2021 NEARSHORE MONITORING OF CYANOBACTERIA (BLUE-GREEN ALGAE) IN SENECA & OWASCO LAKES.

THE 2021 ANNUAL REPORT TO THE SENECA LAKE PURE WATERS ASSOCIATION, FRED L. EMERSON FOUNDATION AND CAYUGA COUNTY

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INTRODUCTION

The recent onset of cyanobacteria (aka blue-green algae, BGA) blooms and their associated toxins (HABs) has heightened awareness about water quality issues in Seneca, Owasco and neighboring Finger Lakes. Blooms were first reported in Owasco Lake during 2012 and in Seneca Lake during 2015 (NYS-DEC Data). The largest measured cyanobacteria concentrations in the Finger Lakes are typically localized and along the shoreline, where lakeshore residents want to use the lake. The blooms have also impacted municipal drinking water supplies. For example, cyanobacteria toxins were detected in the Auburn and Owasco municipal drinking water supplies in 2016 that draw water from Owasco Lake. Since then, toxins were also detected in the City of Syracuse's municipal water intake that draws water from Skaneateles Lake in 2017, and in Rushville's municipal drinking water that draws water from Canandaigua Lake in 2018. By 2017, all of the Finger Lakes reported HABs events, even the three oligotrophic (low productivity) lakes, Skaneateles, Canandaigua and Keuka. Seneca & Owasco Lakes are no exception and both have been listed on the New York State Department of Environmental Conservation's (DEC) HABs website with documented BGA blooms, many with high toxin concentrations. These events stimulated concerned citizens in each watershed to form HABs volunteer monitoring groups under the guidance and training of DEC staff.

Seneca Lake Pure Waters Association (SLPWA) and Owasco Watershed Lake Association (OWLA) have spearheaded volunteer HABs monitoring efforts in the Finger Lakes region. They have also advanced methods to report HABs events to the local community. With exceptional leadership, SLPWA's program has grown quickly, and now over 100 HABs volunteers survey approximately 100 km of the 130 km long shoreline entering HABs detection reports and photos electronically using cell phones or tablets. HABs locations and photos are pinpointed on and linked to a google earth map. The mapping app has been adopted by New York State DEC, and it forms the backbone of the State's NYHABs statewide monitoring/mapping system. A critical result of these and neighboring monitoring programs is that cyanobacteria blooms are concentrated along the shoreline, and are sporadic in both space and time during the late August through early (now late?) October HABs season.

This report details our 2021 findings from the Seneca and Owasco Lake dockside monitoring programs (Fig. 1). The data from both lakes were combined into one report to provide an interesting comparison. It follows up on promising research by Halfman and his collaborators[1], which documented a number of key findings:

- Cyanobacteria blooms were sporadic in both space and time.
- Sufficient nutrients were lacking in the offshore and, more importantly, the nearshore water column to support the observed bloom concentrations.
- HABs were hypothesized to form along the shoreline after onshore wind and/or rain events during the subsequent calm and sunny day.
- Shoreline geometry influenced nearshore wind speeds and directions enough to dictate where and/or when localized shoreline blooms develop.

These dockside studies were designed to investigate the following questions:

- Why are bloom events variable in both space and time?
- What is(are) the source(s) of nutrients for the shoreline blooms?
- Most importantly, what is(are) the trigger(s) for cyanobacteria blooms in both Seneca and Owasco Lakes?

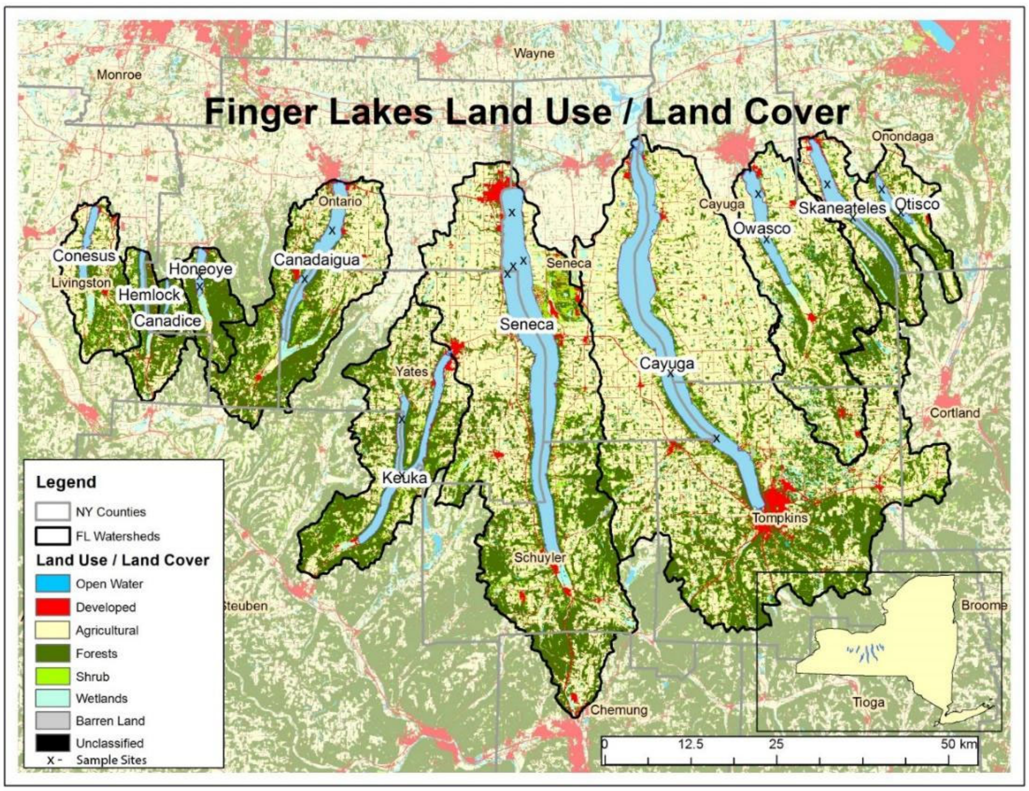

Fig. 1. Land Use / Land Cover (NDLC 2011 data) map of the Finger Lakes Watersheds. Seneca & Owasco Lakes are the focus of this report.

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[1] Halfman, J.D., et al., 2020. Dockside monitoring of Blue-Green Algae in Seneca Lake. The 2019 FLI report to the Seneca Lake Pure Waters Association. Finger Lakes Institute, Hobart and William Smith Colleges. 40 pg.
Halfman, J.D., et al., 2020. Blue-Green Algae in Owasco Lake, the 2019 Update. The 2019 Annual Report to the Fred L. Emerson Foundation. Finger Lakes Institute, Hobart and William Smith Colleges. 38 pg.
Halfman, J.D., et al., 2021. 2020 Nearshore Monitoring of Cyanobacteria (Blue-Green Algae) in Seneca & Owasco Lakes. The 2020 Report to the Seneca Lake Pure Waters Association, Fred L. Emerson Foundation and Cayuga County. Finger Lakes Institute, Hobart & William Smith Colleges. 62 pg.

EXECUTIVE SUMMARY

2021 Research Highlights:

- The second largest number of Cyanobacteria blooms were detected in both Seneca Lake (72) and Owasco Lake (47) in 2021 compared to past years. The bloom count increased in Seneca Lake but decreased in Owasco Lake from 2020.
- Water quality - limnological data from both lakes revealed borderline oligotrophic-mesotrophic systems, previously thought unable to support cyanobacteria blooms. Minimal differences in the offshore limnology over space and time were detected that could not explain the variance in bloom counts in these two lakes.
- The offshore plankton communities in Owasco Lake had significantly more cyanobacteria than Seneca Lake in 2020 and 2021, perhaps reflecting the longer length of time cyanobacteria were in Owasco Lake and/or the slightly more productive state of Owasco Lake, sufficient winds that mixed nearshore blooms offshore, and/or additional or more extensive nutrient sources.
- The FLI buoys on Owasco and Seneca Lakes recorded suitable water temperatures, air temperatures, calm periods, and light intensities for bloom development.
- Water temperatures in 2021 were nearly as warm as 2020, and similar to the previous 5 years in both lakes. A gradual warming trend observed over the past few decades is due to global warming. The coincidence with the onset of HABs events suggests that these lakes have recently warmed enough to exceed the tipping point to foster cyanobacteria blooms.
- Faster winds were detected by the offshore buoys in 2020 than 2019 and 2021 during the HABs season, especially in Seneca Lake. Persistently faster winds and the associated larger waves in Seneca Lake may have reduced bloom development, whereas a dip in wind speeds and a smaller number of wind events promoted bloom development in Owasco Lake. The return to pre-2020 wind speeds in 2021 may have allowed for the 2nd largest number of blooms in both lakes.
- In 2020, strong and persistent winds and large waves dominated Seneca Lake, and most likely retarded bloom events. Whereas slightly subdued winds, smaller waves (smaller fetch), more frequent calm periods, and lower lakes levels most likely released a bumper crop of nutrients and a larger number of blooms in Owasco Lake.
- Nearshore and offshore surface water temperature across Seneca and Owasco Lakes occasionally decreased just before cyanobacteria blooms. The declines suggest that precursor wind and/or storm events and their associated waves, that likely caused the surface water temperature decrease, also disturbed the nearshore sediments, and released nutrients to the water column to stimulate nearshore cyanobacteria blooms. The actual bloom typically (but not always) occurred on the next sunny (and apparently overcast) and calm day.
- The dock site automated cameras detected cyanobacteria blooms. The cameras detected blooms missed by local HABs volunteers; and conversely, the volunteers detected blooms missed by the camera's limited field of view.
- Imaged cyanobacteria blooms were again most frequent during the afternoon hours. A bloom's duration lasted a few hours, ranging from less than an hour up to 12 hours in a day. The timing and duration varied from site to site.
- Nearshore wind speeds decreased and dominant wind directions shifted between individual nearshore sites, and between the nearshore sites and the mid-lake buoy. The shoreline geometry consistently decreased speeds and altered directions from the regional winds, and

because each shoreline orientation is unique, each site experienced unique wind fields. It suggests that one shoreline can experience calm conditions and a cyanobacteria bloom, whereas neighboring shorelines with different orientations may experience sufficient winds to retard bloom development. The wind characteristics, along with nutrient availability, provides a potential reason why surface blooms are localized in time and space.

- Large precipitation events and their associated nutrient loads from the watershed in 2021 contributed to the blooms in Seneca Lake, and especially Owasco Lake.
- Statistical analysis of the 2019, 2020 and 2021 nearshore daily mean meteorological and water temperature data indicated that days with blooms consistently correlated to less rainfall, especially less rain on the preceding day, and slower wind speeds, and do not consistently correlate to water temperature, wind direction, air temperature and solar intensity.
- Water quality (WQ) sondes deployed in Owasco Lake detected daily oscillations in dissolved oxygen (DO) concentrations. Photosynthesis increased DO during the day and respiration decreased DO at night. It highlights the importance of biological activity in the nearshore areas, even shorelines with rocky lake floors.
- The WQ sondes also revealed hour long episodes of elevated total and cyanobacteria-PC fluorescence during periods of turbid water. It suggests that waves dislodged benthic algae during onshore wind events, and highlights the importance of nearshore biological activity, even along rocky shorelines. The sondes deployed ~1m below the water surface did not detect surface hugging cyanobacteria blooms.
- Like the Martin S site in 2020, organic matter periodically clogged the Burtis Pt deployment pipe and temporarily caused total chlorophyll, cyanobacteria-chlorophyll, and salinity to increase and dissolved oxygen to decrease inside the pipe. We suggest that the respiratory release of nutrients stimulated cyanobacteria blooms inside the pipe, and highlights the importance of an extra source of nutrients to support these blooms.
- Nutrient limitation studies indicated that Owasco Lake was the only lake to show serial P or P-only limitation compared to the other Finger Lakes tested in 2021 including Cayuga, Canandaigua, and Honeoye. Interestingly, the nutrient augmentations stimulated more growth of green algae and diatoms, and less cyanobacteria and cryptophytes.
- Nutrient flux experiments indicated that the nearshore sediments are a viable source of soluble reactive phosphate.
- Zebra/Quagga mussel and macrophyte surveys described a viable supply of nutrients to the nearshore regions once the mussels and macrophytes die and decompose in the later part of the summer.

ACKNOWLEDGEMENTS

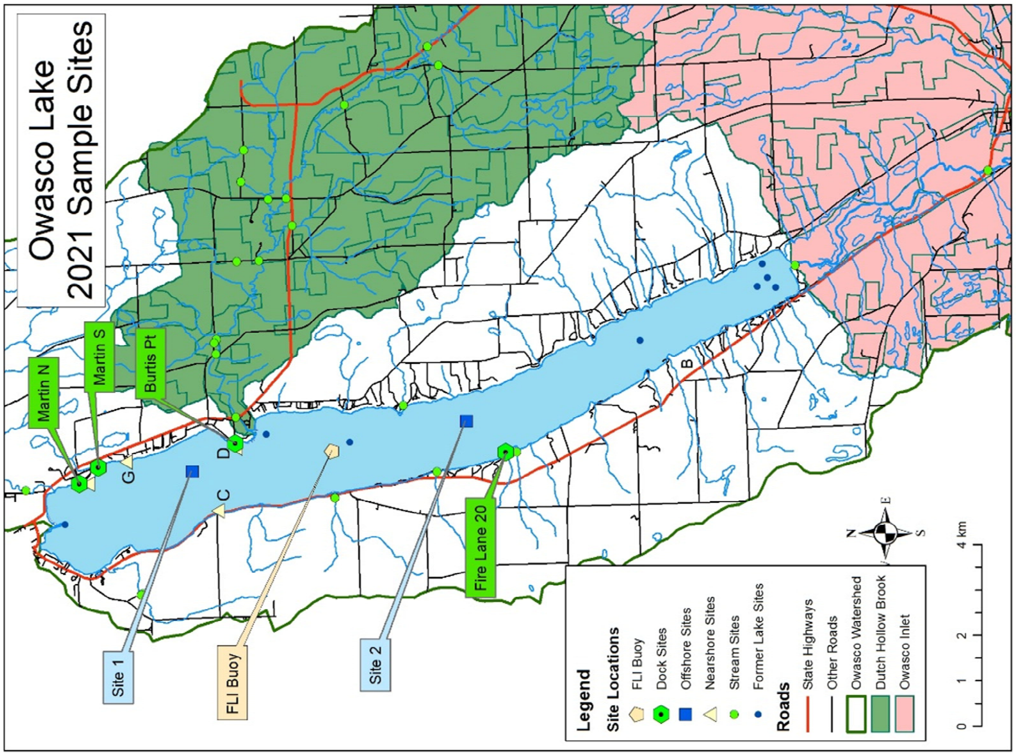
The 2021 research was supported by the Fred L. Emerson Foundation, Cayuga County Legislature, Finger Lakes – Lake Ontario Watershed Protection Alliance for the work on Owasco Lake, and Seneca Lake Pure Watershed Association for the work on Seneca Lake. Initial support to purchase the dock equipment deployed at Seneca Lake originated from the Tripp Foundation. We thank members of the Owasco Watershed Lake Association and Seneca Lake Pure Waters Association, specifically the homeowners for access to their docks: Brian, Barbara, Ed, and Jim on Owasco Lake, and Grant, Frank, Mary, Rick, Dick, Maura, Terri, and especially Bill on Seneca Lake. We're very grateful to Bill for pushing this project from an idea to a reality. Thanks are also extended to members of the Cayuga County Planning Department, Cayuga County Water Quality Management Agency, Owasco Watershed Lake Management Council, Cayuga County Health Department, Owasco Watershed Lake Association, the Cayuga County Soil and Water District, the Institute for the Application of Geospatial Data and NYS Department of Environmental Conservation for their help over the past few decades of effort.

