Analysis of Phytoplankton Community Dynamics: Is Onondaga Lake at Risk for Cyanobacterial Blooms?

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Executive Summary

Harmful algal blooms (HABs) dominated by cyanobacteria are becoming increasingly common in freshwater systems globally, including in many lakes in the United States (Ho and Michilak 2015). Often such blooms occur in hypertrophic lakes and streams, and anthropogenic nutrient enrichment, especially by phosphorus, is usually seen as the principal driving factor. Indeed, efforts to reduce anthropogenic sources of phosphorus in lakes, rivers and streams of the United States in the late 1970s and 1980s led to improvement in nutrient conditions and reduction in the frequency of HABs, and, since then, the management of water quality has focused, therefore, principally on controlling total phosphorus (TP) concentrations.

Before remediation began in Onondaga Lake, HABs were common, but with reduced inputs of phosphorus, resulting from advanced nutrient treatment at the Metropolitan Syracuse Wastewater Treatment Plant (Metro), major blooms were eliminated and minor blooms have occurred only infrequently. Nonetheless, renewed awareness of the manifold factors that affect HABs, the continued occurrence of HABs in nearby Oneida Lake, and increased occurrence in the New York Finger Lakes and Lake Erie suggest that it is prudent to investigate the likelihood of HABs returning to a recovering Onondaga Lake. Moreover, there is evidence from recent years that algal blooms are becoming more common in Onondaga Lake, and cyanobacteria are becoming more abundant.

The recent increase in the frequency of HABs and their geographically widespread occurrence, including in oligotrophic, mesotrophic and eutrophic lakes, has spurred research into potential contributing factors other than the ambient phosphorus concentration. Although some of the apparent increase in the occurrence of HABs globally may be due to increased awareness of the public health threats of the toxic species that comprise many HABs, interest has focused as well on several biotic and abiotic factors. Among abiotic factors, nutrient enrichment remains a major focus, and, in some cases, excess phosphorus remains the principal culprit, perhaps more often coming from diffuse non-point sources resulting from changes in land-use, rather than from point sources such as wastewater treatment facilities. But inputs of other nutrients, especially nitrogen, or the relative amounts of two or more nutrients (stoichiometry) may also play a role.

The light environment can also be important. Many cyanobacteria species—the most important component of HABs—use light more efficiently than do other phytoplankton species, especially under low-light conditions

(Anneville et al. 2015, Filtstup et al. 2016). Furthermore, cyanobacteria can regulate their buoyancy and form surface concentrations that effectively reduce the transparency of the water, giving cyanobacteria an advantage over species lower in the water column. Increasing water temperatures and other climate interactions may also play an important role. Several cyanobacteria species have higher optimum temperatures for growth than do eukaryotic species, giving them an advantage in a globally warming climate.

Biotic factors may also play a role through both “top-down” or indirect “bottom-up” effects in the food-web. Selective filtration by invasive zebra and quagga mussels (Dreissenidae) can lead to the dominance of at least some cyanobacteria in the phytoplankton assemblage (Vanderploeg et al. 2001), although under other circumstances dreissenid grazing can reduce cyanobacteria biomass (Waajen et al. 2016). Dreissenid mussel grazing may also affect the availability of phosphorus in the system, representing an indirect “bottom-up” effect, encouraging phytoplankton growth, including that of cyanobacteria. Predation by zooplanktivorous fish may have an important “top-down” effect of increasing phytoplankton biomass by relieving grazing.

While cyanobacteria still comprise a small proportion of the phytoplankton community of Onondaga Lake, the fact that their relative abundance has recently increased coupled with the widespread occurrences both globally and in nearby New York waterbodies are of concern. Lake managers need to continue investigating the potential factors causing this increase.

