	< 0.10	NR
Chickenbone Lake near Old Portage at Isle Royale, MI	480429088431001	6/21/2012	1155	< 0.10	NR
		7/23/2012	1710	0.10	NR
		8/14/2012	1250	< 0.10	NR
		6/20/2013	1115	< 0.10	NR
		7/30/2013	1120	< 0.10	NR
		8/18/2013	1200	< 0.10	NR
Chickenbone Lake near W CB Campground at ISRO, MI	480426088415401	6/21/2012	1225	< 0.10	NR
		7/23/2012	1645	< 0.10	NR
		8/14/2012	1225	< 0.10	NR
		6/20/2013	1135	< 0.10	NR
		7/30/2013	1140	< 0.10	NR
		8/18/2013	1225	< 0.10	NR
Lake Ahmik near Portage at Isle Royale, MI	480856088322601	6/19/2013	1206	< 0.10	NR
		7/18/2013	1040	< 0.10	NR
		8/19/2013	1040	< 0.10	NR

Table 7. Microcystin results for samples collected at Isle Royale National Park, 2012–13.—Continued

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; µg/L, microgram per liter; E, East; CB, Chickenbone; ISRO, Isle Royale National Park; MI, Michigan; <, less than; NR, not recorded; W, west; S, south; NE, northeast; NW, northwest; Tr, trail; LeSage Lake is referred to as Lake LeSage]

USGS site name	USGS site number	Sample collection date	Sample collection time	ELISA microcystin, in µg/L	Visual presence of algal bloom
Lake Ahmik near South Shore at Isle Royale, MI	480856088322001	6/19/2013	1218	< 0.10	NR
		7/18/2013	0950	< 0.10	NR
		8/19/2013	1055	< 0.10	NR
Lake Ahmik near West End at Isle Royale, MI	480841088323401	6/19/2013	1235	< 0.10	NR
		7/18/2013	1005	< 0.10	NR
		8/19/2013	1120	< 0.10	NR
Lake Desor near S Desor Campground at Isle Royale, MI	475814088582001	6/25/2012	1350	< 0.10	NR
		7/22/2012	1240	< 0.10	NR
		7/22/2012	1410	< 0.10	NR
		8/23/2012	1130	< 0.10	NR
		6/19/2013	1310	< 0.10	NR
		8/16/2013	1420	< 0.10	NR
Lake Harvey near NE of Lake at Isle Royale, MI	480308088471401	6/14/2012	1245	< 0.10	NR
		7/18/2012	1330	< 0.10	NR
		8/15/2012	1225	< 0.10	NR
		7/1/2013	1200	< 0.10	NR
		7/16/2013	1155	< 0.10	NR
		8/28/2013	1325	0.20	NR
Lake LeSage near NE end of Lake at Isle Royale, MI	480338088415901	6/21/2012	1635	< 0.10	NR
		7/23/2012	1330	< 0.10	NR
		8/16/2012	1200	< 0.10	NR
Lake LeSage near NW Portage at Isle Royale, MI	480318088430801	6/21/2012	1615	< 0.10	NR
		7/23/2012	1255	< 0.10	NR
		8/16/2012	1140	< 0.10	NR
Lake LeSage near South Portage at Isle Royale, MI	480317088422601	6/21/2012	1625	< 0.10	NR
		7/23/2012	1315	< 0.10	NR
		8/16/2012	1305	< 0.10	NR
Lake Richie at Moskey Portage Isle Royale, MI	48030888410001	8/16/2012	1410	< 0.10	NR
		8/22/2012	1300	< 0.10	Yes
Lake Richie near Bedrock Beach at Isle Royale, MI	480305088410601	6/15/2012	1100	< 0.10	NR
		7/25/2012	1145	0.12	NR
		8/22/2012	1310	< 0.10	Yes
		6/27/2013	1240	< 0.10	No
		7/19/2013	1335	0.15	No
		8/26/2013	1040	< 0.10	Yes

Table 7. Microcystin results for samples collected at Isle Royale National Park, 2012–13.—Continued

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; µg/L, microgram per liter; E, East; CB, Chickenbone; ISRO, Isle Royale National Park; MI, Michigan; <, less than; NR, not recorded; W, west; S, south; NE, northeast; NW, northwest; Tr, trail; LeSage Lake is referred to as Lake LeSage]

USGS site name	USGS site number	Sample collection date	Sample collection time	ELISA microcystin, in µg/L	Visual presence of algal bloom
Lake Richie near Canoe Campground at Isle Royale, MI	480237088415701	6/15/2012	1145	< 0.10	NR
		7/25/2012	1210	< 0.10	NR
		8/22/2012	1335	< 0.10	Yes
		6/27/2013	1300	< 0.10	Yes
		7/19/2013	1310	0.19	Yes
		8/26/2013	1100	< 0.10	NR
Lake Richie near Indian Portage Tr at Isle Royale, MI	480155088412101	6/15/2012	1410	< 0.10	NR
		7/25/2012	1230	< 0.10	NR
		8/22/2012	1300	< 0.10	Yes
		8/22/2012	1350	< 0.10	NR
		6/27/2013	1330	< 0.10	NR
		7/19/2013	1140	0.14	No
		8/26/2013	1125	< 0.10	Yes
Sargent Lake near NE end of Lake at Isle Royale, MI	480557088391001	7/26/2012	1400	0.10	NR
		8/17/2012	1344	< 0.10	NR
		6/24/2013	1530	< 0.10	NR
		7/17/2013	1405	< 0.10	NR
		8/20/2013	1120	< 0.10	NR
Sargent Lake near NW end of Lake at Isle Royale, MI	480518088401401	6/19/2012	1600	< 0.10	NR
		7/26/2012	1420	< 0.10	NR
		8/17/2012	1415	< 0.10	NR
		6/24/2013	1500	< 0.10	NR
		7/17/2013	1345	< 0.10	NR
		8/20/2013	1300	0.10	NR
Sargent Lake near S Basin Portage at Isle Royale, MI	480535088390901	6/19/2012	1545	< 0.10	NR
		7/26/2012	1230	0.11	NR
		8/17/2012	1200	< 0.10	NR
		6/24/2013	1345	< 0.10	NR
		7/17/2013	1230	< 0.10	NR
		8/20/2013	1145	< 0.10	NR

Pictured Rocks National Lakeshore (PIRO)

Microcystin levels for the four inland lakes at PIRO are listed in table 8 and shown in figures 7 and 9. Approximately 21 percent of the samples (5 of 24 samples) collected at PIRO had detectable microcystin concentrations. Trappers Lake (fig. 7) was the only location with detectable microcystin in 2012 and 2013. In 2012, microcystin was detected during all three sampling events, with the highest concentration detected in July 2012 (1.1 µg/L) (table 5).

In 2012, 12 samples were analyzed from PIRO, 25 percent of the samples (3 samples) had detectable microcystin concentrations that ranged from less than the MRL of 0.10 to 1.10 µg/L. The overall median concentration was less than the MRL of 0.10 µg/L. In 2013, approximately 17 percent (2 samples) of the 12 samples analyzed had detectable levels of microcystin. Concentrations ranged from less than 0.10 to 0.59 µg/L. The median concentration was less than the MRL of 0.10 µg/L (table 6).

In 2012 and 2013, approximately 17 percent of samples from PIRO exceeded the EPA 10-day health advisory drinking-water level for children preschool age and younger (0.3 µg/L), and no samples exceeded the health advisory for school-age children through adults (1.6 µg/L). Four samples collected at Trappers Lake exceeded the drinking-water advisory for children preschool age and younger; with three exceedances in 2012 and one exceedance in 2013 (table 8).

Field crews visually observed algal blooms during three sampling events; two occasions at Trappers Lake in June and July 2012 and one occasion at Miners Lake (fig. 3) in August 2013. No notation was made regarding the visual presence of algal blooms for the remaining sampling events. Microcystin concentrations at Miners Lake in August 2013 were less than the MRL; however, in 2012 and 2013, the visual presence of algal blooms at Trappers Lake was consistent with microcystin detections above 0.3 µg/L (table 8).

Table 8. Microcystin results for samples collected at Pictured Rocks National Lakeshore, 2012–13.