METHODS

Nearshore Data: This project monitored the meteorological and limnological conditions at eight dock sites distributed around Seneca Lake and four dock sites around Owasco Lake. The sites utilized homeowners who already were SLPWA and OWLA HABs volunteers and were willing to host the dockside instrumentation (Fig. 2). The Seneca & Owasco sites duplicated the sites surveyed in 2020 (Seneca: NE Adams, NES Bloss, SEC Toole, NNW Allen , NW Roege, NWC Downs, SWC DiOrio, and SW Rose; Owasco: NNE Martin North, NE Martin South, NEC Burtis Point, and SW Fire Lane 20).

At each site, a weather station, an automated camera, and a water temperature logger were deployed to detect and elucidate occurrences of nearshore cyanobacteria blooms, and water quality and weather information for each bloom (Fig. 3). A water quality sonde was also deployed at the four Owasco locations. The weather station (Ambient 1002-WS or WS-2000 Osprey, the discontinued 1002-WS replacement) recorded air temperature, rainfall, barometric pressure, humidity, light intensity, wind speed and direction every 30 minutes. A Brinno TLC-200 automated camera, deployed on the weather station pole approximately 3 m above the lake's surface, recorded daily images of the lake's surface every 10 minutes from dawn to dusk (7 am to 6 pm). Each day was saved in a separate file, and used to manually log clear vs turbid water conditions, and the presence of obvious cyanobacteria blooms. The camera's 60° field of view imaged a 2x3 to 3.5x5 meter area of the lake's surface depending on the exact deployment height. A *HOBO* TidBit MX or *HOBO* U20L-04 data logger was placed inside a 2" PVC pipe and the assembly was strapped to a dock post at each site in ~1-m of water to record water temperature every 30 minutes. PVC pipes protected the loggers from wave action. An *In-Situ* Aqua Troll 600 water quality sonde with temperature, conductivity, total fluorescence (chlorophyll) and cyanobacteria phycocyanin fluorescence sensors was deployed at each dock on Owasco Lake except one (Fire Lane -20 Site), where a *YSI/Xylem* EXO2 water quality sonde with temperature, conductivity, dissolved oxygen, turbidity, and total fluorescence and cyanobacteria phycocyanin fluorescence was deployed instead. The sondes were deployed inside 4" diameter PVC pipes for their protection from waves. Each deployment pipe had numerous holes for continuous water flow.

The instrumentation was deployed at Seneca Lake on 7/11 and recovered on 10/27, and deployed at Owasco Lake on 7/7 and recovered on 10/13, timeframes anticipated to span the HABs season. The Fire Lane 20 site on Owasco Lake had a slightly later deployment, 7/10, to interface with the local homeowner's wishes. The Owasco deployments were recovered earlier than Seneca to allow homeowners to remove their docks for the winter and the onset of winter ice. Each site was visited every two to three weeks to replace the camera batteries (if necessary), and swap the camera's SD memory card for image analysis in the laboratory.



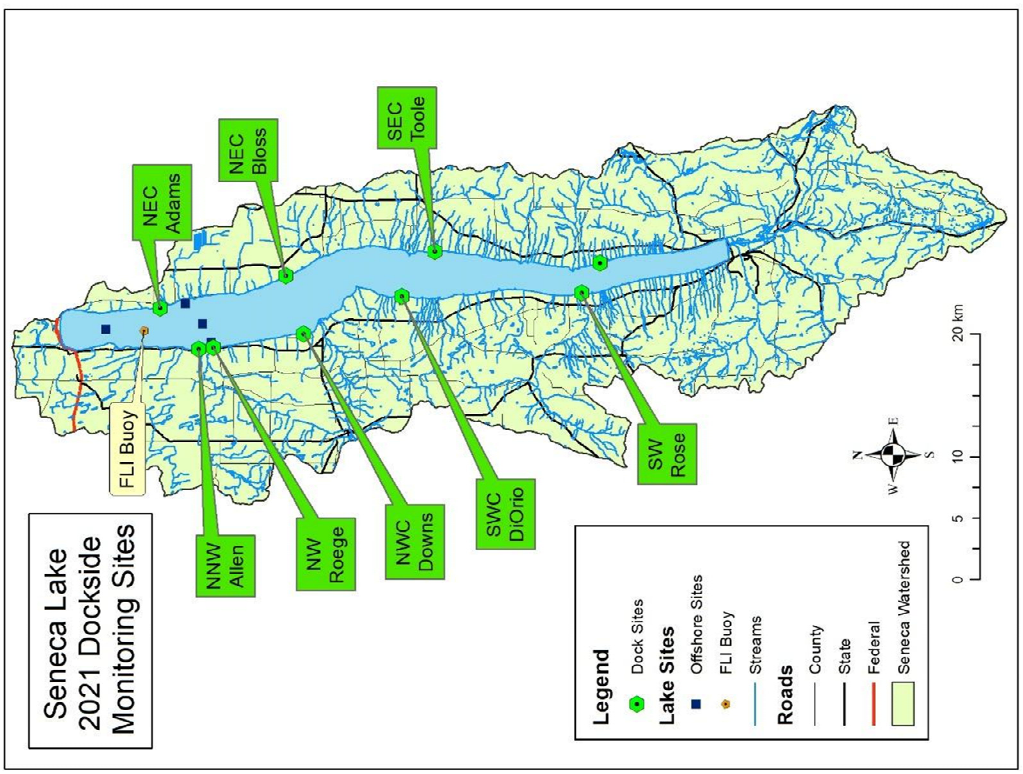


Fig. 2. The 2021 dock, nearshore and offshore site locations in Owasco (above) and Seneca (below) Lakes.

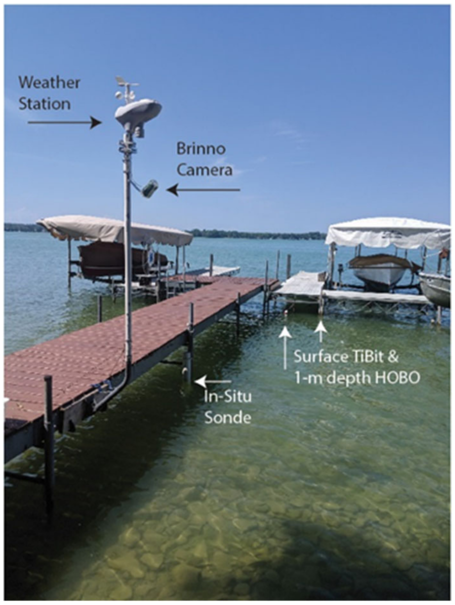


Fig. 3. Weather station, Brinno camera and logger/sonde deployments at a dock (right). The *In-Situ sondes* and a temperature logger (*HOBOs*) were placed inside separate PVC pipes and strapped to a dock leg. The pipes protected the instrumentation from waves.

Offshore Data: Weekly offshore water quality monitoring data from Seneca and Owasco Lakes and daily data from the FLI monitoring buoys were used to place the nearshore data in perspective. Offshore monitoring sampled four sites in the northern portion of Seneca Lake and two sites in Owasco Lake, as these sites provided representative data for the entire lake in the past (Fig. 2). At each site, a CTD water quality profile, Secchi disk depth, vertical plankton tow (80-μm mesh), and surface and bottom water samples were collected. The CTD electronically measures water column profiles of temperature (°C), conductivity (reported as specific conductance, μS/cm, a measurement proportional to salinity), dissolved oxygen (mg/L), pH, turbidity (NTUs), photosynthetic active radiation intensities (PAR, $\mu E/cm^2$-s), and fluorescence (a measure of chlorophyll-a, μg/L) using a SeaBird SBE-25 CTD. The CTD was lowered from the surface to the lake floor, collecting data every 0.5 second (~0.1 meters) along the downcast. Phytoplankton was collected using an 80 μm mesh net integrating the algae through a depth of ~20 m. The net contents were preserved in a lugols (iodine) solution and enumerated to species when possible otherwise to genus level back in the laboratory under a microscope.

Water samples were analyzed onsite for temperature (°C), conductivity (specific conductance, μS/cm), dissolved oxygen (mg/L), and alkalinity (mg/L, $CaCO_3$) using hand-held probes and field titration kits, and aliquots were analyzed back in Halfman's research laboratory for total phosphate (TP, μg/L, P), soluble reactive phosphate (SRP, μg/L, P), nitrate (NO_x, mg/L, N), chlorophyll-a (μg/L) and total suspended solid (TSS, mg/L) concentrations using standard limnological spectrophotometric techniques. Additional aliquots were analyzed by FluoroProbe in the Finger Lakes Institute lab to determine the relative concentrations of: 'green' algae (Chlorophyta and Euglenophyta), 'brown' algae (diatoms: Baccillariophyta, Chyrsophyta, and Dinophyta), 'blue-green' algae (Cyanophyta), and 'red' algae (Cryptophyta).

FLI Monitoring Buoys: A FLI meteorological and water quality monitoring buoy manufactured by YSI/Xylem was redeployed at its mid-lake site in Owasco Lake from 4/18 through 11/2 and at its northern mid-lake site in Seneca Lake from 4/13 through 11/3 (Fig. 2). Each buoy was again programmed to collect water column profiles with an *YSI/Xylem* EXO2 water quality sonde every 12 hours (noon and midnight). The sonde detected temperature, conductivity, dissolved oxygen (by optical sensor), turbidity (by backscattering), and fluorescence. The fluorescence sensor measured both total chlorophyll and cyanobacteria phycocyanin concentrations (after specific pigment excitation by different wavelengths of light). Data were collected every 1.5 meters down the water column starting at 1-m below the surface. The buoy also contained a standard suite of meteorological sensors recording five-minute mean, air temperature, barometric pressure, relative humidity, light intensity, wind speed and wind direction data every 30 minutes. Raw data were periodically transferred to HWS by cellular phone ~1 hour after collection and archived in a database on a user accessible website (http://fli-data.hws.edu/buoy/owasco/). Minimal solar power and other issues prevented collection of water quality data on 9/29 in Owasco Lake and 9/21 – 9/24, 10/4 – 10/5, and 10/24 in Seneca Lake. The meteorological data collection was not interrupted on both buoys.

Each EXO2 sonde was calibrated before and after the deployment, and minimal instrument drift was noted. The raw buoy data were then calibrated against *in situ* CTD and laboratory data collected over the entire field season from the offshore sites, and the calibrated data are presented in this report. The cyanobacteria concentrations were normalized to a constant temperature due to the sensor's temperature sensitivity as well. Calibrated data will be available on this website soon.

Limiting Nutrient Assays: A series of mesocosm experiments to determine limiting nutrients in Owasco water were conducted between June and September on Owasco Lake following the procedures of Lewis et al[2]. Typically, the limiting nutrient for lakes is assumed to be phosphorus, but some lakes can also be nitrogen limited or co-limited with phosphorus and nitrogen. The limiting nutrient can also change from month-to-month. For these experiments, filtered water (153 µm mesh was used to exclude large invertebrates and colonial forms of phytoplankton) was distributed to twelve 500 mL Bitran bags representing triplicates of four treatments – control (no amendments), phosphorus (addition of 13 µg/L of soluble reactive phosphorus, a lower concentration than was used in 2020 mesocosm experiments), nitrogen (addition of 168 µg/L each of nitrate and ammonium), and a combination of the phosphorus and nitrogen treatments.

The mesocosm chambers were then randomly placed into a PVC rack with mesh that allowed for incubation at the water surface, which was a small pond on the HWS Hanley Preserve property (Fig. 4). A screen was placed over the top of the rack to decrease the bag's exposure to solar radiation. Solar radiation and temperature were measured throughout the incubation period using Onset dataloggers. At the conclusion of the five-day incubation period, individual samples were poured off for chlorophyll analysis and were analyzed using the bbe FluoroProbe in the FLI laboratory. Box and whisker plots were completed to determine differences in chlorophyll concentrations within and across treatments.

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[2] Lewis et al. (2020) Inland Waters, 10:1, 42-50, DOI: 10.1080/20442041.2019.1664233

Sediment Nutrient Flux Experiments: Sediment flux experiments were conducted on sediment cores collected at Site D, offshore of Burtis Point (Fig. 2). This location builds on a previous pilot study to better understand the cycling of nutrients to and from sediments. These experiments are based on recently completed work on Honeoye Lake where FLI worked with researchers from Wright State University in OH to examine phosphorus and nitrogen species released from sediment cores to overlying water.

Fig. 4. Mesocosm racks floating in a pond at Hanley Preserve. Incubations were conducted in a small pond at the HWS Hanley Preserve to reduce the likelihood of losing or breaking a rack due to waves and winds in Owasco Lake. Temperature and solar radiation measurements were made at the site every five minutes during the five-day incubation.

The Owasco Lake sediment experiments used eight intact sediment cores with associated overlying site water collected from Site D in September 2021. For time zero (T_0) water samples, water samples for nutrient (SRP, NO_2-NO_3 or NO_x, NH_4) analysis were collected at 0.5 m depth and filtered in the field through sample-rinsed, 0.22-µm, nylon syringe filters. After filtering, sample vials were placed on ice in the field, and frozen upon return to the laboratory where nutrient analysis was performed on the FLI's Lachat system as described below.

For the sediment incubations, eight cores (~10-15 cm of depth) with overlying water were collected by divers using hand core tubes (6.75 cm diameter) at the site in a water depth of ~ 3 m using the methods of Gardner and McCarthy, 2009[3]. In addition, site water for the sediment flux incubations was also collected in four pre-rinsed, 20-L cubitainers® for each treatment group (Figs. 5 & 6).

In the laboratory, continuous-flow incubations of intact sediment cores were started within ~2 hr of field collection. In total, the eight sediment cores collected from the site were incubated over 72 hr with site water (control) as well as the following treatments (i) phosphorus (P), (ii) nitrogen (N), and (iii) a combination of nitrogen plus phosphorus (N+P). Amended treatment groups were representative of ambient nutrient concentrations at the sediment interface. Phosphorous additions consisted of NaH_2PO_4 (phosphate) at a target concentration of 2.5 µg/L. Nitrogen additions consisted of both $NaNO_3$ (nitrate) and NH_4Cl (ammonium) at target concentrations of 50 µg/L and 30 µg/L respectively.

For the incubations, core tubes were wrapped in heavy duty aluminum foil to replicate light levels in the sediment and fitted with a gas-tight plunger using an O-ring seal. Each treatment group received aerated site water from the cubitainer through

[3] Gardner WS, McCarthy MJ, Carini SA, Souza A., Lijun H., McNeal KS, et al. 2009. Collection of intact sediment cores with overlying water to study nitrogen- and oxygen-dynamics in regions with seasonal hypoxia. *Continental Shelf Research* 29:2207-2213.

polyetheretherketone tubing connected to the inflow and outflow ports of a peristaltic pump at a flow rate of ~1.15 mL of site water per minute. Inflow and outflow waters were sampled at 24 hr intervals and were filtered for SRP, NO_3, and NH_4 analyses. Unfiltered water was also collected for TP analysis. All samples were frozen until analysis. Nutrient concentrations were measured with an automated, colorimetric flow-injection analysis system (QuikChem 8500 Lachat Instruments) according to manufacturer methods and standard EPA protocols for SRP, TP, NO_3, and NH_4.