Introduction

Cyanobacterial blooms, also known as blue-green algal blooms or harmful algal blooms (HABs), have become increasingly common in freshwater systems globally, including in many New York lakes. Nutrient enrichment, warming waters, invasive species and changing food webs have all been implicated as potential factors affecting cyanobacterial abundance. In New York, HABs have been documented in lakes with a wide range of phosphorus concentrations; many lakes experiencing cyanobacterial blooms have summer average total phosphorus (TP) concentrations well below the NYS Department of Environmental Conservation (NYSDEC) guidance value of 20 µg/L. All eleven New York Finger Lakes and Oneida Lake experienced cyanobacterial blooms during summer 2017. Onondaga Lake, in contrast, has not had cyanobacterial blooms in recent years, despite summer TP concentrations in the range of 17 – 25 µg/L. This White Paper examines the detailed water chemistry and phytoplankton data from decades of monitoring and research to explore why Onondaga Lake differs, and evaluate the risk of future HABs in this recovering ecosystem.

Onondaga Lake Phytoplankton Community: History and Recent Changes

As part of its long-term ambient monitoring program, Onondaga County Department of Environment Protection (OCDWEP) has sampled and analyzed the phytoplankton community, in addition to monitoring the algal pigment chlorophyll-*a*. Cyanobacterial blooms were common in Onondaga Lake prior to 2005, when advanced phosphorus removal came on line at the Metropolitan Syracuse Wastewater Treatment Plant (Metro). Between 1998 and 2004, cyanobacteria comprised a significant component of the phytoplankton community during the

June to September recreational period (Figure 1). Implementation of advanced phosphorus treatment has led to a substantial decrease in both phytoplankton biomass and the proportional contribution of cyanobacteria to the community (Baker 2013).

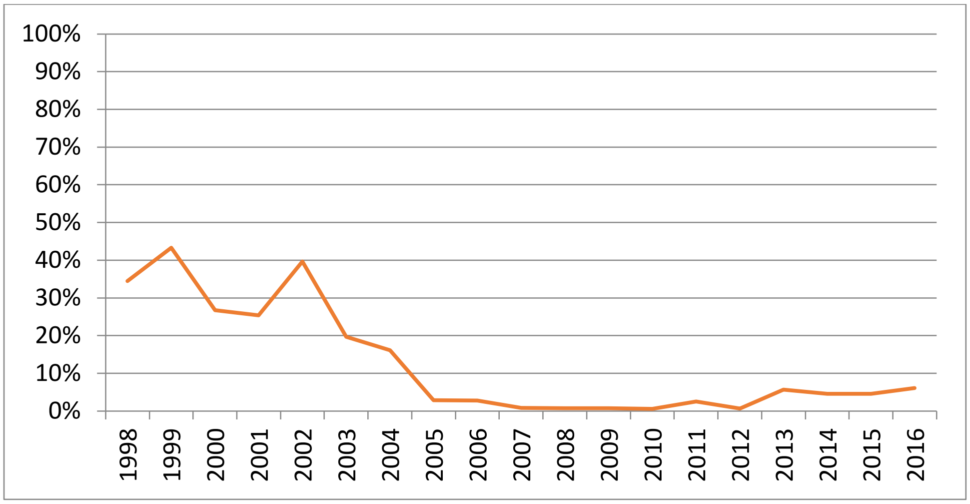

Figure 1. Percent of phytoplankton community biomass composed of cyanobacteria, June 1- Sept. 30.

The Onondaga County Ambient Monitoring Program uses chlorophyll-*a* concentration to indicate bloom conditions; 15 µg/L is the threshold for a “minor” bloom and 30 µg/L indicates a “major” bloom. There have been only minor blooms since 2005 (Figure 2), and none have been dominated by cyanobacteria. Some of these minor blooms have occurred in the spring when diatoms and green algae dominate the community.