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; µg/L, microgram per liter; SC, south-central; MI, Michigan; <, less than; NR, not recorded; E, east; SW, southwest]

USGS site name	USGS site number	Sample collection date	Sample collection time	ELISA microcystin, in µg/L	Visual presence of algal bloom
Beaver Lake near SC Shore at Pictured Rocks, MI	463330086204001	6/21/2012	1350	< 0.10	NR
		7/20/2012	1326	< 0.10	NR
		8/30/2012	1051	< 0.10	NR
		6/17/2013	1120	< 0.10	NR
		7/29/2013	1110	< 0.10	NR
		9/3/2013	1400	< 0.10	NR
Grand Sable Lake near E Shore at Pictured Rocks, MI	463835086015301	6/19/2012	2038	< 0.10	NR
		7/27/2012	1236	< 0.10	NR
		8/31/2012	1310	< 0.10	NR
		6/12/2013	1345	< 0.10	NR
		7/25/2013	1300	< 0.10	NR
		8/29/2013	1308	< 0.10	NR
Miners Lake near SW Shore at Pictured Rocks, MI	462846086321301	6/15/2012	1136	< 0.10	NR
		7/23/2012	1130	< 0.10	NR
		8/27/2012	1218	< 0.10	NR
		6/10/2013	1140	< 0.10	NR
		7/23/2013	1210	< 0.10	NR
		8/26/2013	1245	< 0.10	Yes
Trappers Lake near Campground at Pictured Rocks, MI	463516086185201	6/22/2012	1413	0.35	Yes
		7/31/2012	1250	1.10	Yes
		9/7/2012	1319	0.84	NR
		6/14/2013	1330	< 0.10	NR
		7/24/2013	1225	0.12	NR
		8/28/2013	1300	0.59	NR

Sleeping Bear Dunes National Lakeshore (SLBE)

Microcystin levels for the six inland lakes and four Lake Michigan sampling locations at SLBE are presented in table 9 and figures 8–9. Approximately 50 percent (50 of 101 samples) of the samples collected at SLBE in 2012 and 2013 had detectable levels of microcystin. The highest microcystin concentrations were measured from the end of August through September in 2012 and in August 2013 (table 9).

In 2012, 54 samples were analyzed from SLBE. Of the 54 samples analyzed, 42 samples were collected from inland lakes, and 12 samples were collected from Lake Michigan. Approximately 57 percent of the samples (31 of 54 samples) in 2012 had detectable microcystin concentrations that ranged from less than the MRL of 0.10 to 2.70 µg/L. The overall median concentration at SLBE was just above the MRL, 0.12 µg/L. The highest inland lake microcystin concentration was 2.70 µg/L and was collected at Florence Lake in September 2012 (table 5). Only two of the four Lake Michigan sites had detectable concentrations of microcystin in 2012. The highest concentration among the Lake Michigan sites was 0.33 µg/L and was collected at the site near Platte Point in August, 2012 (table 5).

In 2013, 47 microcystin samples were analyzed that included 35 samples from inland lakes, and 12 samples from Lake Michigan. Approximately 40 percent of the samples (19 of 47 samples) in 2013 had detectable microcystin concentrations that ranged from less than the MRL of 0.10 to 0.88 µg/L. The overall median concentration at SLBE in 2013 was less than the MRL of 0.10 µg/L. The highest inland lake concentration was recorded at Loon Lake in August 2013 (0.88 µg/L) (table 5). Only one of the four Lake Michigan sites had detectable concentrations of microcystin in 2013; the highest concentration among all SLBE sampling sites was 0.43 µg/L at the Lake Michigan site near Platte Point in August, 2013 (table 5, table 9).

In 2012, 22 percent of samples were above the EPA 10-day health advisory drinking-water level for children preschool age and younger (21 samples), and 2 percent of samples (1 sample) exceeded the guideline for school-age children through adults (1.6 µg/L). In 2013, 9 percent of samples were above the EPA 10-day health advisory drinking water level for children preschool age and younger (0.3 µg/L), and no samples exceeded the guideline for school-age children through adults (1.6 µg/L). No observations were recorded if lake microcystin samples were collected while an algal bloom was visibly present at SLBE.

Table 9. Microcystin results for samples collected at Sleeping Bear Dunes National Lakeshore, 2012–13.

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; µg/L, microgram per liter; SBDNL, Sleeping Bear Dunes National Lakeshore; MI, Michigan; <, less than; SE, southeast; Lake Manitou is referred to as Manitou Lake]

USGS site name	USGS site number	Sample collection date	Sample collection time	ELISA microcystin, in µg/L
Bass Lake North near North Shore at SBDNL, MI	445543085530801	6/19/2012	1710	0.25
		7/24/2012	1645	0.18
		9/17/2012	1625	0.14
		6/25/2013	1645	0.11
		8/8/2013	1345	< 0.10
		9/6/2013	1600	0.18
Bass Lake North near SE Boat Launch at SBDNL, MI	445518085525301	6/19/2012	1640	0.17
		7/24/2012	1625	0.17
		9/17/2012	1600	0.16
		6/25/2013	1550	< 0.10
		8/8/2013	1250	0.10
		9/6/2013	1530	0.12
Bass Lake North near Glen Lake Benchmark at SBDNL, MI	445518085525401	6/19/2012	1625	0.12
		7/24/2012	1630	0.17
		9/17/2012	1610	0.17
		6/25/2013	1610	< 0.10
		8/8/2013	1310	0.12
		9/6/2013	1540	0.15

Table 9. Microcystin results for samples collected at Sleeping Bear Dunes National Lakeshore, 2012–13.—Continued

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; µg/L, microgram per liter; SBDNL, Sleeping Bear Dunes National Lakeshore; MI, Michigan; <, less than; SE, southeast; Lake Manitou is referred to as Manitou Lake]

USGS site name	USGS site number	Sample collection date	Sample collection time	ELISA microcystin, in µg/L
Florence Lake near Boat Launch at SBDNL, MI	450037086070801	6/21/2012	1250	0.11
		7/31/2012	1330	0.95
		9/13/2012	1315	2.70
		6/18/2013	1200	< 0.10
		7/25/2013	1230	0.25
		9/9/2013	1155	0.23
Lake Michigan near County Road 669 at SBDNL, MI	445623085522101	6/20/2012	1445	< 0.10
		8/2/2012	1115	< 0.10
		10/2/2012	1600	< 0.10
		6/27/2013	1320	< 0.10
		8/7/2013	1315	< 0.10
		9/4/2013	1000	< 0.10
Lake Michigan near Esch Road at SBDNL, MI	444546086043501	6/19/2012	1400	< 0.10
		8/2/2012	0930	0.14
		10/1/2012	1720	< 0.10
		6/26/2013	1635	< 0.10
		8/7/2013	1045	< 0.10
		9/3/2013	1120	< 0.10
Lake Michigan near Glen Haven at SBDNL, MI	445418086013401	6/20/2012	1545	< 0.10
		8/2/2012	1240	< 0.10
		10/2/2012	1630	< 0.10
		6/27/2013	1450	< 0.10
		8/7/2013	1200	< 0.10
		9/4/2013	1100	< 0.10
Lake Michigan near Platte Point at SBDNL, MI	444355086091101	6/19/2012	1150	< 0.10
		8/2/2012	0900	0.33
		10/1/2012	1645	< 0.10
		6/26/2013	1500	< 0.10
		8/7/2013	1000	0.43
		9/3/2013	0945	0.22
Loon Lake near Boat Launch at SBDNL, MI	444232086073501	6/20/2012	1645	< 0.10
		7/26/2012	1855	0.35
		9/21/2012	1400	0.11
		6/26/2013	1415	< 0.10
		8/1/2013	1635	0.88

Table 9. Microcystin results for samples collected at Sleeping Bear Dunes National Lakeshore, 2012–13.—Continued

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; µg/L, microgram per liter; SBDNL, Sleeping Bear Dunes National Lakeshore; MI, Michigan; <, less than; SE, southeast; Lake Manitou is referred to as Manitou Lake]

USGS site name	USGS site number	Sample collection date	Sample collection time	ELISA microcystin, in µg/L
Loon Lake near Cove at Sleeping Bear Dunes NL, MI	444235086073701	6/20/2012	1625	< 0.10
		7/26/2012	1840	0.35
		9/21/2012	1335	< 0.10
		6/26/2013	1420	< 0.10
		8/1/2013	1625	0.34
Loon Lake near Platte River Inlet at SBDNL, MI	444235086074001	6/20/2012	1615	0.17
		7/26/2012	1830	0.41
		9/21/2012	1325	0.12
		6/26/2013	1410	< 0.10
		8/1/2013	1610	0.37
Manitou Lake near Boat Launch at SBDNL, MI	450714086011301	6/21/2012	2020	< 0.10
		7/31/2012	2040	0.14
		9/13/2012	2025	0.37
		6/18/2013	2005	< 0.10
		7/25/2013	1845	0.11
		9/10/2013	1405	< 0.10
Manitou Lake near Midpoint at SBDNL, MI	450722086011201	6/21/2012	2040	< 0.10
		7/31/2012	2100	0.17
		9/13/2012	2010	0.43
		6/18/2013	1950	< 0.10
		7/25/2013	1900	0.11
		9/10/2013	1330	0.11
Manitou Lake near Point at SBDNL, MI	450729086011901	6/21/2012	2100	< 0.10
		7/31/2012	2025	0.11
		9/13/2012	2000	0.47
		6/18/2013	1935	< 0.10
		7/25/2013	1920	0.10
North Bar Lake near Boat Launch at SBDNL, MI	445037086035301	6/20/2012	1345	< 0.10
		7/25/2012	1445	< 0.10
		9/26/2012	1825	0.73
		7/2/2013	1300	< 0.10
		8/1/2013	1215	< 0.10
North Bar Lake near North Shore at SBDNL, MI	445039086035501	6/20/2012	1340	< 0.10
		7/25/2012	1450	< 0.10
		9/26/2012	1815	0.62
		7/2/2013	1315	< 0.10
		8/1/2013	1205	< 0.10