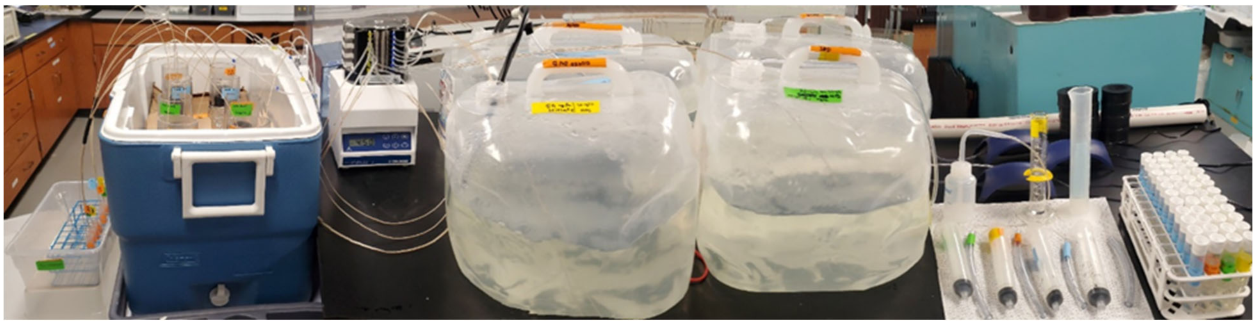

Fig. 5. Sediment nutrient flux experiment setup showing the system inflow of amended source water being pumped at a constant rate to the sediment interface and outflow water being captured for analysis.

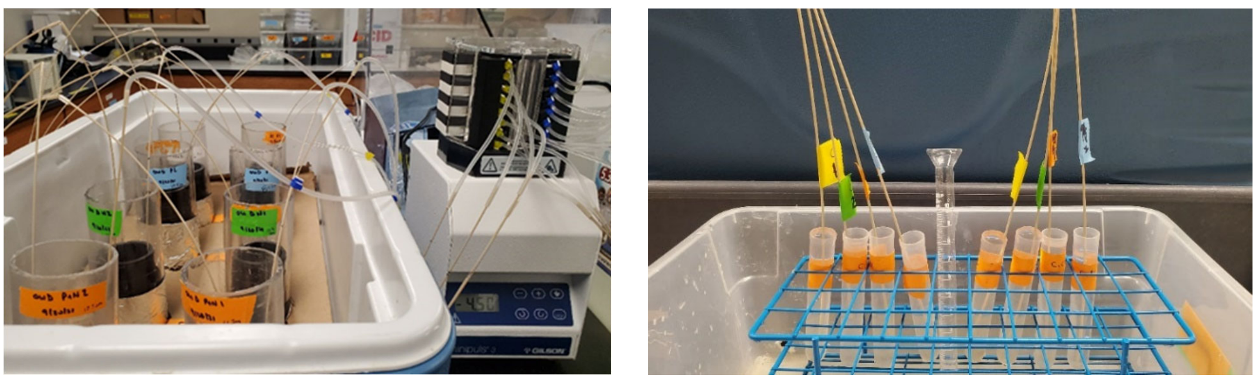

Fig. 6. Flow rates of water for individual sediment cores are adjusted to specific flow rates via a roller tensioning pump to allow for controlled nutrient, water, and sediment interactions.

Mussel & Macrophyte Surveys: Macrophyte and zebra/quagga mussels were sampled in shallow water at three nearshore sites C (near Stone School Rd), D (Burtis Point), and G (Yacht Club), in July 2021 (Fig. 2). Sites were selected based on substrate type, water depth (2 – 3 m), and previous sampling efforts. Site G is categorized by hard substrate where predominantly cobbles and larger boulders are present, whereas Sites C and D have macrophyte covered soft substrate. At each site, three, replicate 0.5 x 0.5m quadrats were randomly tossed into the water. Scuba divers removed all of the plants and mussels in each quadrat and placed them in corresponding labeled mesh dive bags. Collected macrophytes were then separated, identified to species, and weighed. If greater than 200g were collected, subsamples were collected for weights. Mussels present on collected macrophytes were counted, sorted by species (Zebra vs. Quagga), and wet weights were recorded. Mussels were further categorized into small (0-8mm), medium (8-15mm), and large (>15mm) size classes.

SENECA AND OWASCO LAKES

Seneca and Owasco Lakes are two of the eleven Finger Lakes in central New York State (Fig. 1). Both are elongated, north-south orientated, borderline oligotrophic (low productivity) – mesotrophic (medium productivity) lakes, i.e., experience moderate algal productivity and oxygenated bottom waters, and have experienced cyanobacteria blooms. However, important differences exist. For example, Seneca Lake is much larger, deeper, and has a much longer water retention time than Owasco Lake (Table 1). These physical characteristics influence factors like fetch, which impacts the maximum size of wind driven waves, i.e., waves are much larger in Seneca than Owasco Lake given the same wind speed and direction. A smaller watershed to lake surface area ratio in Seneca Lake makes it less susceptible to activities within the watershed like nutrient and sediment loading than Owasco Lake. Both lakes are critical to the local, agro-tourism economy with internationally known wineries. They also supply municipal drinking water to nearby communities.

Table 1. Physical & Other Characteristics of Seneca and Owasco Watersheds[4].

Characteristic	Seneca Lake	Owasco Lake
Maximum Length (km)	57	18
Maximum Width (km)	5.2	2.1
Shoreline Length (km)	123.6	41.3
Lake Surface Area (km^2)	175	27
Watershed Area (km^2)	1,181	470
Watershed/Lake Surface Area Ratio	6.7	17.4
Volume (km^3)	15.5	0.78
Max Depth (m)	198	54
Water Retention Time (yr)	18 (13 to 23)	2 (1.5 to 4)
Land Use (% Forest / Agriculture / Urban / Lake)	38 / 40 / 6 / 15	35 / 49 / 5 /11
Permitted Drinking Water Withdrawals (MGD)	9	16

CYANOBACTERIA AND HARMFUL ALGAL BLOOMS BACKGROUND

Many species of cyanobacteria exist, each trying to gain an ecological advantage over the others. For example, some species of *Dolichospermum* (formerly *Anabaena)* can "fix" atmospheric nitrogen (N_2) for their source of nitrogen to synthesize organic matter. Most other forms of cyanobacteria including *Microcystis* cannot "fix" N_2, and are instead dependent on the dissolved forms of nitrogen like nitrate (NO_3^-), nitrite (NO_2^-), and preferably ammonium (NH_4^+). Nitrogen fixing cyanobacteria have an ecological edge in nitrogen-limited lakes like Honeoye. Nitrogen limitation should not be a concern in Seneca or Owasco and the other phosphorus-limited Finger Lakes, especially in the open water. However, the details of the phosphorus and nitrogen dynamics, especially the different types of nitrogen, are not very well understood. Both *Dolichospermum* and *Microcystis* were most often cyanobacteria genera detected in Seneca and Owasco Lakes. *Dolichospermum* typically preceded *Microcystis* in a given field season, and *Microcystis* dominated the plankton counts on most days when cyanobacteria were detected.

[4] Callinan, C., 2001. Water Quality of the Finger Lakes. New York State Department of Environmental Conservation Report. 152 pg.

Cyanobacteria blooms are not only unsightly surface scums, but they may also produce a variety of toxins that are health threats to humans and other warm-blooded animals (e.g., dogs). The toxin story is complicated. Not all cyanobacteria taxa synthesize toxins. Cyanobacteria taxa that can synthesize toxins do not do it all the time. The environmental triggers that induce toxin production are poorly understood. To complicate the situation, different toxins are synthesized by different cyanobacteria taxa, and each toxin, in sufficient concentrations, can impact different parts of the body, most notably, the skin, liver, gastrointestinal and/or nervous systems. Liver cyanotoxins like microcystins are most commonly found in HAB blooms, and can cause organ damage, heart failure and death at high doses in lab animals. Microcystins are a class of related toxin compounds (heptapeptides) that can be synthesized by various species of *Microcystis* and *Dolichospermum*. Because both are common in NY lakes, total microcystin is commonly measured in New York State to assess cyanobacteria toxin status. Another common toxin group, anatoxins, impact the nervous system, and can be synthesized by *Dolichospermum* and other cyanobacteria genera but not *Microcystis*. The presence of toxins cannot be determined visually but instead requires a chemical test.

The concentration guidelines when these toxins impact human health still remains unclear. The World Health Organization (WHO) has issued a provisional finished drinking water guideline of 1 μg/L for chronic exposure to microcystin, and recreational exposure limit of 20 μg/L[5]. The EPA's drinking water guideline for microcystin is 0.3 μg/L for infants and 1.6 μg/L for school-age children and adults; their recreational contact limit is 4 μg/L. No thresholds are set for anatoxins yet, although 0.5 μg/L is used by Vermont in their drinking water guidelines[6]. The anatoxin half-life, the time interval for decomposition, is very short, less than 24 hours, which makes detection in the water column difficult. The DEC defines a cyanobacteria bloom when the cyanobacteria chlorophyll (phycocyanin) concentration exceeds 25 μg/L, and a bloom is reclassified as a harmful algal bloom (HABs), or a bloom with high toxins, when microcystin concentrations exceed 20 μg/L in nearshore areas and 10 μg/L in offshore areas.

Harmful algal blooms are not unique to Seneca and Owasco Lakes. Major cyanobacteria blooms were confirmed in all of the Finger Lakes in the recent past (Fig. 7). Nearly two hundred lakes in New York State (192) officially reported cyanobacteria blooms in 2021 out of the 7,849 lakes in the state (all identified lakes and ponds with or without monitoring programs, Rebecca Gorney, DEC, pers. comm.). Other lakes may have experienced unreported blooms.

Lakeshore residents with private water systems should use bottled water during cyanobacteria outbreaks along their shoreline because their private water supply systems are challenged to remove cyanobacteria from the water without bursting the organism's cell walls[7]. For example, filtration used by many private systems can easily compromise the cell wall integrity. It is critical because once it is compromised, the toxins can be released to the water, and more easily impact human health. The watershed should seriously consider extending municipal water around the lake to decrease the potential health risks from drinking lake water.

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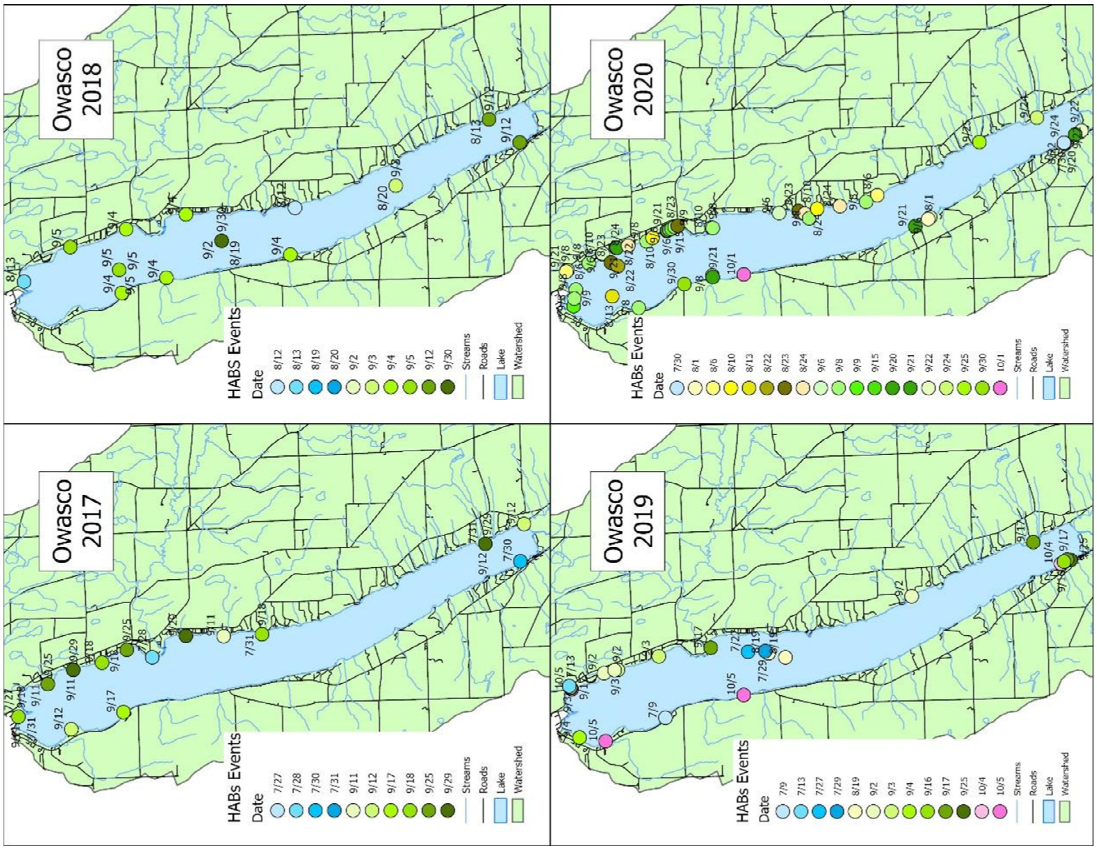
[5] WHO, 2011. Guidelines for Drinking Water Quality. 4th Edition. World Health Organization. Switzerland.

[6] https://www.epa.gov/nutrient-policy-data/guidelines-and-recommendations

[7] A Water Utility Manger's Guide to Cyanotoxins. 2015. Water Research Foundation, American Water Works Association, 18 pgs. www.waterrf.org


Owasco 2017
Owasco 2018
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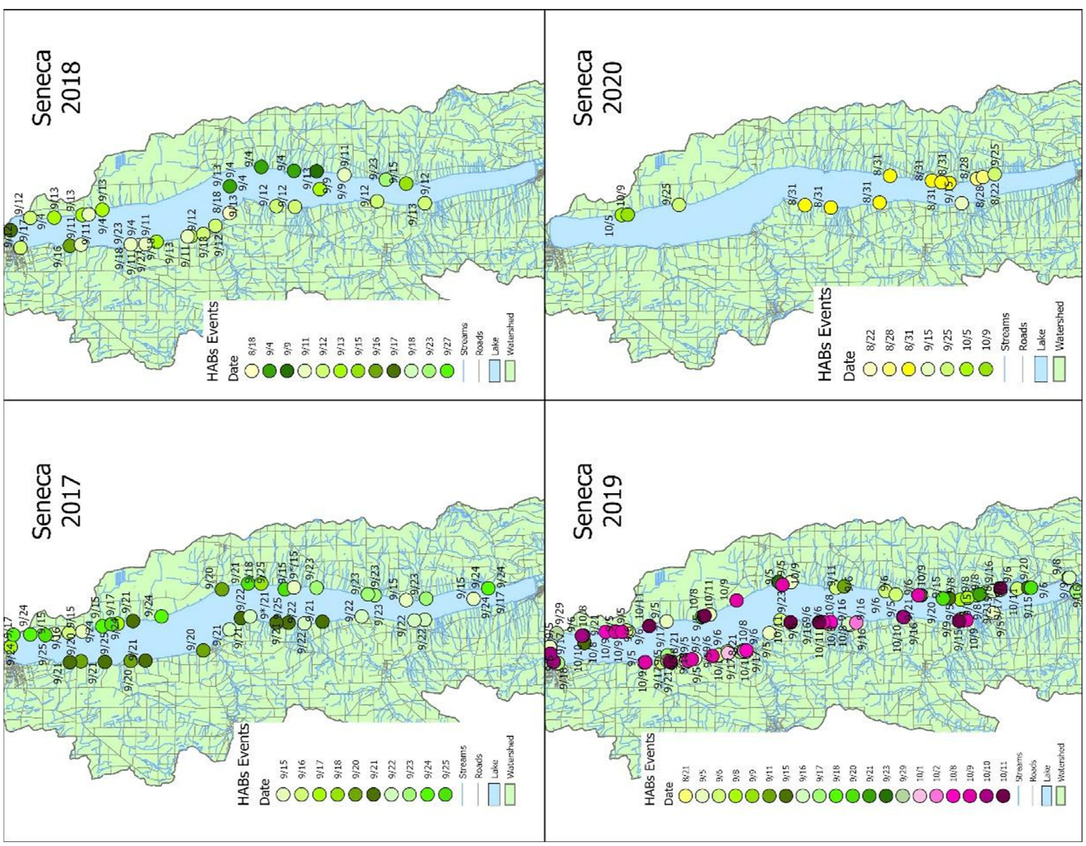
Owasco 2020
HABs Events
Date
Streams
Roads
Lake
Watershed