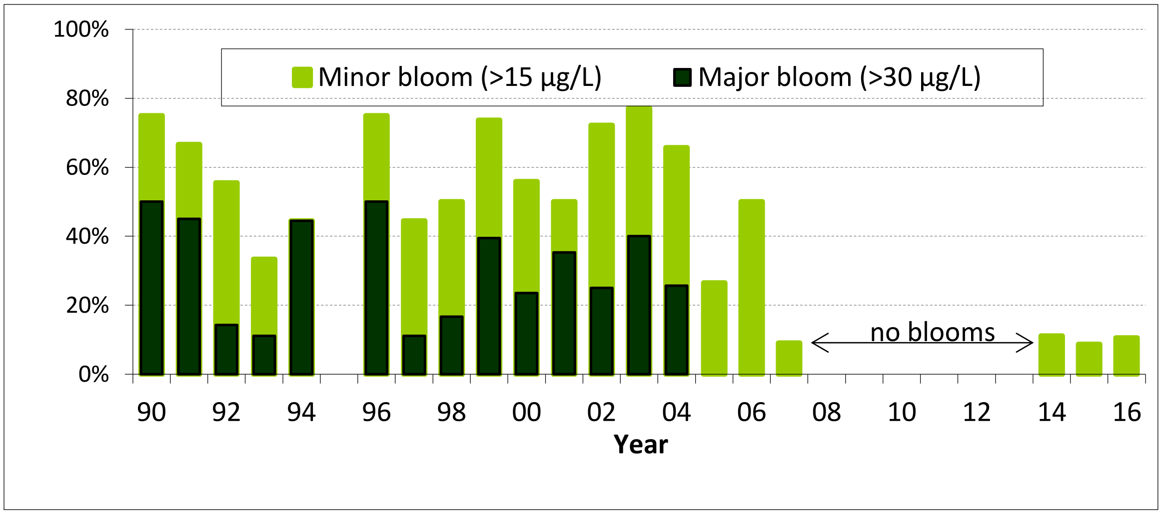

Figure 2. Summer algal bloom frequency, 1990-2016.

Cyanobacteria are often present in the phytoplankton assemblage. The species detected in Onondaga Lake include the potentially toxic genera *Anabaena*, *Dolichospermum (*formerly *Anabaena* in part*), Aphanizomenon*, *Microcystis,* and *Cylindrospermopsis*. The major genera of cyanobacteria present in Onondaga Lake in 2016 are plotted in Figure 3.