Table 9. Microcystin results for samples collected at Sleeping Bear Dunes National Lakeshore, 2012–13.—Continued

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; µg/L, microgram per liter; SBDNL, Sleeping Bear Dunes National Lakeshore; MI, Michigan; <, less than; SE, southeast; Lake Manitou is referred to as Manitou Lake]

USGS site name	USGS site number	Sample collection date	Sample collection time	ELISA microcystin, in µg/L
North Bar Lake near Outlet at SBDNL, MI	445034086035701	6/20/2012	1330	< 0.10
		7/25/2012	1420	< 0.10
		9/26/2012	1800	0.49
		7/2/2013	1400	< 0.10
		8/1/2013	1155	< 0.10
Shell Lake near East Shore Boat Launch at SBDNL, MI	445657085535501	6/15/2012	1500	0.10
		7/24/2012	1300	< 0.10
		9/17/2012	1725	0.31
		6/21/2013	1410	< 0.10
		7/31/2013	1645	0.21
		9/6/2013	1300	0.17

Within-Lake Microcystin Variability

To address the potential for spatial and temporal variability in microcystin concentrations that may occur within a single lake, samples from multiple sites at select lakes were collected at ISRO and SLBE. Samples were collected at three locations at Lake Manitou, Bass Lake, North Bar Lake, and Loon Lake in SLBE (fig. 4) and collected at least three locations at ISRO lakes (Chickenbone Lake, Lake Ahmik, LeSage Lake, Lake Richie, and Sargent Lake). Samples were not collected from multiple sites at PIRO lakes because of sampling logistics.

Isle Royale National Park (ISRO)

The microcystin concentrations within or among ISRO lakes were similar, temporally and spatially; with the exception of Lake Richie (greatest difference between sample concentrations was 0.09 µg/L) (fig. 10). Lake Richie had the highest frequency of microcystin detections than all other ISRO lakes (8 percent of samples with detectable microcystin in 2012; 33 percent in 2013); however, Lake Harvey had the highest microcystin detection (0.20 µg/L) (table 5, table 7). Within-lake spatial variability at Lake Richie appears to be minimal, with peak concentrations detected in July 2012 and 2013 at all sampling locations. Only one location was monitored at Lake Harvey; thus, spatial variability was not assessed (fig. 10, table 7).

Pictured Rocks National Lakeshore (PIRO)

Water samples were collected from only one location at each of the study lakes within PIRO; therefore, spatial variability was not assessed (fig. 11, table 8). Trappers Lake was the only lake within PIRO where microcystin was detected during the study period. The highest concentrations of microcystin were detected during late July in 2012 (1.10 µg/L) and in late August 2013 (0.59 µg/L) (table 5, table 8).

Sleeping Bear Dunes National Lakeshore (SLBE)

At SLBE, within-lake spatial variability was similar at the four lakes where multiple site locations were sampled (fig. 12, table 9). Most microcystin concentrations at each lake were within 0.01 to 0.10 µg/L. The greatest difference between sample concentrations was 0.54 µg/L collected at Loon Lake during the August 1, 2013, sampling event (table 9).

Unlike the other study areas, SLBE had greater between lake variability and differences in temporal patterns of microcystin. Lake Manitou and North Bar Lake indicated similar temporal patterns and ELISA microcystin concentrations, (with low concentrations throughout the study and a single peak in concentration in September 2012) (fig. 12). For Bass Lake, the peak concentration for two of the three sites occurred in June 2012; however, in 2013, the concentrations for all three Bass Lake sites were lowest in June and highest in September. At Loon Lake, concentrations were highest during the sampling in July 2012 and August 2013, with concentrations near or less than the MRL at all other sampling dates.

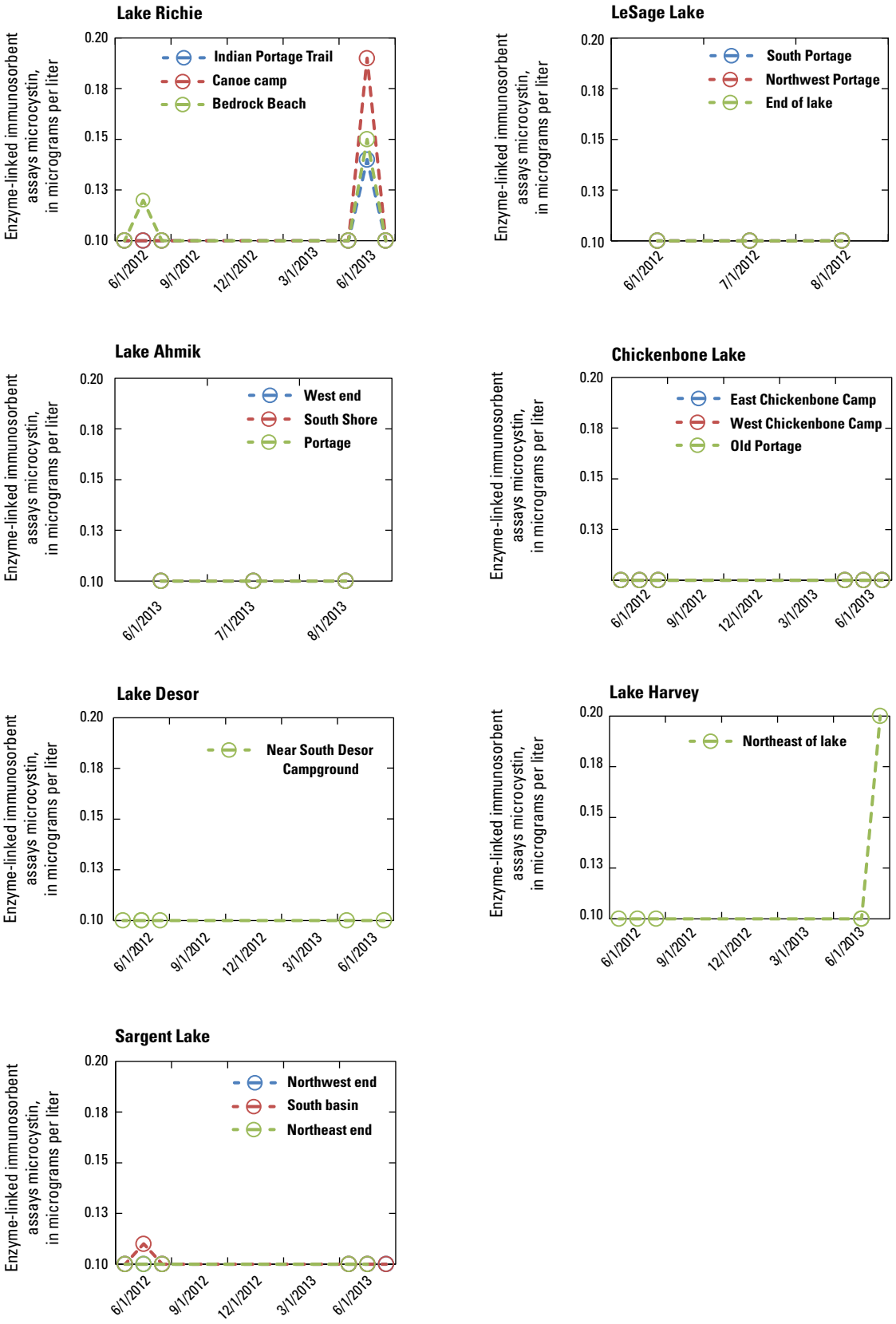


Figure 10. Temporal and spatial variability of microcystin concentrations for Isle Royale National Park.