Seneca 2017
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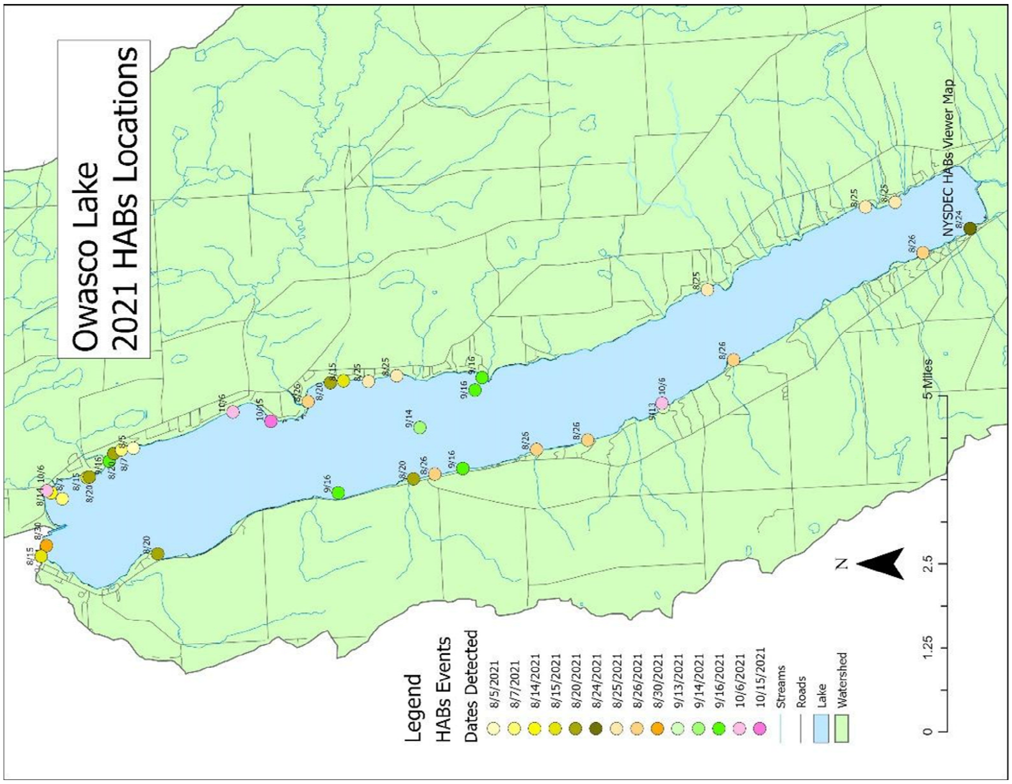


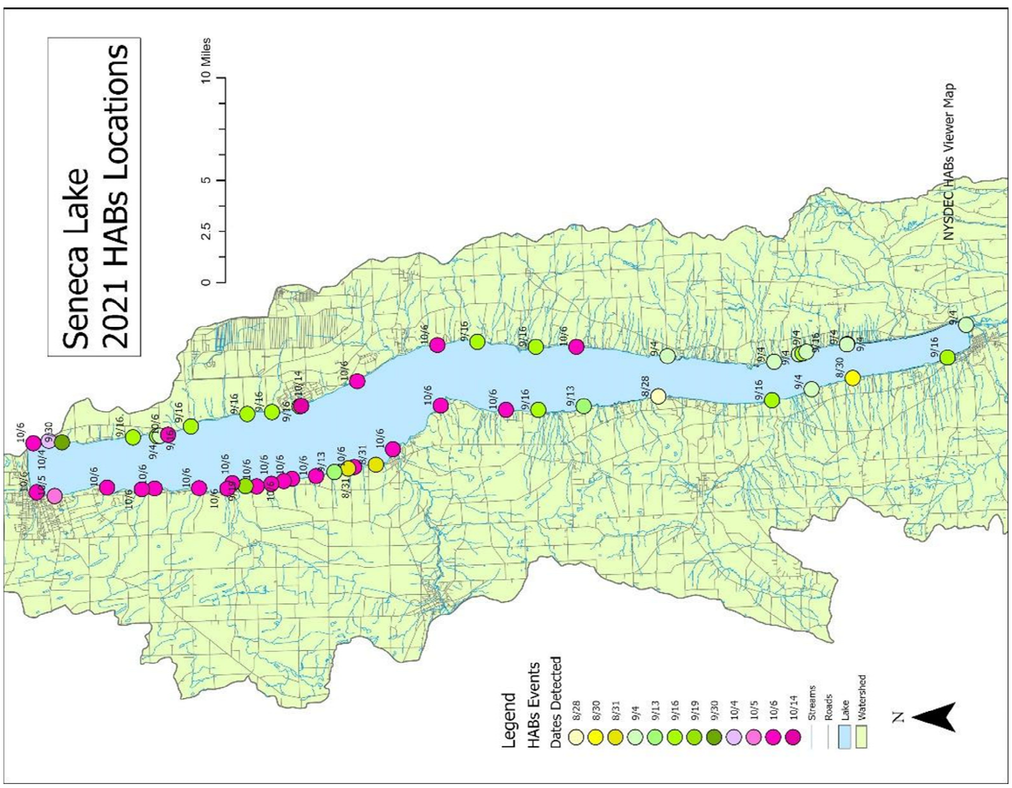


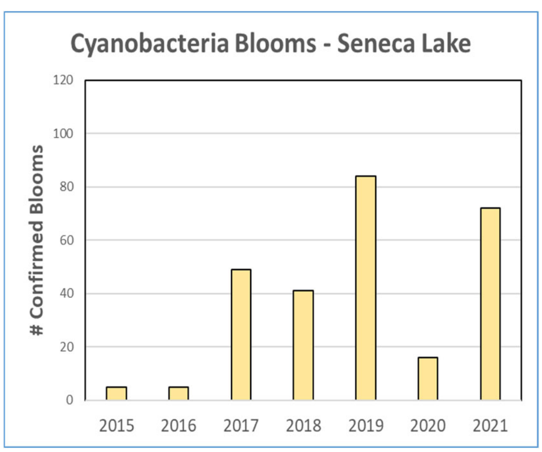
Fig. 7. Confirmed cyanobacteria bloom locations in Seneca and Owasco Lake during 2017-2020 (previous page) and 2021 (above). Data are from the NYS-DEC HABs Map websites.

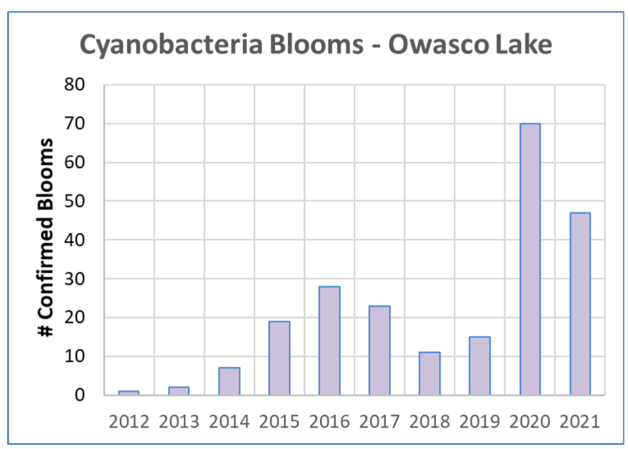
Seneca and Owasco Lakes have experienced significant surface-water, nearshore, cyanobacteria (cyanobacteria) blooms, some with toxic levels of microcystin and other toxins (Fig. 8). In Seneca Lake, blooms were first detected in 2015. Since then, 2017 – 2019 annual mean cyanobacteria concentrations ranged from 3,600 to 6,700 µg/L (Max: 59,000 to 118,000 µg/L) and 2017 – 2018 mycrocystin toxin concentration ranged from 47 to 290 µg/L (Max: 670 to 2,100 µg/L). In Owasco Lake, blooms were first detected in 2012 with annual mean cyanobacteria concentrations ranged from 140 to 4,960 µg/L (Max: 1,100 to 45,500 µg/L) and mycrocystin toxin concentration ranged from 240 to 750 µg/L (Max: 1,100 to 45,500 µg/L; see Table within Fig. 8). The DEC processed concentration and toxin data during 2017 – 2019. DEC confirmed bloom sightings in 2020 and 2021 were tallied from the NY HABS website.[8]

Most importantly, the number of DEC confirmed blooms were significantly different between the two lakes (Fig. 8). From 2017 through 2019, more blooms were detected in Seneca Lake (40 to 85 each year) than Owasco Lake (10 to 23). Lake size explains some of these differences. Normalizing the bloom counts to length of shoreline, the Seneca Lake volunteers detected 0.40 to 0.68 blooms/km of shoreline compared to a similar 0.27 to 0.61 blooms/km of shoreline in Owasco Lake.

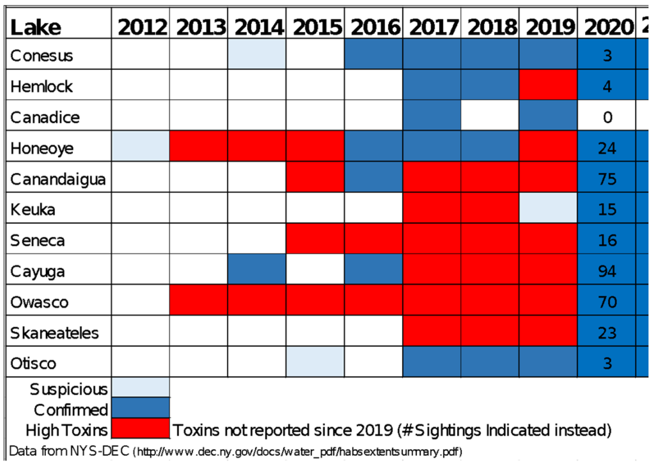
The number of bloom sightings changed drastically in 2020. It decreased to 16 confirmed blooms in Seneca (0.12 blooms/km) and increased to a record high 115 blooms in Owasco (1.7 blooms/km). These changes were probably real despite other potential factors that can influence bloom counts in any one year like, e.g., the number of volunteers, the fraction of shoreline surveyed, the day and time of the weekly survey, and number of days in the survey. This difference is the primary reason why the Seneca and Owasco reports were combined in 2020 to determine potential water quality and/or meteorological variables that influenced this change.

The number of confirmed bloom reports in 2021 was the 2nd largest since 1st official appearance in both lakes (Fig. 8). They increased to 72 in Seneca Lake and decreased to 47 in Owasco Lake from 2020 counts. It appears that conditions were prime for bloom activity in both lakes. As a comparison, Canandaigua reported 84 confirmed blooms in 2021, whereas Cayuga 117, or 1.3 blooms/km and 0.62 blooms/km, respectively. Less than 50% of the Cayuga shoreline was surveyed in 2021, thus its bloom/km value should be proportionally larger.





[8] NY HABs Map.



Cyanobacteria & Mycrocystin Concentrations

Annual Means	Seneca	Owasco
Cyanobacteria (µg/L)		
2017	6,580	4,910
2018	4,280	4,960
2019	3,660	n/a
Mycrocystin (µg/L)		
2017	47	400
2018	290	750

Fig. 8. Annual numbers of confirmed cyanobacteria blooms detected by the volunteers and compiled by DEC (NYS HABs Maps), Seneca (above left), Owasco (above right). The number of Finger Lakes with suspicious bloom activity, confirmed blooms and confirmed blooms with high toxins since 2012 (bottom left, by permission DEC). The DEC stopped cyanobacteria and toxins analyses after 2019. Since then, only report the number of confirmed blooms (2020 and 2021).

OFFSHORE WATER QUALITY MONITORING

The following section compared the open-lake water quality data with the following "preferred" cyanobacteria water quality conditions:

- warm water, temperatures between 15 to 30°C (60 and 80° F);
- elevated (eutrophic) concentrations of nutrients, especially waters rich in phosphorus, the limiting nutrient for many cyanobacteria;
- light levels that are sufficient for photosynthesis and growth;
- lake stratification, as cyanobacteria buoyancy regulation provides a competitive edge in a warm, stratified water column;
- calm or near-calm conditions as turbulence disrupts cyanobacteria buoyancy;
- rainfall, as rain events deliver nutrients to the lake; and,
- an alkaline pH.

This section also points out potential "triggers" for cyanobacteria blooms in these two lakes. Keep in mind, predicting their occurrence remains a challenge due to the large number of cyanobacteria species and the diversity of their habitats. Predicting cyanobacteria blooms in the Finger Lakes is significantly more challenging because most of these lakes are oligotrophic to mesotrophic systems, and not the nutrient-rich, eutrophic lakes, where cyanobacteria blooms were more common in the past. Most importantly, Seneca and Owasco Lakes are not eutrophic.

Algal Populations: Offshore FluoroProbe concentrations revealed low concentrations of cyanobacteria pigments in the plankton communities of both lakes, especially in August and September, the bloom season (Fig. 9). Diatoms dominated the communities in both lakes in the early spring and fall, green algae and cryptophytes in mid-summer, and cyanobacteria in the late summer and early fall. Over the past few years, the relative concentration of cyanobacteria increased in Owasco Lake to 2020 then decreased to 2019 values in 2021. This is consistent with visual observations at Owasco Lake that noted an increased presence of cyanobacteria in the surface water throughout the lake in 2020. Similar fluctuations in cyanobacteria were not observed in Seneca Lake.

Mean annual plankton enumerations paralleled the FluoroProbe results (Fig. 10). *Diatoma* (spring), *Asterionella* (spring) and *Fragillaria* (fall) were the three common species of diatoms. *Dolichospermum* (formerly *Anabaena*) and *Microcystis* were the two common forms of cyanobacteria. Low counts of *Dolichospermum* appeared before and was followed by much larger counts of *Microcystis* later in the HABs season. Varieties of green algae and dinoflagellates make up the rest of the communities. The plankton net mesh is too coarse (80 µm mesh) to collect most cryptophyte species.

Fig. 9. Offshore, surface grab, date averaged, bbe FluoroProbe concentrations of the four algal groups from 2017 through 2021 in Seneca (above) and Owasco (below) Lakes.