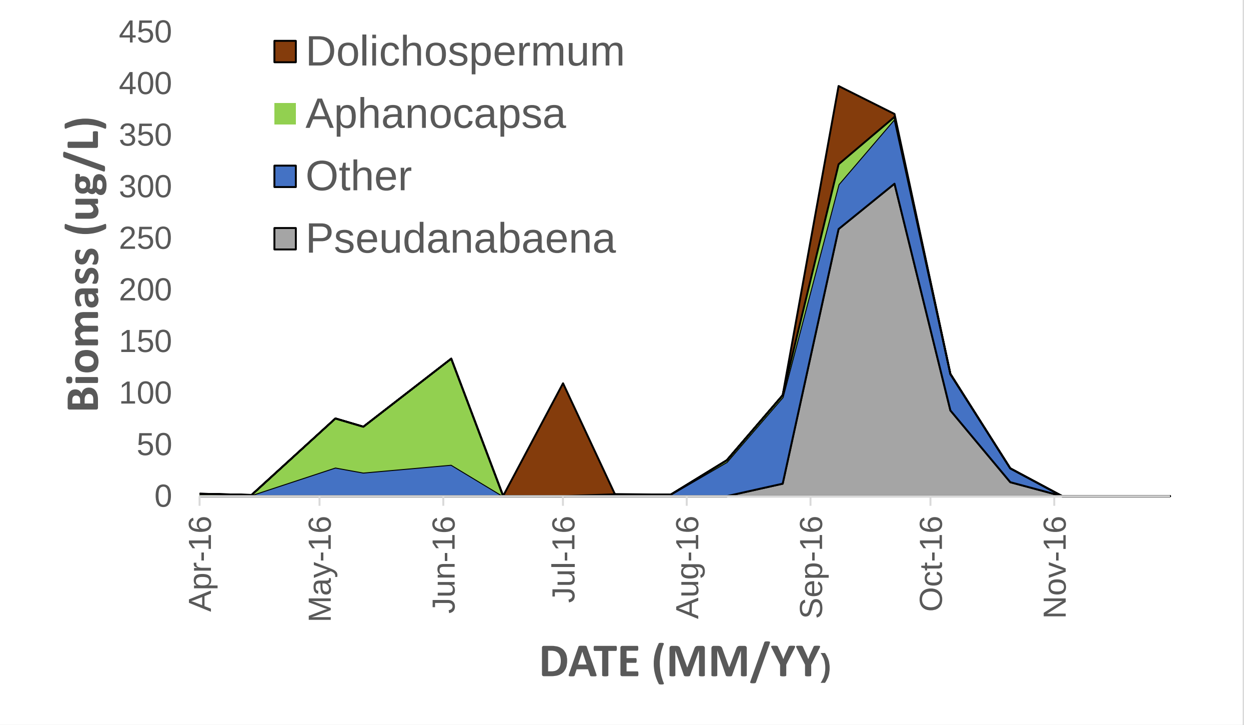

Figure 3. Major genera of cyanobacteria detected in Onondaga Lake, 2016

Although cyanobacteria have not dominated the phytoplankton assembly in recent years, there has been an increase in their total biomass and their proportional contribution to the community since 2012. On 18 sampling days between 6 April and 5 December 2016, the proportional contribution of cyanobacteria to the phytoplankton biomass varied from near zero to 39% (Figure 4 and Table 1) but was generally low overall, constituting only 11% of the open water phytoplankton biomass, except for a large biomass of *Pseudoanabena* (reaching 302 µg/L) on 9/27. During the two dates on which minor blooms occurred (9/13 and 9/27), the contribution of cyanobacteria was relatively high at 11% and 18%, respectively, but it was as high or higher on several other dates on which chlorophyll-*a* concentrations were low.

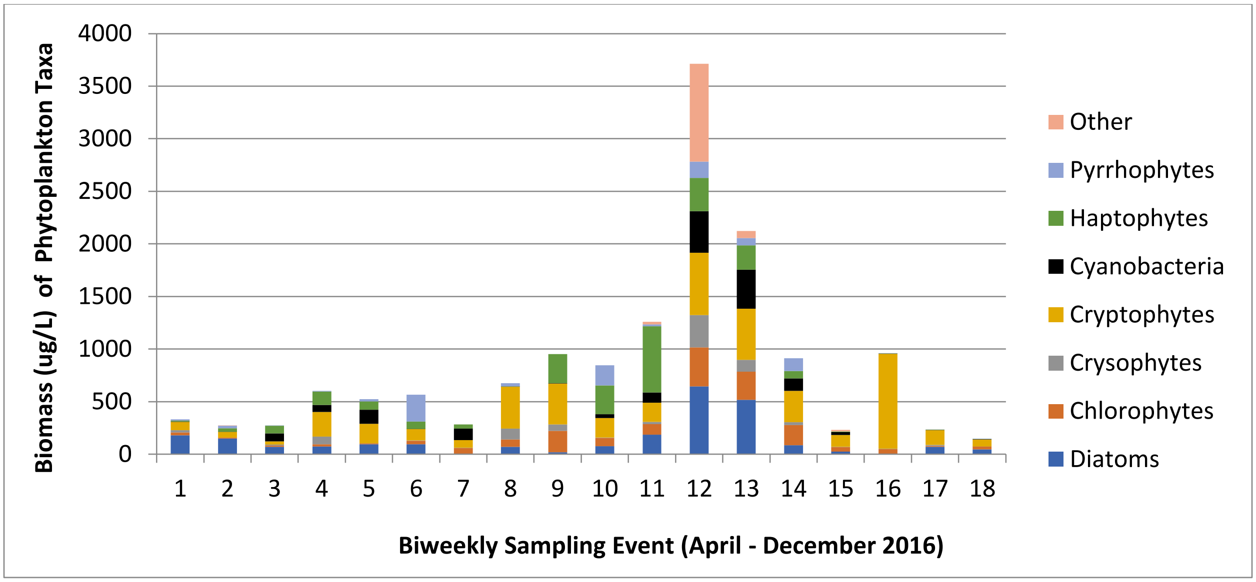

Figure 4. Seasonal pattern of phytoplankton taxa, April - Dec. 2016

Table 1. 2016 Seasonal phytoplankton biomass (µg/L), upper waters (0-3m). Onondaga Lake NY