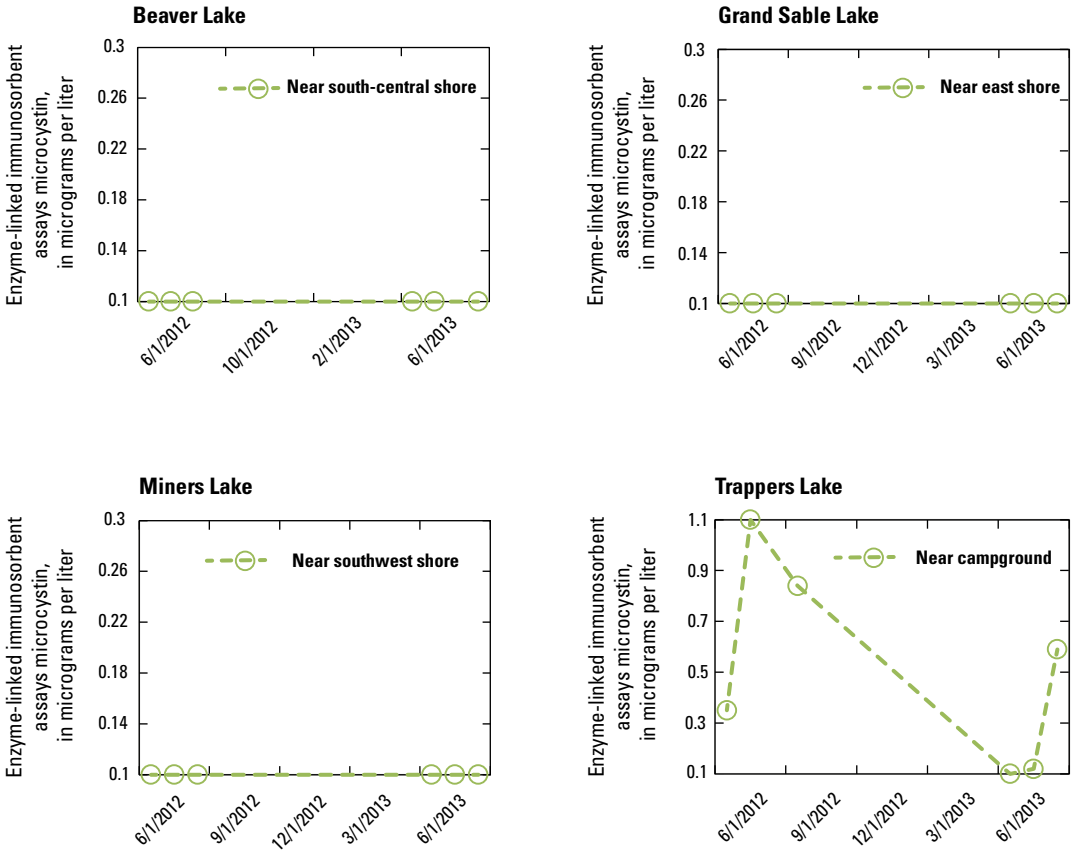


Figure 11. Temporal variability of microcystin concentrations for Pictured Rocks National Lakeshore.

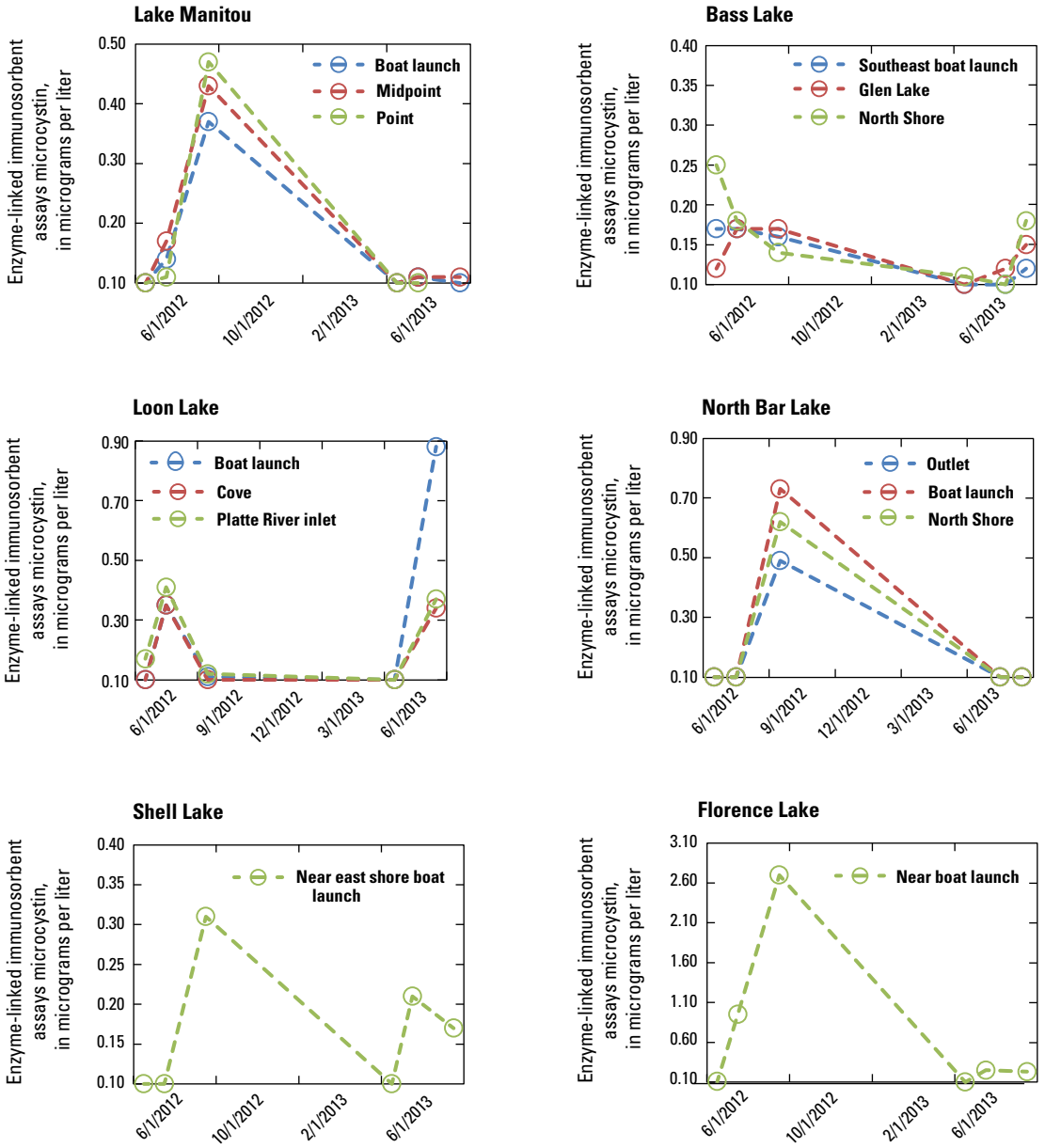


Figure 12. Temporal and spatial variability of microcystin concentrations for Sleeping Bear Dunes National Lakeshore.

Cyanotoxin Results Using the Liquid Chromatography/Tandem Mass Spectrometry Method

A subset of samples (n = 39; 18 percent) were analyzed by LC/MS/MS for toxins from 7 lakes in 2012 and 12 lakes in 2013 (table 10).

The samples analyzed using LC/MS/MS were purposely biased towards lakes with greater microcystin detections by ELISA (74 percent detection frequency) for confirmation of microcystin detections. The LC/MS/MS method also was used to assess the occurrence of anatoxin-a, as well as differentiation of microcystin congeners. No detections were observed above the MRL for anatoxin-a, cylindrospermopsin, domoic acid, nodularin-R, and okadaic acid.

In 2012, samples were analyzed from 1 location at PIRO and 12 locations at SLBE. Based on the low concentrations of microcystin, ISRO was not included in the 2012 LC/MS/MS analyses. Out of 16 samples analyzed, 15 samples had at least 1 microcystin congener detected (table 10). Microcystin-LR was the most frequently detected congener (7 out of 16 samples). Microcystin-WR and microcystin-YR were each detected in 2 out of 16 samples. Microcystin congeners greater than the MRL were added together to estimate total microcystin for each sample. Total concentration estimates ranged from less than the MRL to 0.69 µg/L, with a median value of 0.26 µg/L and a mean value of 0.31 µg/L (table 10).

In 2013, samples were collected and analyzed from 6 locations at ISRO, 1 location at PIRO, and 10 locations at SLBE. A total of 21 samples were analyzed in 2013; 6 samples had at least 1 detectable microcystin congener. Similar to 2012, microcystin-LR was the most frequently detected congener (table 10). Total microcystin concentration estimates for 2013 ranged from less than the MRL to 0.35 µg/L. The median and mean values of the six samples with detectable values were 0.20 and 0.22 µg/L, respectively.

In general, the microcystin results between the ELISA and LC/MS/MS methods were similar with a coefficient of determination (R-squared) of 0.772 (fig. 13), which was derived from a linear regression (Helsel and Hirsch, 2002). Note that the trendline in figure 13 does not include the outlier of 2.70 µg/L (table 5) collected at Florence Lake at SLBE in September 2012. Although LC/MS/MS includes a larger suite of algal toxins, only microcystin congeners were detected. Total microcystin concentrations were similar, although the ELISA results tended to be higher than the summation of LC/MS/MS microcystin congeners (fig. 13, table 10). The higher ELISA results may be because not all congeners are included in the LC/MS/MS method, and the ELISA used for microcystins is reactive with the ADDA functional group ([*2S,3S,8S,9S*]-3-amino-9-methoxy-2,6,8-trimethyl-10-phenyl-deca-4[*E*],6[*E*]-dienoic acid) common to all microcystins and nodularins (Chorus and Bartram, 1999; Graham and others, 2010), making the assay cross-reactivities among the microcystins tested to date fairly similar (for example, approximately 80 to 120 percent compared with microcystin-LR) (Abraxis, 2017; Fischer and others, 2001).

Quality Control Results

Most of the environmental samples for which field replicates were collected had nondetectable concentrations of microcystin using the ELISA method. For samples with detectable concentrations of microcystin using the ELISA method (6 samples), the mean relative percent difference was 10 percent for field replicates.