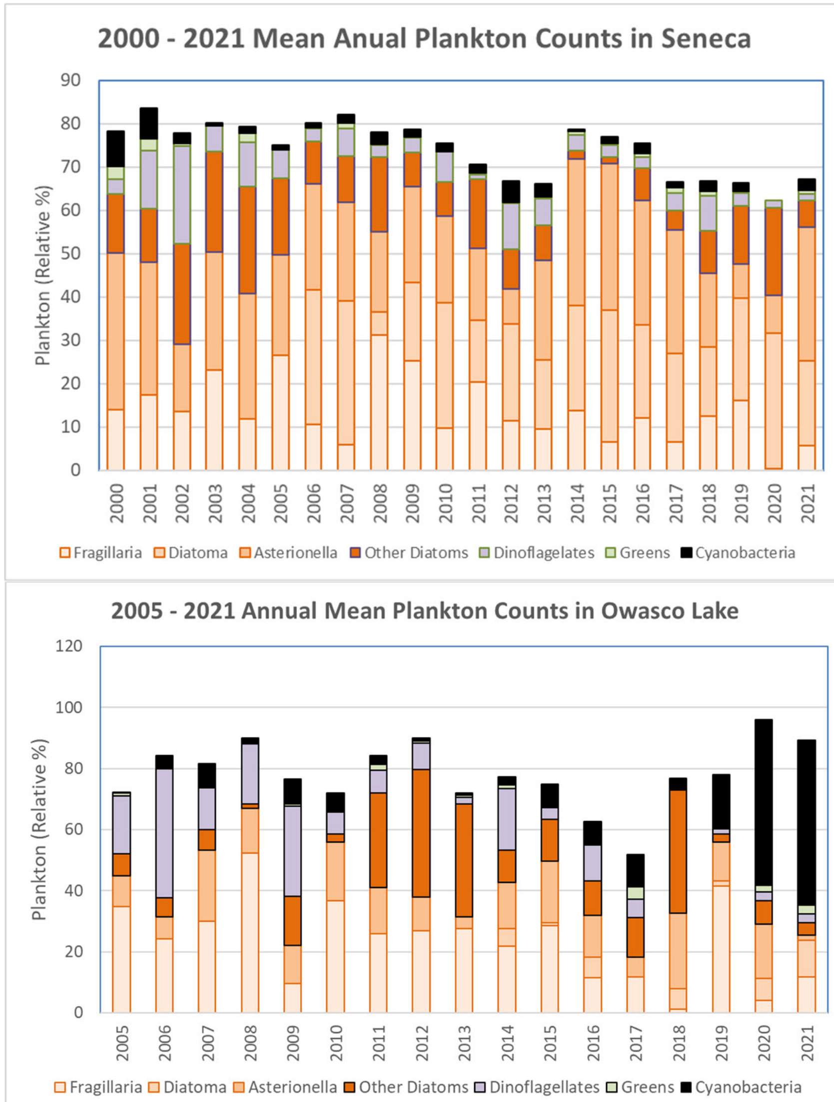
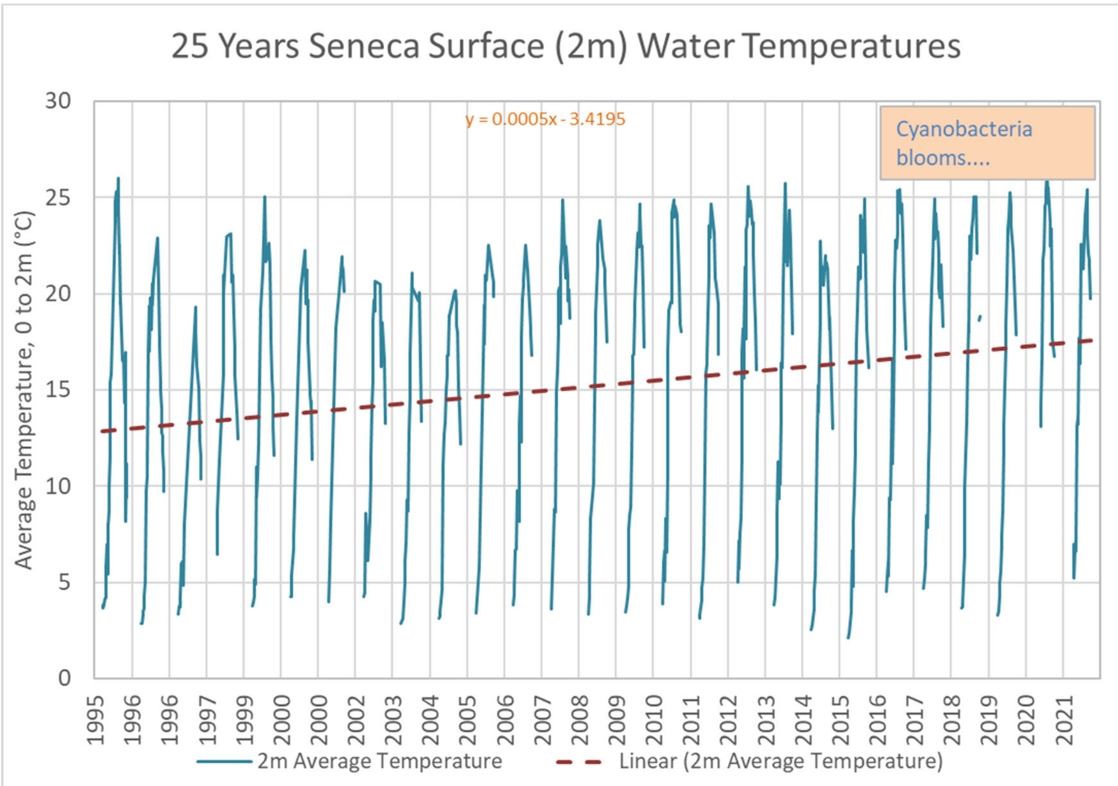
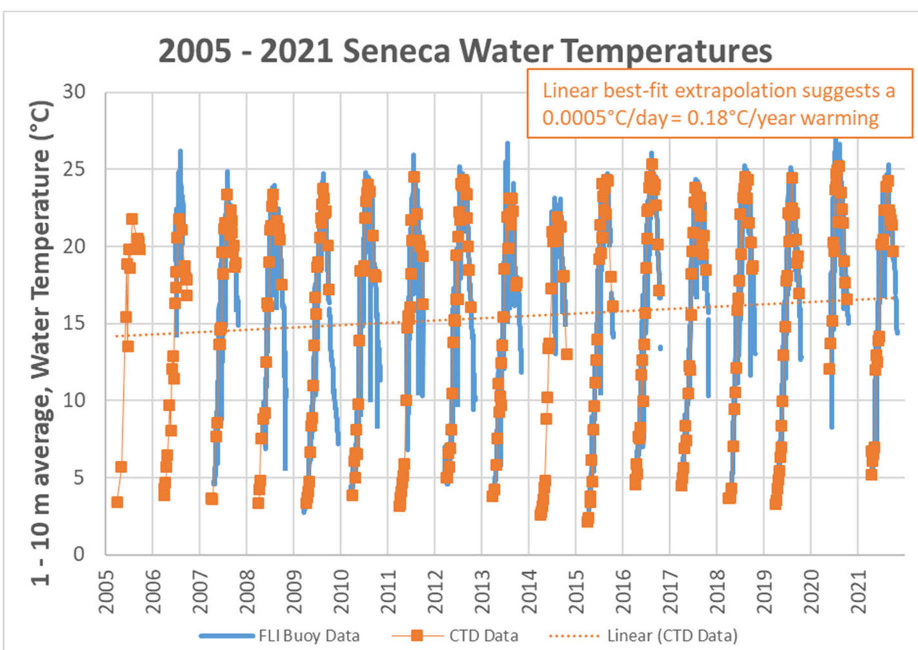


Fig. 10. Mean annual plankton counts from offshore vertically integrating (15m deep) plankton tows (80 µm mesh) in Seneca (above) and Owasco (below) Lakes.

Cyanobacteria dominated the plankton counts (40 to 95%) in Owasco Lake during the 2020 and 2021 August to September HABs season but not Seneca Lake. Perhaps cyanobacteria had additional time to become more firmly established in Owasco Lake and/or nutrient sources were more ideal for cyanobacteria proliferation in Owasco Lake than Seneca Lake.

Surface Water Temperatures by CTD: Surface water temperatures measured by CTD since 1995 in Seneca Lake indicate that surface waters have warmed over the past two decades (Fig. 11). Water temperatures detected in 2020 were the warmest in this dataset, and the 2021 maximum temperatures were similar to those over the past 5 years. The linear, best-fit line to the data suggests that Seneca Lake has warmed approximately 0.18°C/year, a result of Global Warming (0.0005°C/day). The warming was not uniform but instead occurred in a step function with a few years occasionally deviating above and below the linear warming trend. More importantly, the water temperatures over the past five years were the warmest detected over the past two decades, the warming coincident with cyanobacteria blooms. A similar warming trend was detected in Owasco Lake (0.21°C/year). Since 2012, the first detection of cyanobacteria in Owasco Lake, the surface water was at its warmest, especially the past 7 years. Warmer water probably stimulated blooms in these two lakes as surface water temperatures were within the preferred range for cyanobacteria blooms, and warmer water stimulates faster bacterial respiration, thus releasing more nutrients to support HABs events.





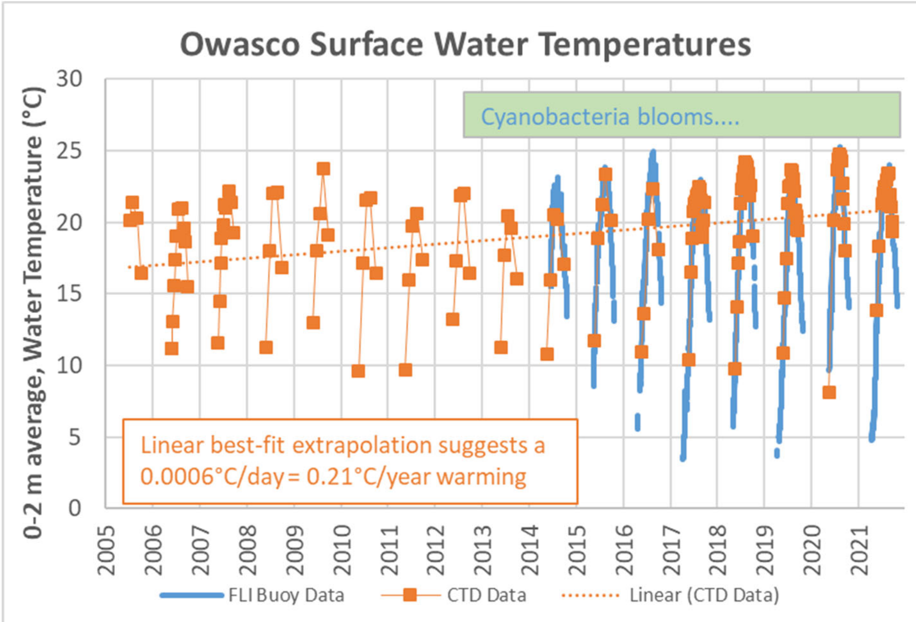


Fig. 11. Surface water temperatures from Seneca (above 1995 to 2021 and 2005 to 2021 datasets) and Owasco (below) Lakes measured by CTD and FLI Buoy. Years with reported cyanobacteria blooms are shown.

Secchi Disk Depths, and Nutrient, Turbidity & Chlorophyll-a Concentrations: Secchi depths, total phosphorus, soluble reactive phosphate, nitrate, total suspended solids and chlorophyll-a concentrations have also changed over time (Fig. 12). In Seneca Lake, deviations in these limnological parameters during the 1990's are related to the introduction and proliferation of zebra mussels, and their impact on the ecology of the lake[9]. During the past decade and coincident with detected cyanobacteria blooms, larger concentrations and larger variability in each year's data was observed, especially the largest values in each year, i.e., the upper whisker of the box and whisker plots. The decade-long increase is attributed to continued nutrient loadings to both lakes.[10] Two years, 2014 and 2015, detected larger concentrations of TP and SRP (2014), and shallower Secchi depths, and larger TSS and chlorophyll concentrations (2015) in Seneca Lake. The unusually high concentrations are interpreted to reflect significant additions of phosphorus and sediments from localized storm events and the resulting runoff (flood-like) events. The 2014 and 2015 timing also corresponds to the initial detection of cyanobacteria blooms in the lake. The historical data suggest that the addition of extra phosphorus, the limiting nutrient in the lake, and the onset of warmer water pushed Seneca Lake over a tipping point in 2015 that triggered subsequent cyanobacteria blooms. Nitrate did not significantly change, perhaps because it is not the limiting nutrient except for a small decline in concentration over the past 4 to 5 years. Once nutrients enter a lake, nutrient recycling typically regenerates the nutrients again and again for additional algal growth in subsequent years. These limnological

[9] Halfman, J.D., 2017. Decade-scale water quality variability in the eastern Finger Lakes, New York. Clear Waters. Fall 2017, v. 47, No. 3, pg. 20-32.

[10] Halfman, J.D., 2017. Decade-scale water quality variability in the eastern Finger Lakes, New York. Clear Waters. Fall 2017, v. 47, No. 3, pg. 20-32.

precursors to the onset of cyanobacteria blooms are also observed in the water quality data from neighboring Finger Lakes[11].

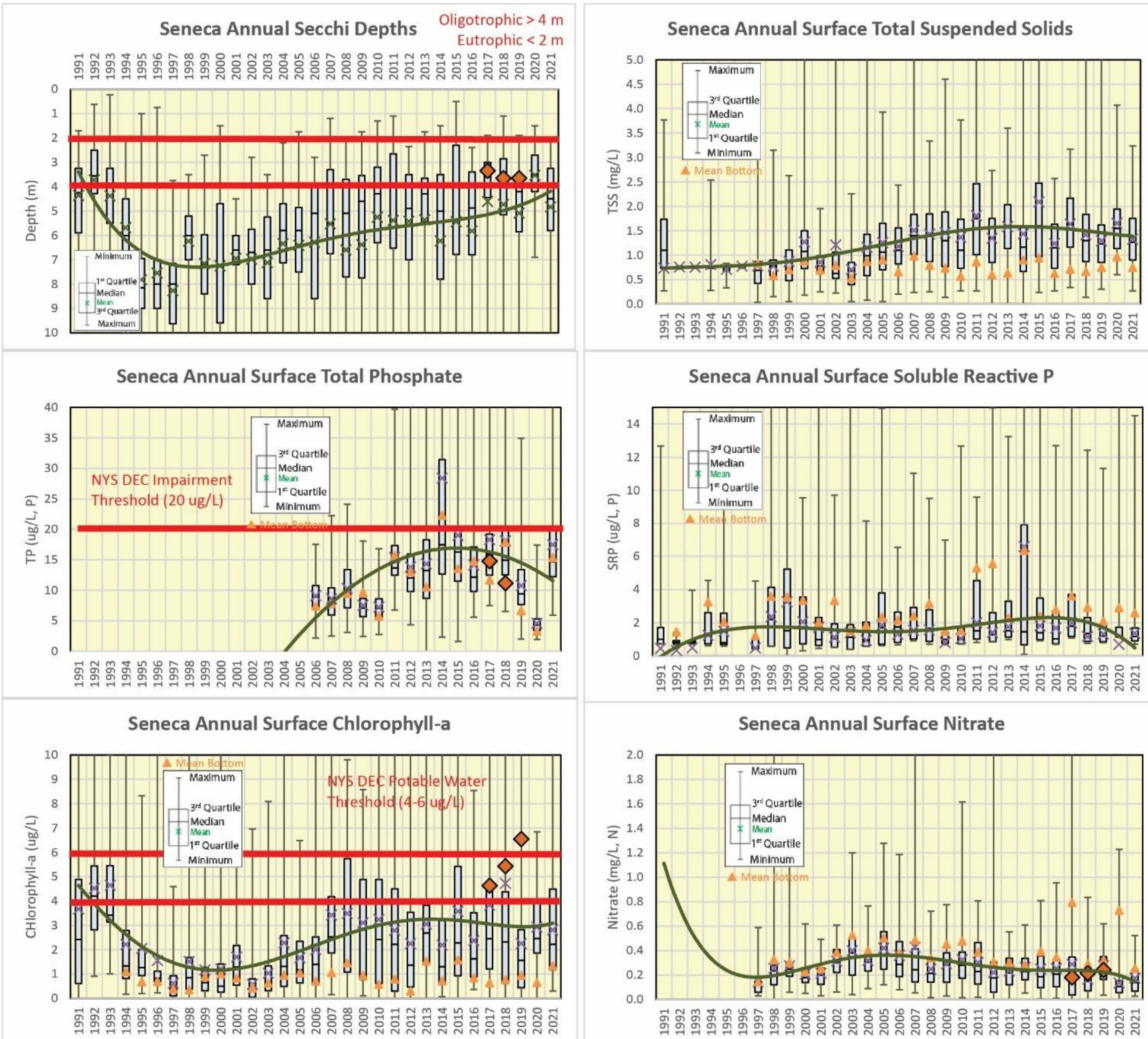


Fig. 12. Historical Secchi depths, nutrient and chlorophyll data from the Seneca Lake monitoring program. The box in the box and whisker plots contain 50% of the available annual data. The lower and upper whiskers correspond to the minimum and maximum values of the available annual data. The orange diamonds plot mean annual C-SLAP data.

[11] Halfman, J.D., 2017. Decade-scale water quality variability in the eastern Finger Lakes, New York. Clear Waters. Fall 2017, v. 47, No. 3, pg. 20-32.