Date	Diatoms	Greens	Chrysophytes	Cryptophytes	Cyanobacteria	Euglenoids & Misc.	Haptophytes	Pyrrhophyta	Total	Percent cyanobacteria
6-Apr	181	28	19	81	2	0	7	12	331	1%
19-Apr	151	8	0	55	1	4	33	22	274	0%
10-May	72	10	10	31	75	0	73	2	273	28%
17-May	74	20	74	234	67	0	127	9	604	11%
8-Jun	96	9	1	184	133	0	79	22	524	25%
21-Jun	95	34	3	108	0	0	69	255	565	0%
6-Jul	5	55	1	73	109	0	38	0	282	39%
19-Jul	72	70	102	397	2	0	2	32	677	0%
2-Aug	20	203	62	389	2	0	276	0	951	0%
16-Aug	78	78	4	185	35	0	274	192	846	4%
30-Aug	185	101	23	182	98	26	630	15	1260	8%
13-Sep	645	371	307	592	398	930	315	156	3714	11%
27-Sep	518	266	114	486	371	0	233	68	2055	18%
11-Oct	87	191	27	298	118	0	70	122	914	13%
26-Oct	25	42	3	113	27	15	6	0	232	12%
8-Nov	3	46	4	901	1	0	2	3	960	0%
30-Nov	70	11	9	140	1	0	1	0	231	0%
5-Dec	46	28	0	69	1	0	0	4	148	1%

Environmental Conditions That Encourage Cyanobacterial Growth

Nutrient Stoichiometry

The absolute or relative concentrations of nutrient elements other than phosphorus may contribute to the growth of cyanobacteria. For example, the ratio of nitrogen to phosphorus (TN:TP) may determine whether or not HABs occur, and HABs are thought to be rare in lakes where N:P ratios exceed 29:1 (by weight) (Filstrup et al. 2016, Smith 1983). This is partly because cyanobacteria can take up and use nitrogen more efficiently than true (eukaryotic) algae, thus potentially giving cyanobacteria a competitive advantage in conditions where the concentration of nitrogen becomes limiting. In fact, some cyanobacteria, unlike eukaryotic algae and plants, can “fix” atmospheric molecular nitrogen (N_2) dissolved in the water. Nitrogen-fixing ability, however, is not the only attribute of cyanobacteria that can increase their competitive ability over other phytoplankton. Many non-N-fixing cyanobacteria species have superior nitrogen storage capacity, and Ferber et al. (2004) found that cyanobacteria had a small proportion of “fixed” N_2, accumulating N in inorganic form, principally as ammonia but also as nitrate$^-$.

A review by Beutel et al. (2016) demonstrated that addition of nitrate to surface waters affects water-quality improvements by several routes, including the suppression of cyanobacteria in favor of eukaryotic algae, mostly greens. In an early Swedish study (Ripl and Lindmark 1979), addition of nitrate to a group of small quarry lakes converted the plankton community from one dominated by cyanobacteria and small-bodied zooplankton to one dominated by green algae and large-bodied zooplankton.

In Onondaga Lake, nitrification of the Metro effluent began in 2004, greatly reducing the loading of ammonia to the lake and increasing the water-column concentration of nitrate by a factor of 2. This brought about several salutary effects on the lake’s water quality, including a late summer reduction in the mobilization of phosphorus from the sediments. Since 2011, concentrations of nitrate have been augmented by the addition of hypolimnetic calcium nitrate to prolong these effects. It is difficult to separate the reduction of phosphorus from the increase in nitrogen in their effects on the phytoplankton community, but, in addition to any effect on phytoplankton community structure, nitrate additions have reduced internal phosphorus loading, further curtailing eutrophication and the concomitant encouragement of HABs. It has also reduced the methylation of mercury in the sediments and its entrance into the food chain, and has improved water quality in several other ways.

Light

In any given nutrient environment, cyanobacteria may realize a competitive advantage over other types of phytoplankton because of their more efficient use of light (Ferber et al. 2004, Kosten et al. 2012, Smith 1983, 1986). Not only do cyanobacteria grow more rapidly, especially under low-light conditions, but because they have buoyancy-regulating gas vacuoles, they rise to the surface and shade out other species, and because their buoyancy reduces their sinking rate, cyanobacteria remain in the well-lighted, upper level of the water column. As surface scums, cyanobacteria are also moved by wind-driven currents and may accumulate on leeward shores or protected embayments.