Two of the three samples analyzed as laboratory replicates using the LC/MS/MS method resulted in nondetects for all toxins. One sample was positive for microcystins-LA and microcystins-LR, with a mean relative percent standard deviation of 17 percent. The two samples with nondetects were spiked in the laboratory with a toxin standard mix of 1.0 µg/L equivalent for each toxin, with a mean percent recovery of 111 percent, which is within the acceptable limits of 80–120 percent for the laboratory (Magnusson and Örnemark, 2014).

All field blanks had reported microcystin concentrations of less than the MRL. Quality control results for field blanks and replicates are available in the USGS National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN.

Table 10. Results of the liquid chromatography/tandom mass spectrometry analysis for Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore , 2012–13.

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; µg/L, microgram per liter; MCLA, microcystin-LA; MCLY, microcystin-LY; MCLR, microcystin-LR; MCWR, microcystin-WR; MCYR, microcystin-YR; MCHtYR, microcystin-HtYR; MCLW, microcystin-LW; MCRR, microcystin-RR; LC/MS/MS, liquid chromatography/tandem mass spectrometry; MC, microcystin; W, west; CB, Chickenbone; ISRO, Isle Royale National Park; MI, Michigan; <, less than; ND, not detected; NE, northeast; SBDNL, Sleeping Bear Dunes National Lakeshore; NL, National Lakeshore; Lake Manitou is referred to as Manitou Lake]

USGS site name	USGS site number	Collection date	ELISA microcystin, in µg/L	MCLA, in µg/L	MCLY, in µg/L	MCLR, in µg/L	MCWR, in µg/L	MCYR, in µg/L	MCHtYR, in µg/L	MCLW, in µg/L	MCRR, in µg/L	Sum of microcystins measured (LC/MS/MS, in µg/L)	Difference between ELISA and sum of LC/MS/MS MC/ nodularins
Isle Royale National Park													
Chickenbone Lake near W CB Campground at ISRO, MI	480426088415401	7/30/2013	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Chickenbone Lake near W CB Campground at ISRO, MI	480426088415401	8/18/2013	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Lake Ahmik near Portage at Isle Royale, MI	480856088322601	6/19/2013	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Lake Ahmik near South Shore at Isle Royale, MI	480856088322001	7/18/2013	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Lake Ahmik near South Shore at Isle Royale, MI	480856088322001	8/19/2013	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Lake Harvey near NE of Lake at Isle Royale, MI	480308088471401	8/28/2013	0.20	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Lake Richie near Bedrock Beach at Isle Royale, MI	480305088410601	7/19/2013	0.15	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Lake Richie near Bedrock Beach at Isle Royale, MI	480305088410601	8/26/2013	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Lake Richie near Canoe Campground at Isle Royale, MI	480237088415701	7/19/2013	0.19	<0.10	<0.10	<0.10	<0.10	0.10	<0.10	< 0.30	<0.10	0.1	0.09
Pictured Rocks National Lakeshore													
Trappers Lake near Campground at Pictured Rocks, MI	463516086185201	6/22/2012	0.35	0.16	< 0.10	0.11	< 0.10	< 0.10	< 0.10	< 0.30	< 0.10	0.27	0.08
Trappers Lake near Campground at Pictured Rocks, MI	463516086185201	7/31/2012	1.05	0.26	<0.10	0.42	<0.10	<0.10	<0.10	< 0.30	<0.10	0.68	0.37
Trappers Lake near Campground at Pictured Rocks, MI	463516086185201	9/7/2012	0.84	0.16	<0.10	0.25	<0.10	<0.10	<0.10	< 0.30	<0.10	0.41	0.43
Trappers Lake near Campground at Pictured Rocks, MI	463516086185201	8/28/2013	0.59	0.13	<0.10	0.16	<0.10	<0.10	<0.10	< 0.30	<0.10	0.29	0.3

Table 10. Results of the liquid chromatography/tandom mass spectrometry analysis for Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore , 2012–13.—Continued

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; µg/L, microgram per liter; MCLA, microcystin-LA; MCLY, microcystin-LY; MCLR, microcystin-LR; MCWR, microcystin-WR; MCYR, microcystin-YR; MCHtYR, microcystin-HtYR; MCLW, microcystin-LW; MCRR, microcystin-RR; LC/MS/MS, liquid chromatography/tandem mass spectrometry; MC, microcystin; W, west; CB, Chickenbone; ISRO, Isle Royale National Park; MI, Michigan; <, less than; ND, not detected; NE, northeast; SBDNL, Sleeping Bear Dunes National Lakeshore; NL, National Lakeshore; Lake Manitou is referred to as Manitou Lake]

USGS site name	USGS site number	Collection date	ELISA microcystin, in µg/L	MCLA, in µg/L	MCLY, in µg/L	MCLR, in µg/L	MCWR, in µg/L	MCYR, in µg/L	MCHtYR, in µg/L	MCLW, in µg/L	MCRR, in µg/L	Sum of microcystins measured (LC/MS/MS, in µg/L)	Difference between ELISA and sum of LC/MS/MS MC/ nodularins
Sleeping Bear Dunes National Lakeshore													
Bass Lake North near North Shore at SBDNL, MI	445543085530801	9/6/2013	0.18	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Shell Lake near East Shore Boat Launch at SBDNL, MI	445657085535501	9/17/2012	0.31	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Shell Lake near East Shore Boat Launch at SBDNL, MI	445657085535501	7/31/2013	0.21	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Bass Lake North near Glen Lake Benchmark at SBDNL, MI	445518085525401	9/6/2013	0.15	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Florence Lake near Boat Launch at SBDNL, MI	450037086070801	7/31/2012	0.95	0.36	<0.10	<0.10	0.12	<0.10	<0.10	< 0.30	<0.10	0.48	0.47
Florence Lake near Boat Launch at SBDNL, MI	450037086070801	9/13/2012	2.71	0.69	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	0.69	2.02
Florence Lake near Boat Launch at SBDNL, MI	450037086070801	7/25/2013	0.25	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Lake Michigan near Platte Point at SBDNL, MI	444355086091101	8/2/2012	0.33	0.14	<0.10	0.12	<0.10	<0.10	<0.10	< 0.30	<0.10	0.26	0.07
Lake Michigan near Platte Point at SBDNL, MI	444355086091101	8/7/2013	0.43	<0.10	<0.10	0.19	<0.10	<0.10	<0.10	< 0.30	<0.10	0.19	0.24
Loon Lake near Boat Launch at SBDNL, MI	444232086073501	7/26/2012	0.35	0.10	<0.10	0.16	<0.10	<0.10	<0.10	< 0.30	<0.10	0.26	0.09
Loon Lake near Boat Launch at SBDNL, MI	444232086073501	8/1/2013	0.88	<0.10	<0.10	0.35	<0.10	<0.10	<0.10	< 0.30	<0.10	0.35	0.53
Loon Lake near Cove at Sleeping Bear Dunes NL, MI	444235086073701	7/26/2012	0.35	<0.10	<0.10	0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	0.1	0.25
Loon Lake near Cove at Sleeping Bear Dunes NL, MI	444235086073701	6/26/2013	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND

Table 10. Results of the liquid chromatography/tandom mass spectrometry analysis for Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore , 2012–13.—Continued

[USGS, U.S. Geological Survey; ELISA, enzyme-linked immunosorbent assay; µg/L, microgram per liter; MCLA, microcystin-LA; MCLY, microcystin-LY; MCLR, microcystin-LR; MCWR, microcystin-WR; MCYR, microcystin-YR; MCHtYR, microcystin-HtYR; MCLW, microcystin-LW; MCRR, microcystin-RR; LC/MS/MS, liquid chromatography/tandem mass spectrometry; MC, microcystin; W, west; CB, Chickenbone; ISRO, Isle Royale National Park; MI, Michigan; <, less than; ND, not detected; NE, northeast; SBDNL, Sleeping Bear Dunes National Lakeshore; NL, National Lakeshore; Lake Manitou is referred to as Manitou Lake]

USGS site name	USGS site number	Collection date	ELISA microcystin, in µg/L	MCLA, in µg/L	MCLY, in µg/L	MCLR, in µg/L	MCWR, in µg/L	MCYR, in µg/L	MCHtYR, in µg/L	MCLW, in µg/L	MCRR, in µg/L	Sum of microcystins measured (LC/MS/MS, in µg/L)	Difference between ELISA and sum of LC/MS/MS MC/ nodularins
Sleeping Bear Dunes National Lakeshore—Continued													
Loon Lake near Cove at Sleeping Bear Dunes NL, MI	444235086073701	8/1/2013	0.34	<0.10	<0.10	0.19	<0.10	<0.10	<0.10	< 0.30	<0.10	0.19	0.15
Loon Lake near Platte River Inlet at SBDNL, MI	444235086074001	7/26/2012	0.41	<0.10	<0.10	0.14	<0.10	<0.10	<0.10	< 0.30	<0.10	0.14	0.27
Loon Lake near Platte River Inlet at SBDNL, MI	444235086074001	8/1/2013	0.37	<0.10	<0.10	0.21	<0.10	<0.10	<0.10	< 0.30	<0.10	0.21	0.16
Manitou Lake near Boat Launch at SBDNL, MI	450714086011301	9/13/2012	0.37	<0.10	<0.10	<0.10	<0.10	0.15	<0.10	< 0.30	<0.10	0.15	0.22
Manitou Lake near Boat Launch at SBDNL, MI	450714086011301	6/18/2013	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
Manitou Lake near Midpoint at SBDNL, MI	450722086011201	9/13/2012	0.43	<0.10	<0.10	<0.10	<0.10	0.13	<0.10	< 0.30	<0.10	0.13	0.3
Manitou Lake near Point at Sleeping Bear Dunes NL, MI	450729086011901	9/17/2012	0.47	0.10	<0.10	<0.10	0.10	<0.10	<0.10	< 0.30	<0.10	0.2	0.27
North Bar Lake near Outlet at SBDNL, MI	445034086035701	9/26/2012	0.49	0.18	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	0.18	0.31
North Bar Lake near Boat Launch at SBDNL, MI	445037086035301	9/26/2012	0.73	0.4	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	0.4	0.33
North Bar Lake near Boat Launch at SBDNL, MI	445037086035301	7/2/2013	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	< 0.10	ND
North Bar Lake near North Shore at SBDNL, MI	445039086035501	9/26/2012	0.62	0.23	<0.10	<0.10	<0.10	<0.10	<0.10	< 0.30	<0.10	0.23	0.39