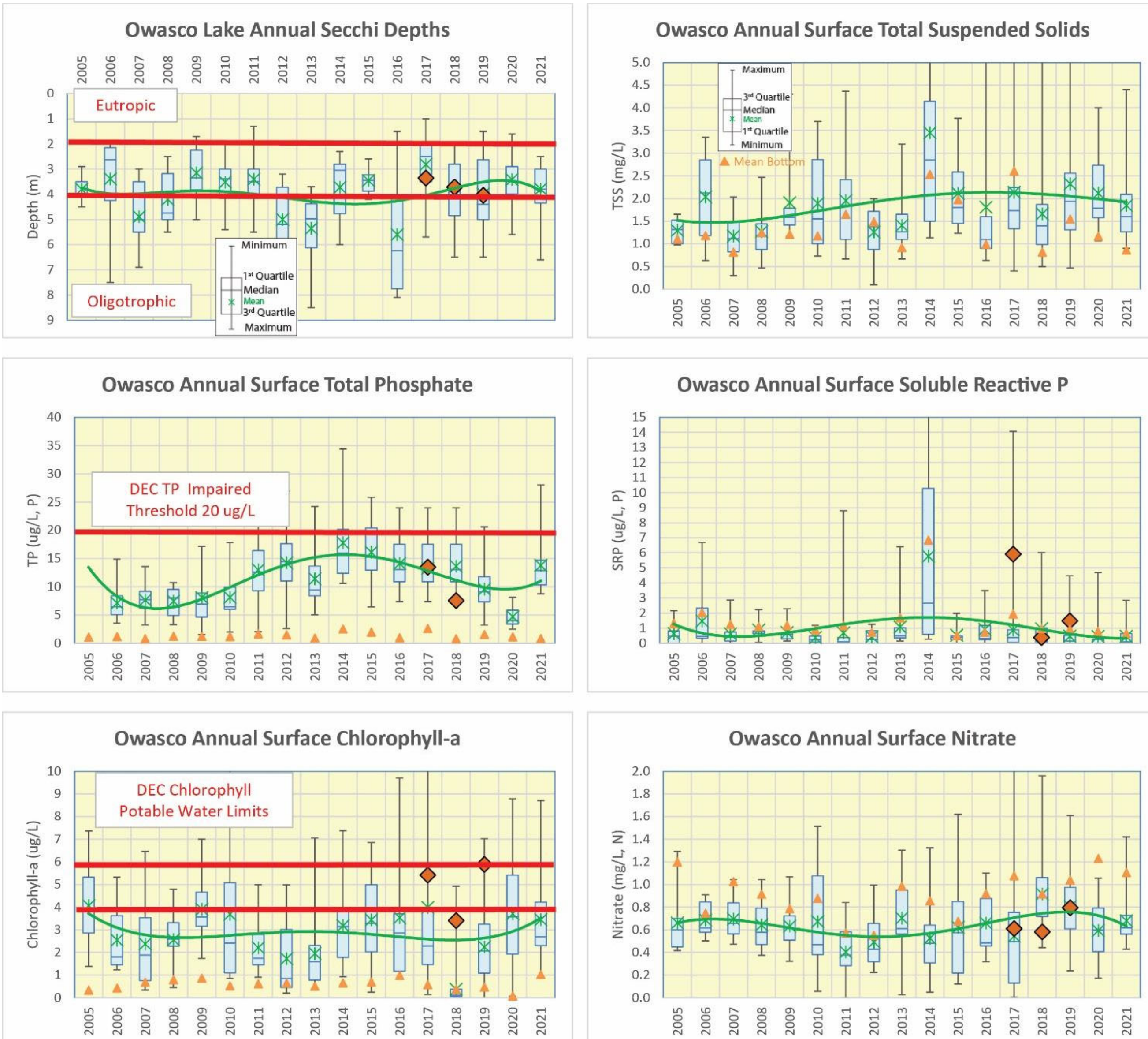


Fig. 12 continued. Historical Secchi depths, nutrient and chlorophyll data from the Owasco Lake monitoring program. The box in the box and whisker plots contain 50% of the available annual data. The lower and upper whiskers correspond to the minimum and maximum values of the available annual data. The orange diamonds plot mean annual C-SLAP data.

Similar changes in limnological parameters were detected in Owasco Lake within the overlapping time frame (Fig. 12). Owasco experienced shallower Secchi disk depths and slightly larger chlorophyll-a concentrations, especially earlier in the record than Seneca. Owasco was also slightly more turbid, experienced smaller maximum total phosphate and soluble reactive phosphate concentrations, and slightly larger nitrate concentrations. These differences indicate that Owasco is slightly more productive, i.e., more mesotrophic than Seneca, and the differences can be attributed to its smaller size, larger watershed to lake surface area ratio, and slightly more agricultural land use / land cover in its watershed. The increased productivity at Owasco Lake may have promoted more blooms earlier in the HABs season than Seneca Lake.

These limnological parameters were not unique enough from themselves or from year to year to influence differences in the cyanobacteria activity in these lakes. The nutrient concentrations available in the open water and nearshore settings of Owasco Lake are, by an order or magnitude (or more), insufficient to support the amount of P and N required for typical cyanobacteria blooms[12].

One 2021 change was noteworthy. Larger total phosphorus (TP) concentrations were detected in both lakes in 2021 compared to 2020. It suggests that an increase in TP concentrations should increase the number of blooms in both lakes. The increase can be attributed to an increase in rainfall in 2021. However, TP does not covary with bloom counts from year to year in either lake. The best example is from 2020 to 2021 where TP increased in both lakes; however, bloom counts increased in Seneca but not Owasco Lake. This nutrient-bloom inconsistency reaffirms that open water nutrients were not the primary nutrient source for the cyanobacteria blooms and stimulated the search for nutrients in the nearshore sediments and lake-floor biota (e.g., macrophytes, *Cladophora* and mussels).

Lake Temperatures by Buoy: The FLI Monitoring buoys provided higher resolution water quality data than the weekly (to monthly) limnological surveys (Fig. 13). On Seneca Lake, the USGS buoy[13] data was used because the FLI buoy was inoperative. The USGS buoy was deployed in shallower water north of the FLI buoy site, and the shallower site influenced the apparent warming of the bottom water temperatures in 2020, as the USGS bottom temperatures sampled the lower epilimnion / upper hypolimnion, instead of the hypolimnion at the FLI buoy site. In other respects, the USGS buoy temperature data were consistent with previous FLI buoy results[14].

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[12] Halfman, J.D., B. Kharrazi*, E. Wilber*, A. Leavitt*, J. Andrews*, W. White*, E. Moore*, P. Spacher, I. Dumitriu, M. Kastan, E. Rosser, T Massey & L.B. Cleckner, 2020. Blue-Green Algae in Owasco Lake, the 2019 Update. The 2019 Annual Report to the Fred L. Emerson Foundation. Finger Lakes Institute, Hobart and William Smith Colleges. 36 pg

[13] https://ny.water.usgs.gov/maps/habs/

[14] Halfman, J.D., et al., 2018. Blue-Green Algae in Owasco Lake: The 2018 Update. The 2018 Annual Report to the Fred L. Emerson Foundation, Finger Lakes Institute, Hobart and William Smith Colleges. 37 pg.

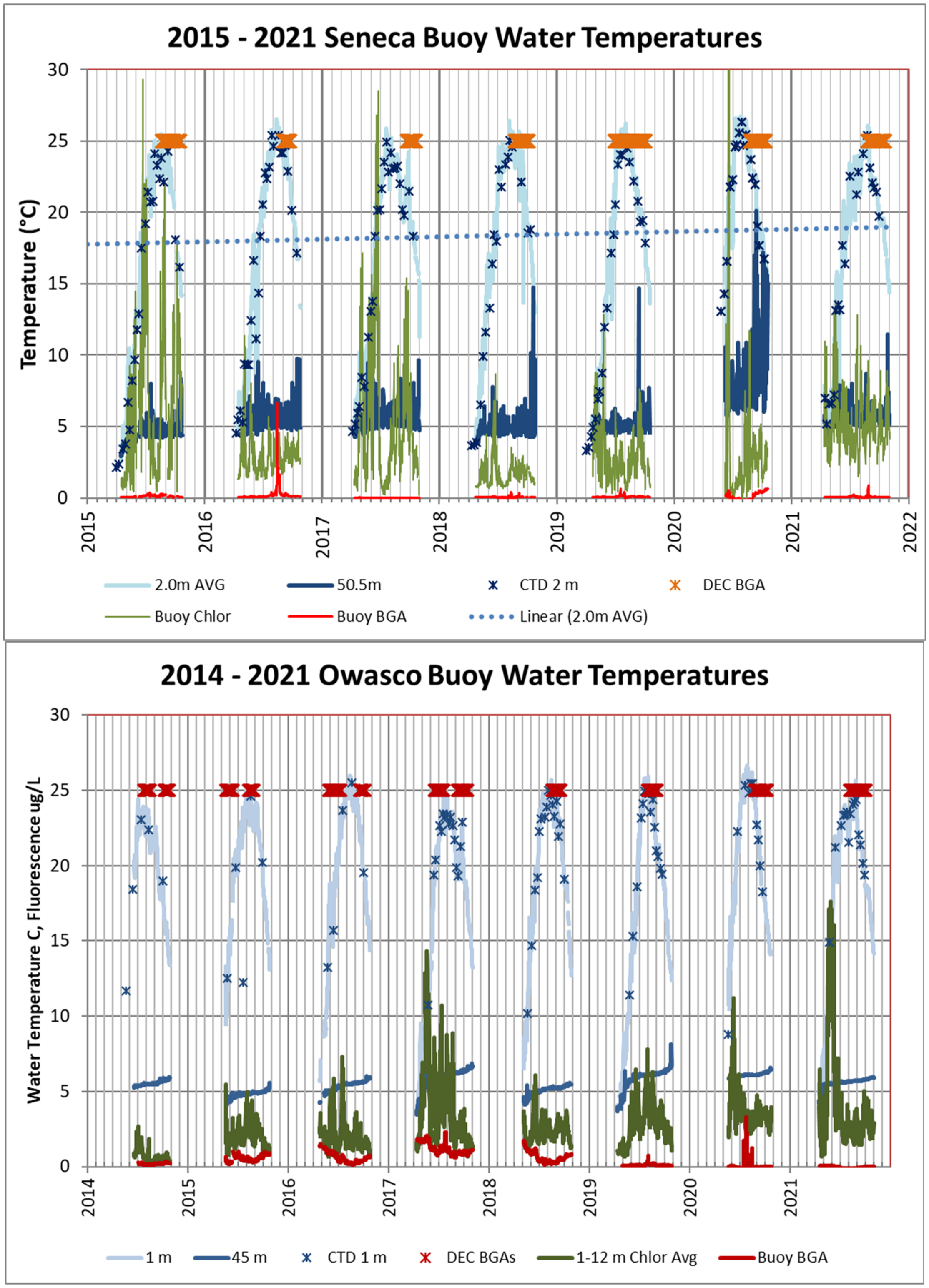


Fig. 13. Field season surface and bottom water temperatures at the Seneca (above) & Owasco (below) buoys. Surface water (1-m) CTD data were superimposed onto the buoy temperatures. The USGS buoy on Seneca Lake was used for its 2020 data. The weeks these lakes were on DEC's HABs Notification Page are also shown.

Shoreline cyanobacteria blooms were detected when the surface water was warm, 18 to 26°C (65 – 80°F) since their initial detection in each lake (Fig. 13). However, blooms typically did not appear until a week or two after the warmest water temperatures of the summer season. The exception in Seneca was during 2019, and during 2015, 2016, 2017 and 2021 in Owasco. The delay indicates that warm water by itself does not directly trigger bloom activity. The delay may instead provide enough time for sufficient bacterial decomposition of organic matter and storage of nutrients in the environment for subsequent cyanobacteria blooms. Cyanobacteria activity may have started earlier in some years because more nutrients were available, e.g., from more rainfall or other sources and/or Owasco's larger watershed to lake surface area ratio, to jumpstart the blooms. Alternatively, bloom watch volunteers were better at detecting blooms and/or looked for blooms earlier in the season in those years. Cyanobacteria blooms were not detected after the surface water cooled below 15°C (60°F).

Since 2014, the buoy data indicate that Owasco Lake warmed (0.6°C) more quickly in the late spring and early summer (May and June) and cooled (0.1°C) more quickly in the late summer and early fall (August – October) than Seneca Lake (Fig. 14). The difference was calculated by subtracting the Seneca buoy surface water temperature from the Owasco Buoy surface water temperature (Owasco – Seneca) for every common date in the record. Owasco Lake could warm and cool more quickly due to its smaller volume and smaller size, all other things like solar intensity, wind speeds/directions and ice cover being equal. However, the springtime warming in Owasco Lake would be delayed if it had a thick ice cover the previous winter. The implications, warmer water in the spring would enable earlier biological activity in the spring, i.e., earlier offshore blooms and respiration by bacteria. Cooler water in the fall would decrease respiration by bacteria earlier in the season. The earlier warming may explain why blooms are detected earlier in the summer at Owasco Lake than Seneca Lake, although the difference may reflect bloom watch volunteer protocols and procedures at each lake.

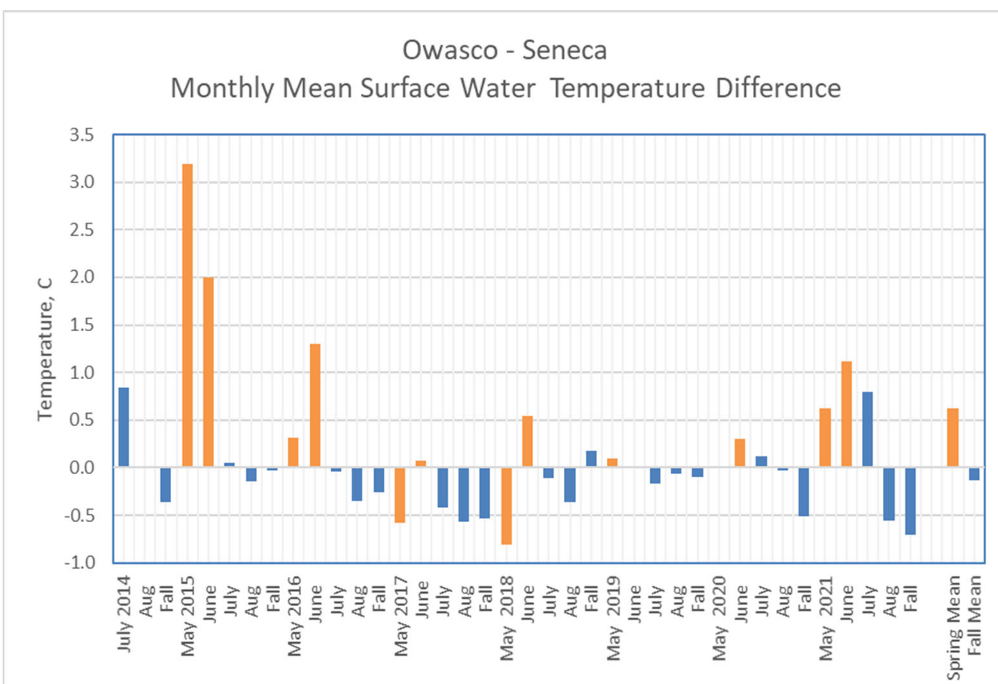


Fig. 14. The difference in surface water temperatures (Owasco – Seneca) in the two lakes, averaged by season (May, June, July, August and Fall: September + October).

Water temperatures were warm enough for cyanobacteria blooms in these two lakes. However, blooms were frequently detected after the warmest water in each season. The warm season occurred earlier in the field season at Owasco than Seneca Lake, and may have jumpstarted biological activity in Owasco Lake. Annual water temperature patterns did not parallel the annual shoreline cyanobacteria bloom counts in these two lakes.