Climate Change

There are several reasons to predict that global climate change will favor the growth of cyanobacteria in surface waters, leading to an increase in the frequency of HABs, and the increased frequency of HABs worldwide is likely not due solely to increased eutrophication (Mantzouki et al. 2016, Paerl and Otten 2016). The direct and indirect effects of warming may play an important role in changing the properties of aquatic ecosystems (Elliott 2012; Kosten et al. 2012; Paerl and Huisman 2008).

Warmer waters directly favor cyanobacteria over eukaryotic algae because the optimal temperature for the growth of many cyanobacteria is greater than that for most algae species (Butterwick et al. 2005). Warmer surface water temperatures are also associated with more stable thermal stratification and less turbulent mixing.

In addition, the thermocline in these warmed lakes will be shallower and more stable for a longer time, which can encourage the growth of certain cyanobacteria taxa (Paerl and Huisman 2008). Under stable water column conditions, positively buoyant cyanobacteria will be able to regulate their position in the water column and remain in the euphotic zone, while negatively buoyant algae will sink in the absence of turbulent mixing. The concentration of cyanobacteria in surface layers will shade levels beneath the surface, further enhancing the growth advantage of the cyanobacteria on the surface. Furthermore, dense light-absorbing aggregations of cyanobacteria near the surface will further warm the water, enhancing the dominance of the cyanobacteria.

Dense phytoplankton growth can outstrip the supply of C, but buoyant cyanobacteria, closer to the surface will have better access to CO_2 diffusing from the surface and to atmospheric CO_2 that is continuing to increase. Other attributes of a changing climate may affect the occurrence of HABs. Intensified precipitation will lead to higher terrestrial nutrient-laden runoff, exacerbating eutrophication and further encouraging blooms. Other extreme events associated with global climate change may increase the likelihood of HABs. Heatwaves, for example, especially those accompanied by sunny calm weather conditions, have been associated with local cyanobacterial blooms.

Comparison to Oneida Lake

Average summer values of chlorophyll-a concentrations and inferred phytoplankton densities in Oneida Lake are lower than those in Onondaga Lake, although total phosphorus concentrations in the two lakes are similar (Cuhel and Aguilar 2016). Oneida Lake is shallower than Onondaga Lake and more of its bottom is suitable for dreissenid mussel grazing. Nonetheless, large summer blooms of cyanobacteria and concentrations of cyanobacterial toxins over current health guidelines occur during the summer in Oneida Lake (Dr. Greg Boyer, personal communication 2017).

One relevant difference between the two lakes with regard to cyanobacteria blooms is their different N:P ratios. It is well-documented that cyanobacteria dominate primarily in lakes with N:P ratios (by weight) below 29 (Smith 1983). The low proportion of cyanobacteria in Onondaga Lake is consistent with its elevated summer N:P ratio, which has been well above the 29:1 threshold since before 1998. This ratio has been very high, over 100:1 since 2007 (Figure 5). This is not the case in Oneida Lake, where summer N:P ratios are substantially lower. Between 2011 and 2016, the N:P ratio varies between 14 and 26 with summer minima between 6 and 15 (Rudstam 2017). Thus, N is more limiting in Oneida Lake giving cyanobacteria a competitive advantage. Other attributes potentially promoting cyanobacteria (total P concentrations, warmer temperatures, more stable water column, and increased P release from sediments) do not appear to be dramatically different in the two lakes.