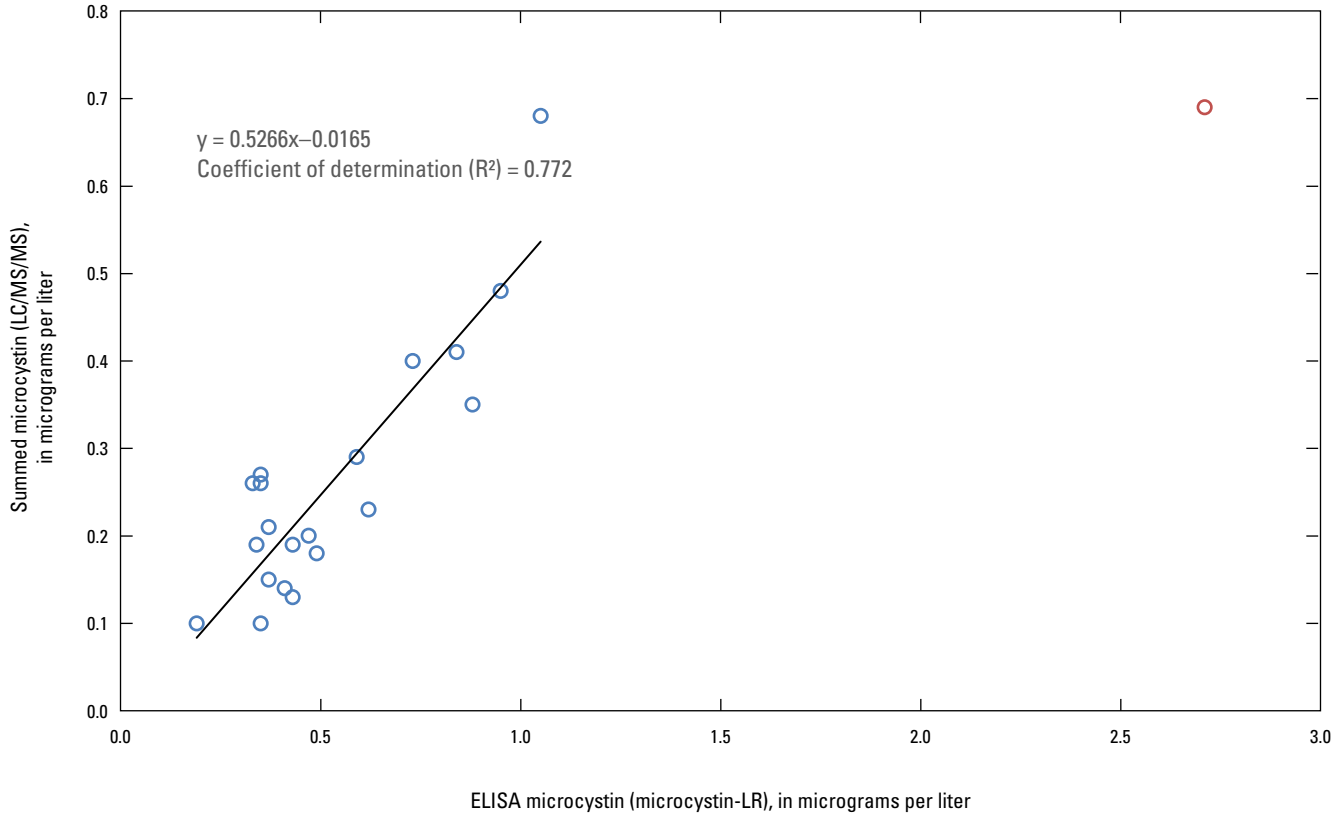


Figure 13. Comparison of total microcystin (by summation of liquid chromatography/tandem mass spectrometry [LC/MS/MS] congeners [y]) to enzyme-linked immunosorbent assay (ELISA) microcystin (x) results at Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore.

Nutrients and Chlorophyll *a* at National Park Service Lakes

Nutrients are essential for natural plant and animal growth; however, elevated nutrient concentrations in streams and lakes can trigger the growth of harmful algae, which can be potentially toxic to fish and other organisms, including humans (U.S. Geological Survey, 2014). Sixteen of the lakes included in this cyanotoxin study also were monitored by the NPS for a variety of water-quality monitoring parameters including TP, TN, chlorophyll *a*, and Secchi-disk transparency, which is a measure of water transparency. Water-quality data for each lake are presented in table 11. Nutrient and chlorophyll *a* samples were collected from the deepest areas of the lakes, whereas the samples collected for cyanotoxin analysis were collected in waist deep water near the shoreline from 0.5 to 1.0 meter below the water surface where people would be most likely to enjoy recreation or obtain water for drinking. However, for most sites, the nutrient and chlorophyll *a* samples were collected from each lake on the same day as cyanotoxin monitoring. The TP concentrations were, on average, highest at the ISRO lakes, whereas TN concentrations were highest at SLBE.

Mean lake concentrations of TP, TN, chlorophyll *a*, and water transparency were compared to the percentage of ELISA microcystin detections (fig. 14). Chlorophyll *a*, TP, and Secchi-disk transparency, when related to ELISA percent microcystin detection, resulted in an R-squared less than 0.045. The range of TP and chlorophyll *a* concentrations in this study may not have been large enough to fully characterize the relation between microcystin and nutrients, thus potentially impacting the relation between chlorophyll *a*, TP, and secchi-disk transparency to microcystins detections. However, TN and TN:TP ratio resulted in an R-squared of 0.269 and 0.340, respectively (2012 and 2013 combined dataset, derived from linear regression) (fig. 14). Results indicated a positive correlation overall when comparing TN to the percentage of microcystin detections for all the sites.

The average annual TN:TP ratios for the 16 lakes within the national park and national lakeshores study areas ranged from about 20 to 89 (table 11). The majority of the TN:TP ratios observed in this study are higher than the significant ranges identified in previous studies (Scott and others, 2013; Orihel and others, 2012). Nutrient ratios tended to be lower in samples collected from ISRO and PIRO compared to SLBE. However, Trappers Lake at PIRO had TN:TP ratios more similar to lakes at SLBE. The TN:TP ratios were compared with microcystin concentrations for those lakes that had microcystin detections using ELISA (greater than 0.1 µg/L) and for those lakes with nutrient data (figs. 14–15). Overall, the results indicated a slight increase (positive trendline) in percentage of microcystin concentrations with an increase in TN:TP ratio (figs. 14–15), most likely because of the few higher microcystin detections collected at Florence Lake (SLBE) and Trappers Lake (PIRO). A minimal overall upward trend (R-squared = 0.012) related increased TN:TP ratios to increased microcystin concentrations.

Scott and others (2013) reported that TN:TP ratio was the strongest predictor of microcystin. The highest microcystin concentrations were detected when the TN:TP ratio was less than 12 or greater than 23 (Scott and others, 2013). This determination is somewhat opposite of what was indicated at the NPS lakes in Michigan; however, in only two samples collected during this study were microcystin concentrations greater than 1 µg/L, which was the lowest value used in the model by Scott and others (2013). Trappers Lake (PIRO) and Florence Lake (SLBE) had some of the highest cyanotoxin concentrations as well as the some of the highest TN:TP ratios, contrary to previously published literature (Scott and others, 2013; Orihel and others, 2012).

Thus, even though the TN:TP ratios were high in this study, microcystin concentrations averaged approximately 0.16 µg/L (not much greater than the detection limit for ELISA at 0.10 µg/L), which may not be comparable to studies such as Scott and others (2013) where higher concentrations of microcystin were detected.

Potential Future Studies

This study provided a baseline to assess the current cyanotoxin occurrence and distribution at ISRO, PIRO, and SLBE. Future monitoring may be needed, however, because climate change can affect lake temperatures, thermal stratification, and nutrient delivery to these lakes. Climate change and human activities that increase nutrient inputs into the environment (for example, agriculture, wastewater discharge, and stormwater runoff) may encourage algal growth and potential for toxin production (Adrian and others, 2009).