Buoy Total and Cyanobacteria-PC Fluorescence: Minimal correlations were observed between the buoy total fluorescence and buoy cyanobacteria-PC, or between the buoy total fluorescence and recorded shoreline cyanobacteria blooms (Figs. 15 - 17). It indicates that the open water productivity utilizes a unique source of nutrients than the bulk of the cyanobacteria blooms. The buoy detected higher algal concentrations and more frequent offshore algal blooms in 2015, 2017 and 2021 compared to 2016, 2018, 2019 and 2020. More rain fell in 2015, 2017 and 2021, and the associated increased nutrient loads from its runoff probably stimulated more algal growth during these impacted years.

Cyanobacteria blooms were rarely detected at the buoy sites. The absence may reflect the 1-m shallowest depth for the buoy measurements, a depth below the surface hugging cyanobacteria blooms. Alternatively, smaller and/or less frequent blooms occurred offshore compared to nearshore areas. Perhaps an automated camera should be deployed on the buoy to monitor the presence or absence of cyanobacteria at this offshore site.

Offshore total and PC fluorescence data did not parallel the annual cyanobacteria bloom counts at the shoreline. It reaffirms that the nearshore blooms require a unique nutrient source.

Buoy Air Temperatures: Like water temperatures, the shoreline cyanobacteria blooms commonly occurred a few weeks after peak air temperatures (23 to 24°C, 70-75°F) for the summer season (Fig. 15). Colder air temperatures in the fall, i.e., 10°C (50°F), coincided with seasonal end for cyanobacteria blooms. Thus, blooms prefer warm air and water temperatures, and are terminated by cold air and water temperatures. The parallel nature for air and water temperatures is not surprising because both air and water temperatures are linked to and ultimately forced by changes in solar insolation.

Offshore air temperature data was warm enough to support blooms. Fluctuations in air temperature from one year to the next did not parallel the annual cyanobacteria bloom counts at the shoreline.

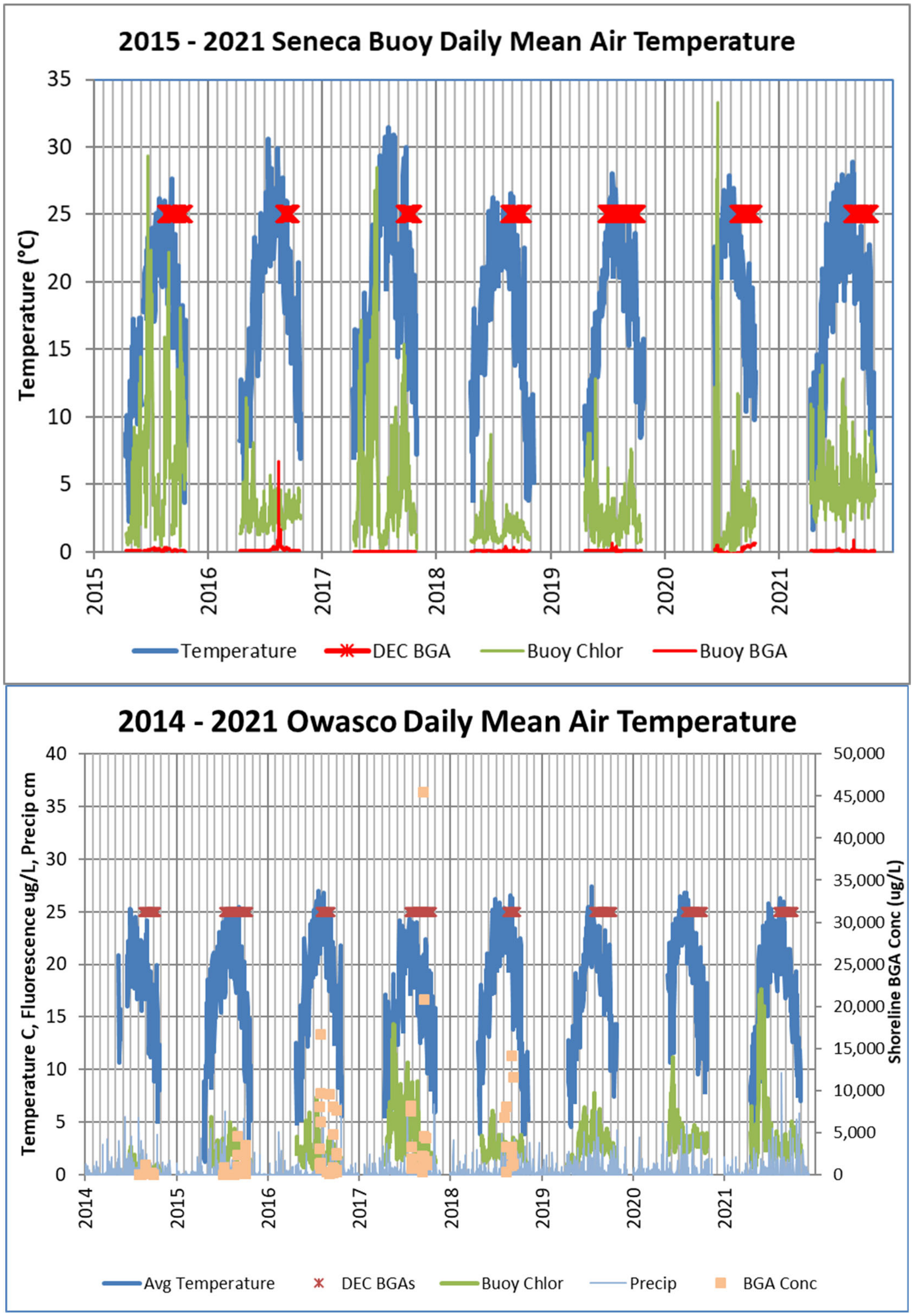
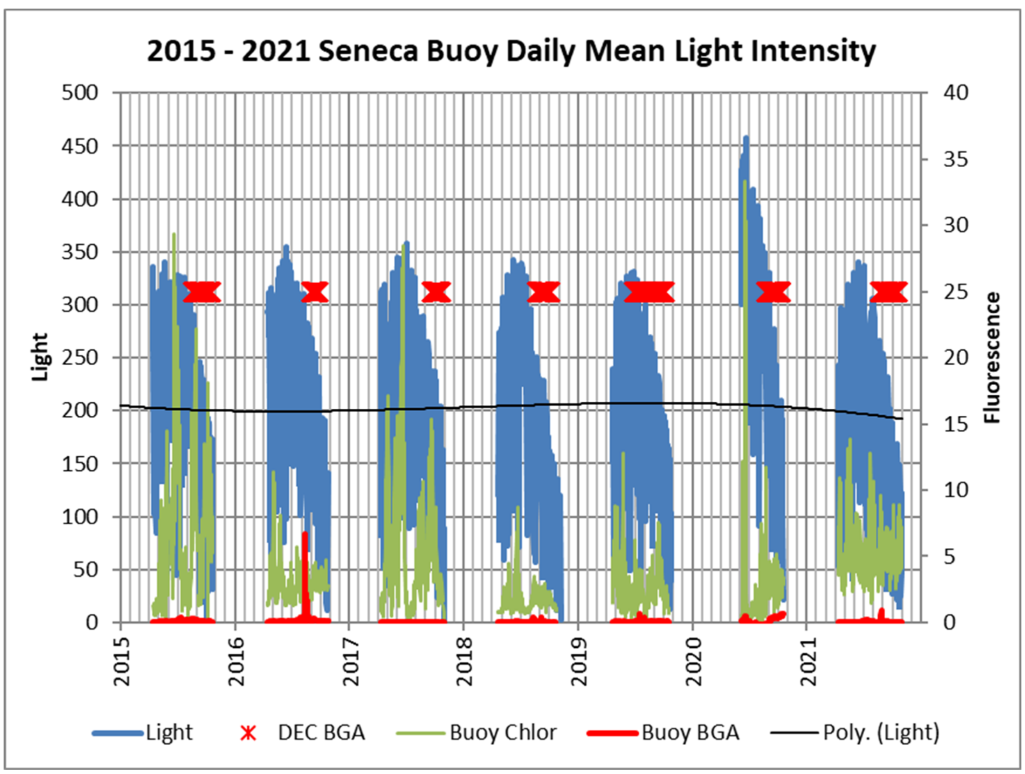


Fig. 15. Field season air temperatures at the Seneca (above) & Owasco (below) FLI Buoys. The 2020 Seneca data used the USGS buoy, anchored farther north and in shallower water than the FLI site. The weeks these lakes were on DEC's HABs Notification Page are also shown.

Buoy Sunlight Intensity: The first cyanobacteria blooms for the season typically happened after summer solstice, the day of maximum insolation for the year, and cyanobacteria blooms were no longer detected in this study when mean daily insolation (sunlight) decreased from just above 340 $\mu E/cm^2$ in mid-June to below 150 $\mu E/cm^2$ by mid to late October in both lakes (Fig. 16). The insolation data for 2020 from the USGS buoy are slightly larger than other years measured by the FLI buoy and those detected at the dock sites. The difference is an artifact of using different sensors. FLI light intensity data are more consistent with the meteorological data from the dock sites. Warmest water and air temperatures also peaked after summer solstice noting that water takes time to warm, and warms more slowly than air. All three typically peaked before the cyanobacteria blooms. Lower light levels experienced in the early fall might favor cyanobacteria blooms because cyanobacteria can position themselves at depths with optimum light and nutrient levels. Thus, blooms were favored when the air and water were warmer but typically waited until after summer solstice. However, blooms were NOT detected on every warm and sunny day. Thus, solar intensity, air and water temperatures were favorable for bloom development but changes within the HABs season did not parallel, and thus, did not trigger the nearshore blooms.

The sunlight intensity did not parallel the annual cyanobacteria bloom counts at the shoreline.



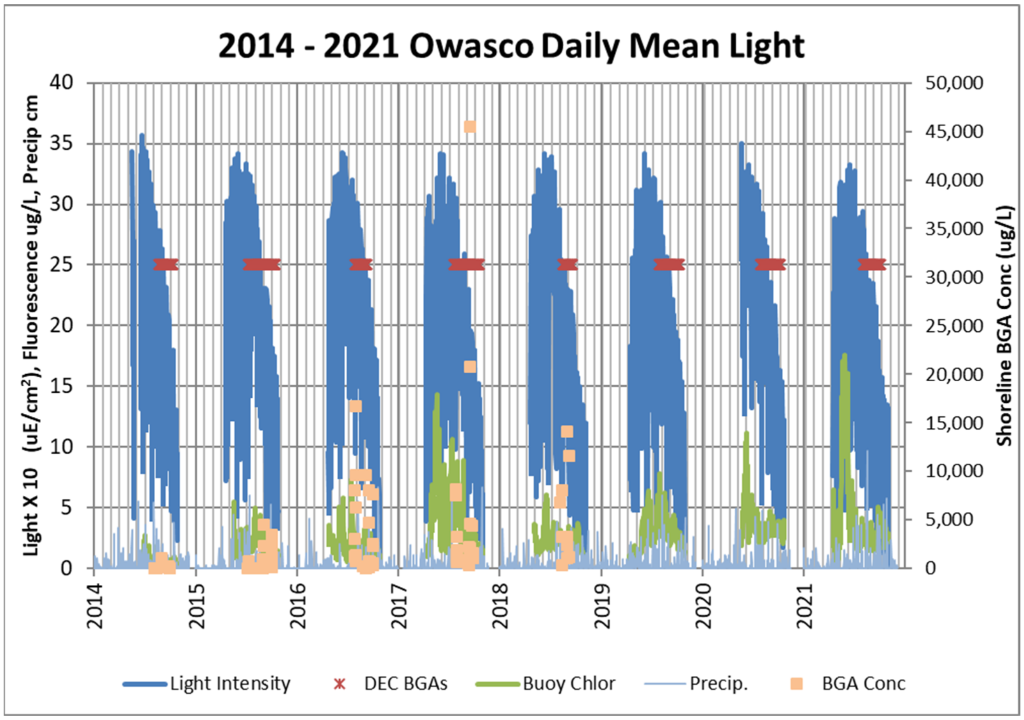


Fig. 16. Field season light intensity data at the Seneca & Owasco FLI Buoys. The 2020 Seneca data used the USGS buoy that used a different sensor thus different results. The weeks these lakes were on DEC's HABs Notification Page are also shown.

Buoy Wind Speed & Direction: At both buoys, 2015, 2017 and 2021 were less windy than 2016, 2018, 2019 and 2020 during the HABs season (Fig. 17). The mean, HABs season, daily wind speeds in 2015, 2017 and 2021 were at or below 9 mph (4 m/s, small waves) with only a few days with wind speeds above 15 mph (7 m/s, large waves with white caps, Fig. 18), whereas they were above 9.5 mph (4.3 m/s) in the other years. In 2020, Seneca Lake experienced many more days with wind speeds above 15 mph and fewer calm days than Owasco Lake. Seneca Lake also has a larger fetch than Owasco, that would foster larger waves, and would more severely impact the exposed shorelines as well. Perhaps the intense 2020 conditions mixed any nearshore cyanobacteria and their nutrient sources throughout the entire epilimnion and towards open water, decreasing nearshore blooms in Seneca Lake. The more frequent calm periods at Owasco Lake during 2020 allowed for more blooms that took advantage of the nutrients released from the nearshore sediments by the strong winds and associated waves (both were larger in 2020 compared to other years at Owasco Lake).

In 2021, a decrease in wind intensity and more frequent calm periods probably allowed for the 2nd largest number of nearshore blooms in both lakes. Winds above 20 mph (8.9 m/s, very large waves with white caps) coincided with the end of the bloom activity in most years.

Turbulence from faster and more persistent winds in 2020 probably contributed to the smaller number of blooms in Seneca than Owasco Lake, and slower winds and more calm periods probably contributed to the 2nd largest number of blooms in both lakes in 2021.