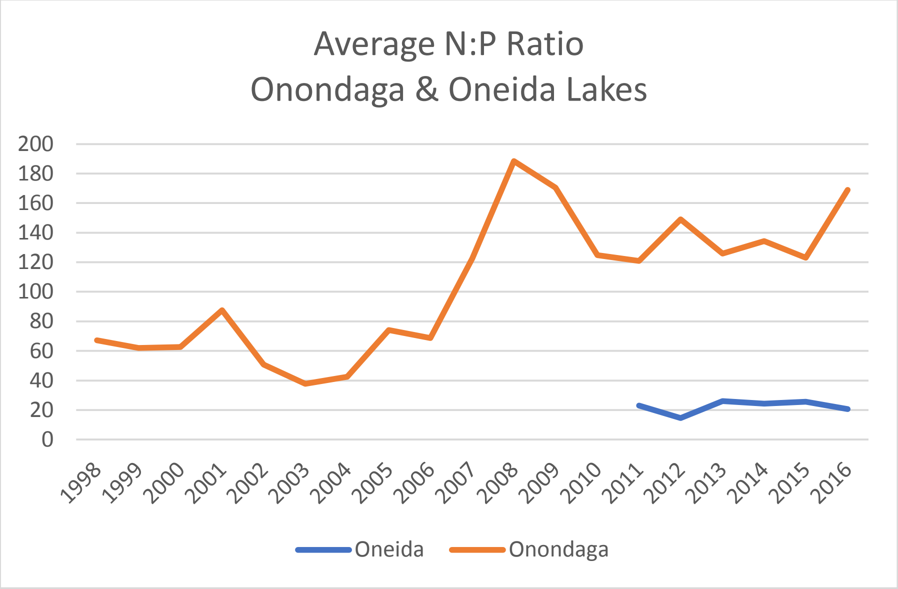

Figure 5. Average N:P ratio in Onondaga Lake (1998-2016) and Oneida Lake (2011-2016)

Lessons from Other Regional Lakes

All the Finger Lakes have experienced cyanobacterial blooms, even oligotrophic lakes (*e.g.*, Skaneateles), but HABs have become more common in Conesus, Honeoye, Canandaigua, Seneca, Owasco and Otisco Lakes. Although Honeoye is eutrophic, with TP between 30 and 45 µg/L, Cayuga, Seneca, Owasco and Otisco are mesotrophic (10<TP<20 µg/L). In 2017, HABs in eight Finger Lakes (Canandaigua, Cayuga, Keuka, Honeoye, Oneida, Owasco, Seneca, and Skaneateles Lakes) were associated with cyanobacterial toxins (http://www.dec.ny.gov/chemical/83310.html). Cayuga and Owasco Lakes experienced HABs in mid to late summer in 2016 and 2017, and, in the case of Owasco Lake, cyanobacteria toxins were detected in the City of Auburn's municipal water supply.

Classification of the trophic status of these lakes is typically made from mid-lake sites, while the HABs typically occur in nearshore locations; cyanobacterial concentrations in blooms far exceed those of open-water. In certain areas, such as nearshore Conesus Lake (Makarewicz et al. 2009), nutrient-laden terrestrial runoff augments the ambient nearshore phosphorus concentrations. However, nearshore concentrations of nutrients in Onondaga, Cayuga, and Owasco Lakes are similar to pelagic values (D. Matthews, pers. com. 2017). Furthermore, the buoyancy-control of many cyanobacteria concentrates them in surface scums carried to nearshore locations by wind-driven currents. In Owasco Lake, the HABs occurred in mid-summer, when air and water temperatures were at their highest and abated when water temperatures decreased. The most intense blooms are typically associated with calm, sunny days, with maximum thermal stratification of the surface and little wind-induced mixing.

Conclusions

Clearly, the causes of cyanobacterial blooms are complex. While high concentrations of limiting nutrients, e.g., phosphorus, have been the principal culprit in hypertrophic and eutrophic bodies of freshwater, it is now clear that less productive waterbodies are not immune from HABs. Onondaga Lake is now less productive than it was before remediation was undertaken, and major algal blooms and the abundance of cyanobacteria has greatly declined. The N:P ratio of the upper waters appears to be a key indicator of risk of HABs, likely exacerbated by warming and more quiescent conditions.

While the evidence from Onondaga Lake reviewed here does not suggest an imminent threat of cyanobacterial blooms, the recent increase in the importance of cyanobacteria in the lake's phytoplankton community, the presence of toxic genera of cyanobacteria in Onondaga Lake, and the experience of HABs in nearby mesotrophic lakes suggest watchfulness.

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