A more comprehensive monitoring effort at SLBE inland lakes would help to further explain why microcystins were more frequently detected and found at higher concentrations at SLBE than the other study areas. As this study indicated, higher microcystin concentrations were often measured later in the summer; thus, the monitoring strategy could concentrate efforts during late summer when microcystin and other cyanotoxin concentrations would likely be at their highest. This study also highlights the fact that microcystin concentrations were detected even when algal blooms were not noted, and thus sampling during the presence and the absence of blooms would be beneficial and would aid in determining the driver(s) of cyanotoxin detections. A similar monitoring strategy also could be considered for Trappers Lake (PIRO), Lake Harvey (ISRO), Lake Richie (ISRO), and Sargent Lake (ISRO).

Table 11. Mean and standard deviations of lake water-quality data collected at Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore, 2012–13.

[µg/L, microgram per liter; mg/L, milligram per liter; TN:TP, total nitrogen to total phosphorus; NA, not available]

Study lake	Year	Total phosphorus (µg/L)	Total nitrogen (mg/L)	TN:TP	Chlorophyll *a* (µg/L)	Secchi-disk transparency (feet)
		Mean (standard deviation)	Mean (standard deviation)	Mean[1] (standard deviation)	Mean (standard deviation)	Mean (standard deviation)
Isle Royale National Park						
Chickenbone Lake	2012	23.86 (6.71)	0.56 (0.04)	24.66 (6.19)	2.04 (0.41)	6.87 (0.18)
Lake Desor	2012	11.19 (0.68)	0.59 (0.05)	53.06 (4.65)	4.14 (2.12)	6.92 (0.39)
	2013	11.42 (2.42)	0.53 (0.01)	47.20 (8.77)	3.96 (1.03)	6.97 (1.17)
Lake Harvey	2012	12.81 (1.26)	0.60 (0.02)	47.19 (4.60)	1.30 (0.11)	11.52 (0.42)
	2013	14.57 (4.10)	0.53 (0.01)	38.06 (9.46)	1.35 (0.39)	11.07 (0.21)
LeSage Lake	2012	14.67 (2.50)	0.61 (0.02)	42.21 (6.64)	2.40 (1.12)	5.85 (0.35)
Lake Richie	2012	18.69 (4.40)	0.53 (0.03)	29.34 (4.84)	4.47 (3.82)	7.91 (0.36)
	2013	20.03 (2.82)	0.53 (0.05)	27.03 (4.57)	5.01 (2.54)	8.05 (0.19)
Sargent Lake	2012	16.04 (3.69)	0.49 (0.04)	31.39 (4.77)	1.36 (0.13)	9.73 (0.28)
	2013	16.15 (2.35)	0.44 (0.04)	27.73 (6.92)	1.66 (0.07)	9.79 (0.32)
Pictured Rocks National Lakeshore						
Beaver Lake	2012	9.71 (2.66)	0.25 (0.07)	26.38 (1.98)	1.15 (0.30)	14.51 (1.03)
	2013	13.99 (0.70)	0.28 (0.06)	20.09 (5.45)	2.22 (1.12)	12.30 (0.69)
Grand Sable Lake	2012	9.25 (1.91)	0.31 (0.02)	34.61 (7.59)	2.26 (0.35)	10.87 (0.41)
	2013	9.50 (0.80)	0.28 (0.03)	29.09 (2.21)	1.70 (0.33)	10.10 (0.60)
Miners Lake	2012	16.60 (3.42)	0.44 (0.07)	27.77 (10.65)	3.00 (1.21)	7.00 (0.37)
	2013	21.72 (8.41)	0.60 (0.10)	30.39 (11.42)	3.26 (4.43)	4.81 (0.41)
Trappers Lake	[2]2012	14.64 (1.10)	0.64 (0.51)	45.21 (37.90)	2.95 (1.89)	7.41 (0.67)
	2013	11.19 (0.19)	0.87 (0.06)	77.98 (4.52)	2.18 (0.49)	6.89 (NA)
Sleeping Bear Dunes National Lakeshore						
Bass Lake	2012	9.98 (3.68)	0.74 (0.07)	80.23 (24.04)	2.33 (0.88)	10.83 (0.84)
	2013	9.12 (1.39)	0.66 (0.02)	73.70 (11.68)	1.18 (0.06)	10.17 (0.44)
Florence Lake	2012	11.88 (1.22)	0.64 (0.04)	54.30 (5.37)	2.66 (0.91)	7.82 (0.22)
	2013	12.31 (0.76)	0.65 (0.03)	53.18 (4.15)	2.19 (1.45)	10.58 (1.14)
Loon Lake	2012	15.63 (12.26)	0.47 (0.32)	33.07 (12.37)	1.26 (0.49)	14.82 (1.91)
	2013	11.04 (0.52)	0.35 (0.06)	31.48 (6.76)	1.33 (0.47)	16.57 (1.29)
Lake Manitou	2012	12.10 (2.68)	0.53 (0.01)	45.01 (8.30)	1.83 (0.87)	9.90 (0.25)
	2013	14.60 (1.40)	0.56 (0.03)	38.79 (2.38)	1.90 (0.52)	9.30 (0.09)
North Bar Lake	2012	10.80 (3.47)	0.60 (0.06)	58.79 (14.82)	1.94 (1.11)	9.73 (0.76)
	2013	12.03 (1.92)	0.48 (0.01)	40.38 (7.15)	2.06 (2.22)	8.49 (0.27)
Shell Lake	2012	11.26 (0.85)	0.99 (0.07)	88.67 (10.13)	1.11 (0.32)	10.17 (0.49)
	2013	15.49 (4.93)	0.91 (0.01)	62.58 (18.35)	1.35 (0.43)	9.41 (1.44)

[1]TN:TP ratio calculated based on daily TN:TP concentrations and then averaged by site for the year.

[2]Only two samples collected.

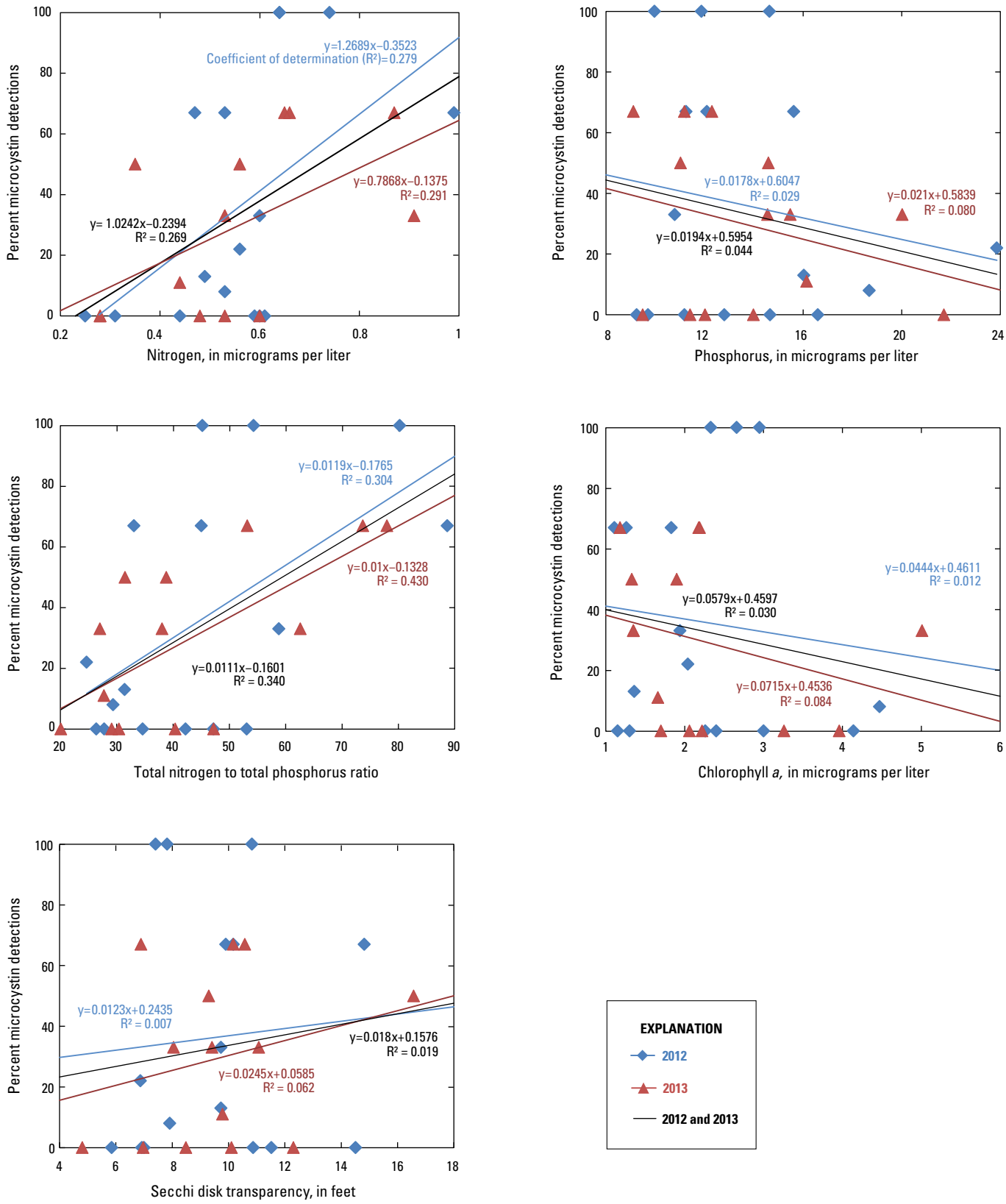


Figure 14. Nutrient, chlorophyll *a*, and Secchi disc indicator (x) comparison to percent microcystin detections (y) for 2012 and 2013 lake data at Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore.

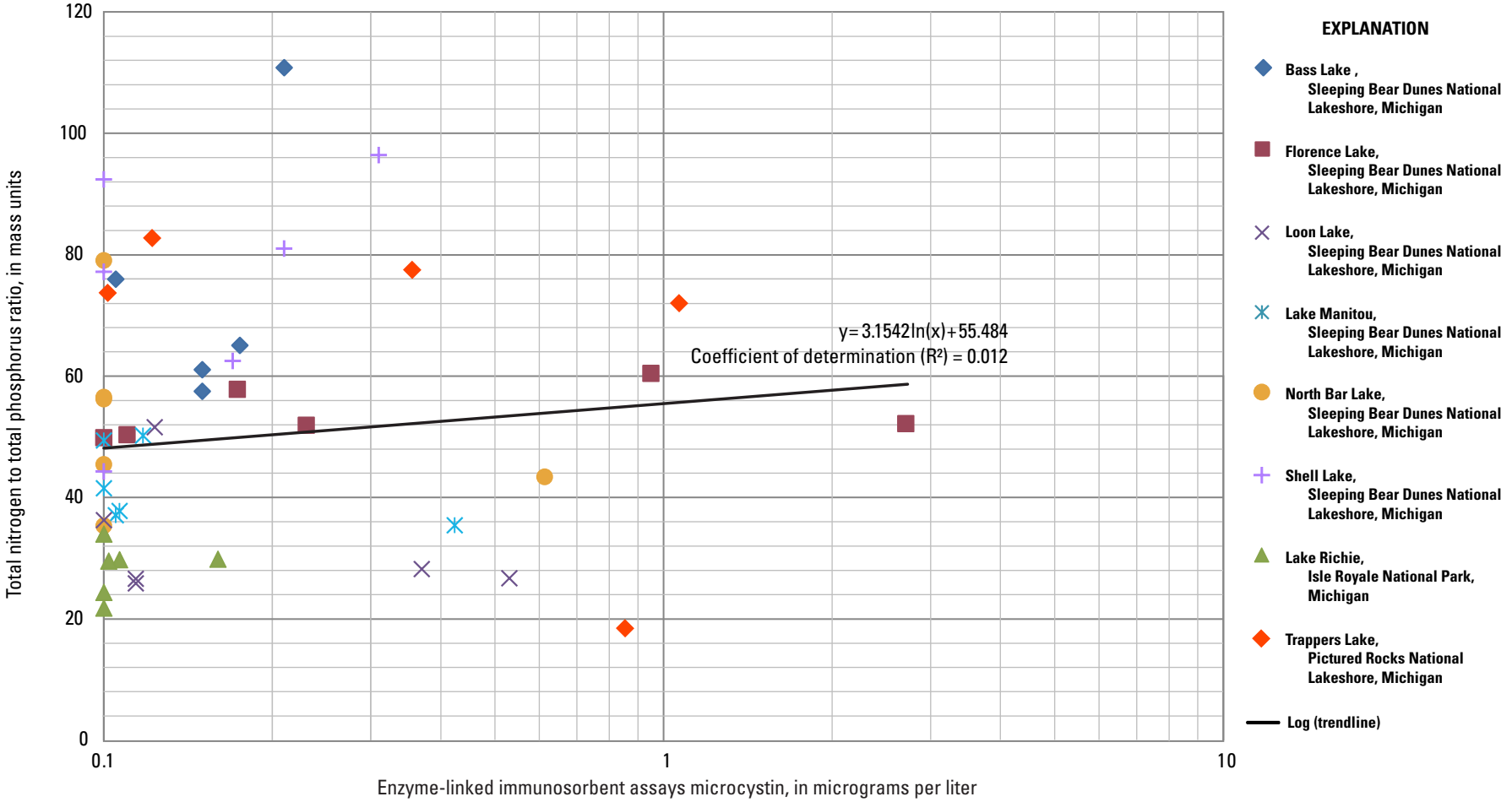


Figure 15. Total nitrogen to total phosphorus ratios (y) versus microcystin concentrations (ELISA) (x) by lake at Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore.

Summary and Conclusions

Harmful blooms of cyanobacterial algae are of increasing concern in the United States because of the potential to produce toxins that can be harmful to humans and wildlife. Climate change and human activities that increase nutrient inputs into the environment (for example, agriculture, wastewater discharge, and stormwater runoff) may encourage algal growth and potential for toxin production. The U.S. Geological Survey and National Park Service led a 2-year study to assess the occurrence of cyanotoxins and to establish a baseline for any future monitoring at Isle Royale National Park (ISRO), Pictured Rocks National Lakeshore (PIRO), and Sleeping Bear Dunes National Lakeshore (SLBE) because of their importance as recreational areas.

The enzyme-linked immunosorbent assay (ELISA) method was used to screen cyanotoxin concentrations for total microcystin, saxitoxin, and cylindrospermopsin in water samples collected nearshore where human and animal contact and use were most likely. Saxitoxin and cylindrospermopsin were not detected in any samples collected in this study. Microcystins were detected in approximately 31 percent of samples, with greatest frequency at SLBE (57 percent in 2012). Maximum microcystin concentrations ranged from 0.88 microgram per liter (µg/L) in 2013 to 2.7 µg/L in 2012, but most samples (approximately 80 percent) were near or less than the minimum reporting level of 0.1 µg/L.

Microcystin concentrations never exceeded the most protective recreational guideline recommended by the World Health Organization of 10 µg/L. However, because backpacking and camping are common in the study areas, lakes possibly could be used as drinking-water sources. Only one sample (Florence Lake at SLBE) exceeded the 1.6 µg/L U.S. Environmental Protection Agency drinking-water recommendation for school-age children through adults (6-years old and older), but 10 percent of samples (n = 211) exceeded the 0.3 µg/L guidance for children preschool age and younger (less than 6-years old). The majority of the samples that exceeded the preschool age and younger recommendations were collected from SLBE inland lakes in 2012. Trappers Lake (PIRO) and Florence Lake (SLBE) were the only sites in which the 0.3 µg/L guidance was exceeded in 2012.

The presence of microcystins was lake specific. Within a single lake on the same date, microcystin concentrations were fairly consistent; however, when concentrations of microcystin among lakes within a national park or national lakeshore were compared, the presence and concentration of microcystin could be quite variable on a given date, particularly at ISRO and SLBE. The majority of detections and higher concentrations of microcystin were on inland lakes in SLBE, potentially because as a result of increased nitrogen concentrations at those lakes or because of higher ratios of total nitrogen (TN) to total phosphorus (TP). Although within-season sampling is limited, results indicated a seasonal temporal change toward higher microcystin concentrations and frequency of detection later in the summer.

Visible blooms were not commonly noted during this study; however, when blooms were noted, microcystin concentrations were generally less than or near the minimum reporting level. Cyanotoxins are produced only by certain cyanobacteria and only under certain conditions. The factors that control cyanotoxin production are not fully understood and also are complicated by movement of the algal bloom or cyanotoxins in the water column and across the lake. This study determined that low level microcystin concentrations could be detected at many of the inland lakes even when blooms were not visible. Further studies would be needed to understand the source and environmental factors controlling toxin presence at these lakes.

Nutrient concentrations are one of the major drivers of algal blooms and cyanotoxin production. The TP concentrations were, on average, highest at the ISRO lakes, whereas TN concentrations were highest at SLBE. Results indicated a positive correlation overall when comparing TN to the percentage of microcystin detections for all the sites. However, results did not indicate a significant correlation between water transparency, TP, or chlorophyll *a* and the percentage of microcystin detections. The ratios of TN:TP were generally high and ranged from 20 to 89. The majority of the TN:TP ratios observed in this study are higher than the significant ranges identified in previous studies. Results indicated a slight increase in the percentage of microcystin detections with higher TN:TP ratios. Trappers Lake (PIRO) and Florence Lake (SLBE) had some of the highest cyanotoxin concentrations as well as the some of the highest TN:TP ratios, contrary to previously published literature.

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For more information about this publication, contact
Director,
Upper Midwest Water Science Center
U.S. Geological Survey
6520 Mercantile Way
Suite 5
Lansing, MI 48911

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