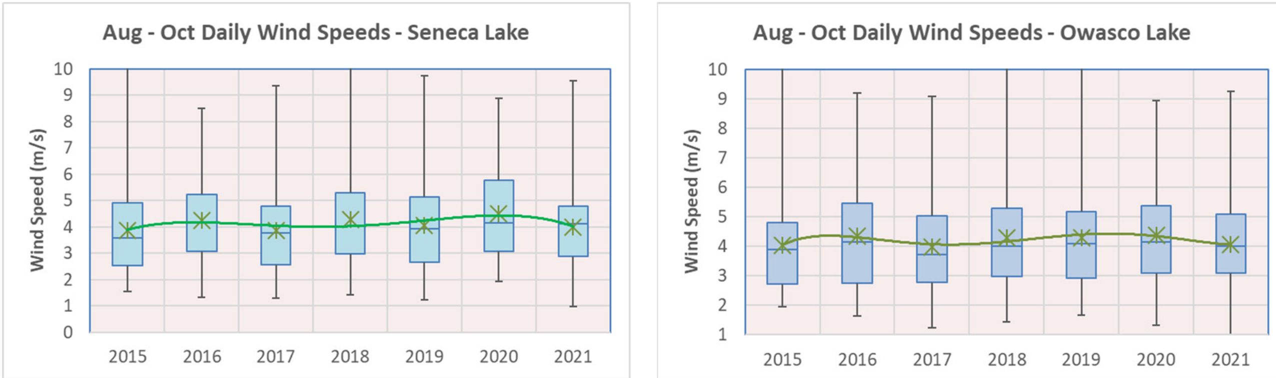
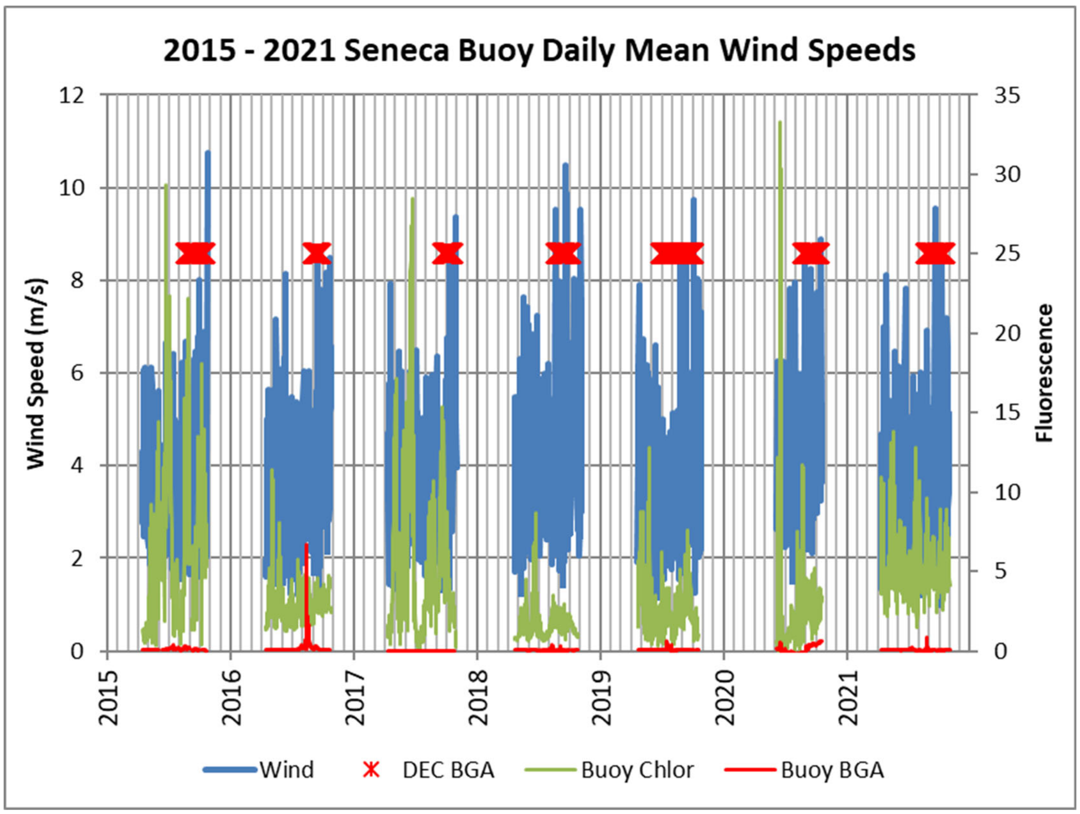


Fig. 17. The 2021 HABs season wind speeds at the FLI buoy in Seneca (left) and Owasco (right) Lakes.



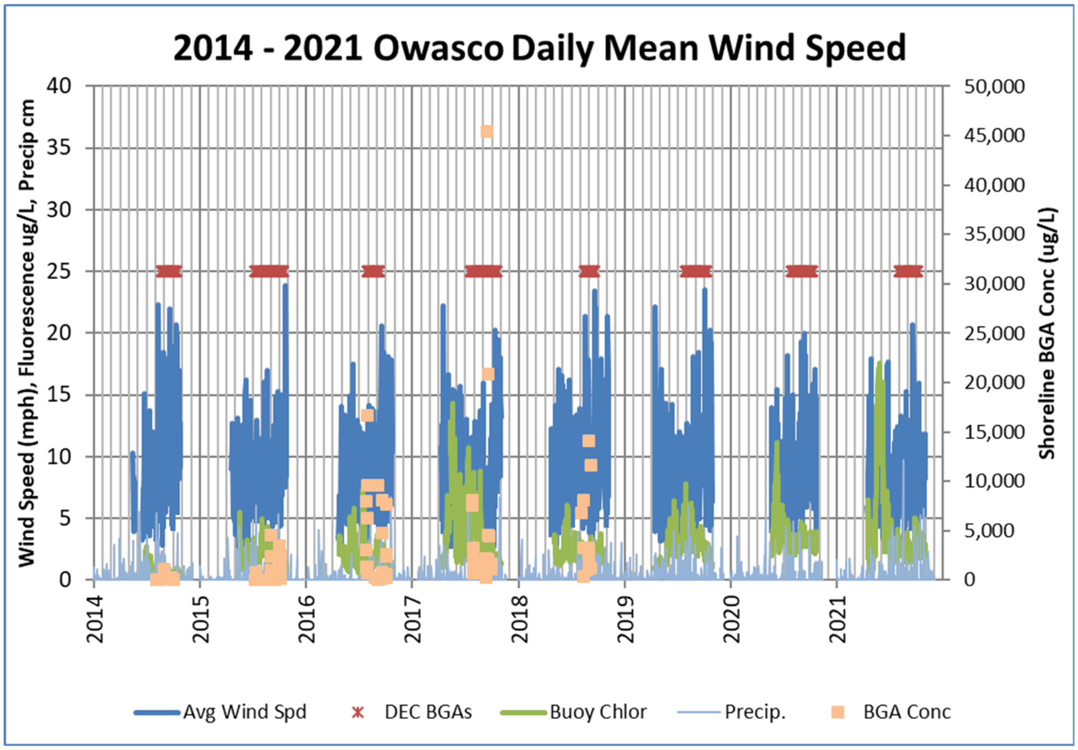
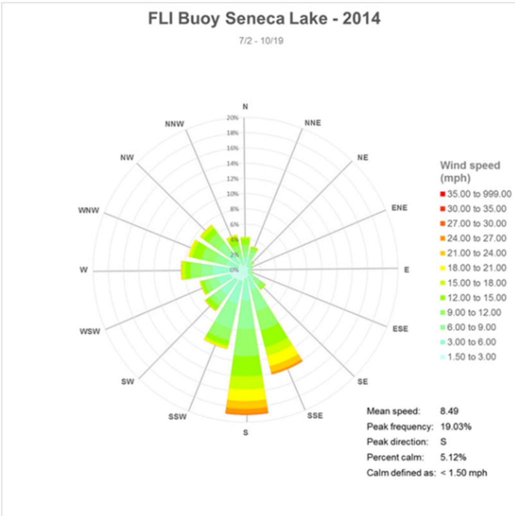


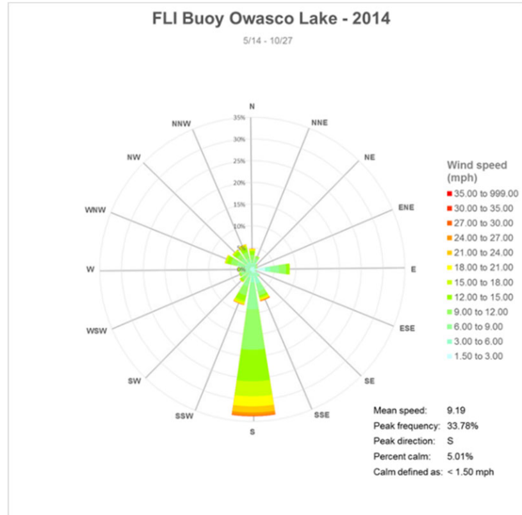
Fig. 18. Field season wind speed data at the Seneca & Owasco FLI Buoys. The 2020 Seneca data used the USGS buoy, anchored farther north and in shallower water than the FLI site. The weeks these lakes were on DEC's HABs Notification Page are also shown.

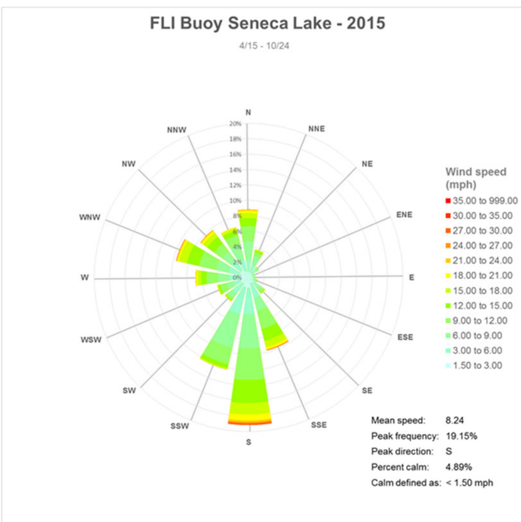
The dominant wind direction measured at the buoys was typically from the south (S), and to a lesser extent from just east of south (SSE), consistent with the North/South elongation of both lakes (Fig. 19). Slight differences exist. SSE winds were dominant during 2018, 2020 and 2021 in Owasco Lake. This change was not observed in Seneca Lake (Fig. 19). Instead, SSE winds were the 2nd most dominant direction during 2014, 2016, 2017, 2018 and 2019 in Seneca. SSW winds were 2nd most dominant in 2021 in Seneca Lake. Seneca, more so than Owasco Lake, also experienced winds from the west and less frequently, northwest and north. These slight changes though do not parallel changes in bloom counts in the entire lake although they may influence the occurrence and frequency of blooms along specific shorelines.

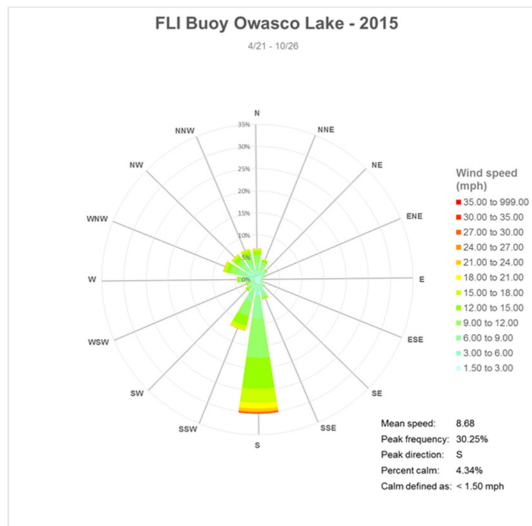
The dominant southerly directions were consistent with the majority of the cyanobacteria blooms located along the northern and northeastern margins of both lakes (Fig. 7). A slight shift in the dominant wind direction in Owasco Lake to the SSE in 2020 and 2021 potentially fostered significantly more blooms detected along the more protected, eastern shoreline than the exposed western shoreline (Fig. 7). If a similar slight eastward shift observed in Owasco Lake occurred at Seneca Lake in 2020, strong winds would have impacted the northwestern shorelines (see dock site wind discussion below). Wind directions detected by local meteorological stations on land are significantly different from the directions detected by the lake buoys. So any shift in the dominant wind direction at Seneca Lake and its impact on bloom counts is open to speculation.

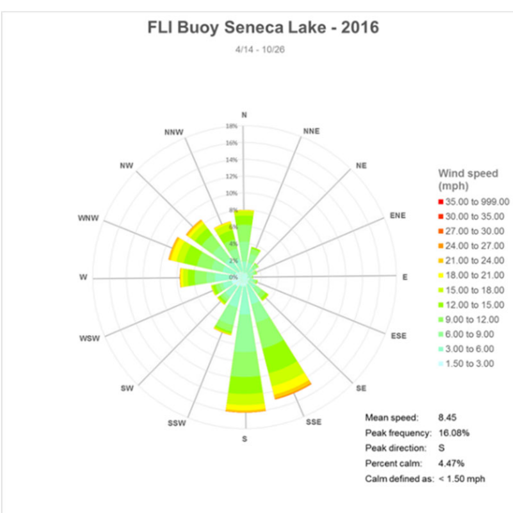
Slight shifts in the open-water wind directions do not parallel the detection of blooms at the shoreline.

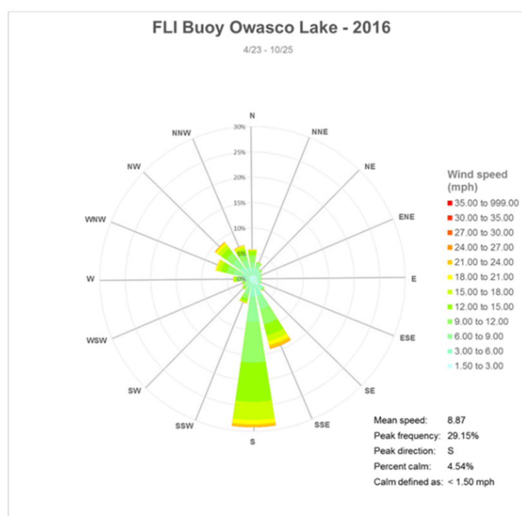

FLI Buoy Seneca Lake - 2014
7/2 - 10/19
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.49
Peak frequency: 19.03%
Peak direction: S
Percent calm: 5.12%
Calm defined as: < 1.50 mph

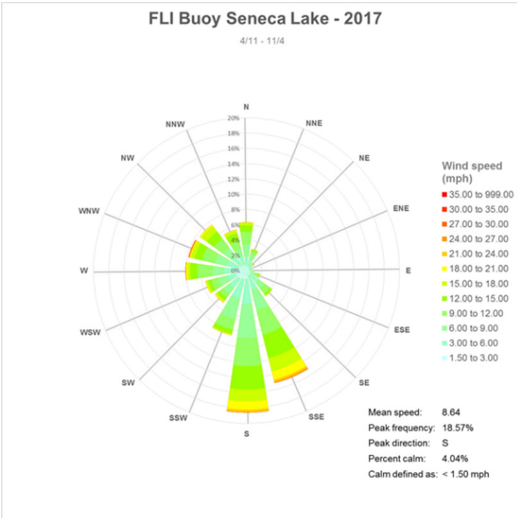

FLI Buoy Owasco Lake - 2014
5/14 - 10/27
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 9.19
Peak frequency: 33.78%
Peak direction: S
Percent calm: 5.01%
Calm defined as: < 1.50 mph

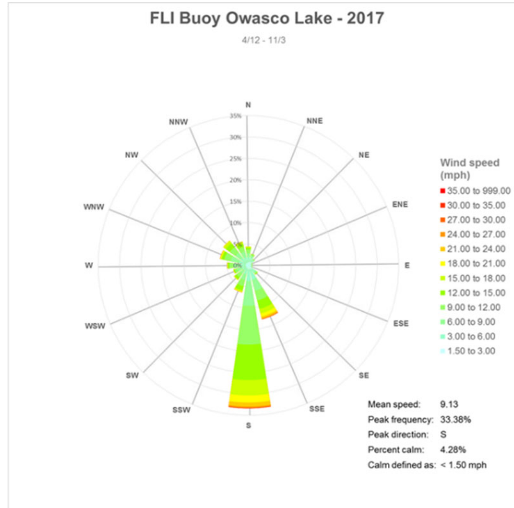

FLI Buoy Seneca Lake - 2015
4/15 - 10/24
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.24
Peak frequency: 19.15%
Peak direction: S
Percent calm: 4.89%
Calm defined as: < 1.50 mph

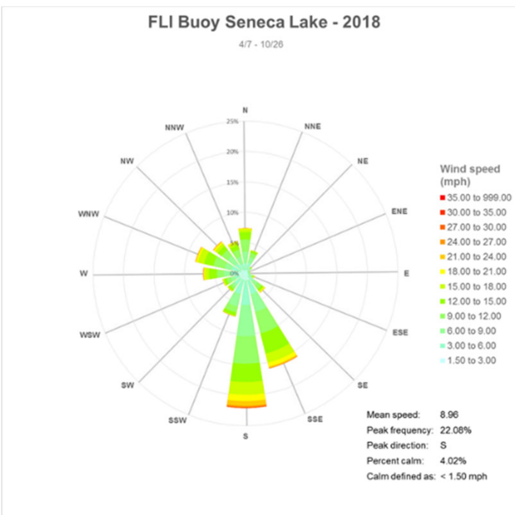

FLI Buoy Owasco Lake - 2015
4/21 - 10/26
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.68
Peak frequency: 30.25%
Peak direction: S
Percent calm: 4.34%
Calm defined as: < 1.50 mph

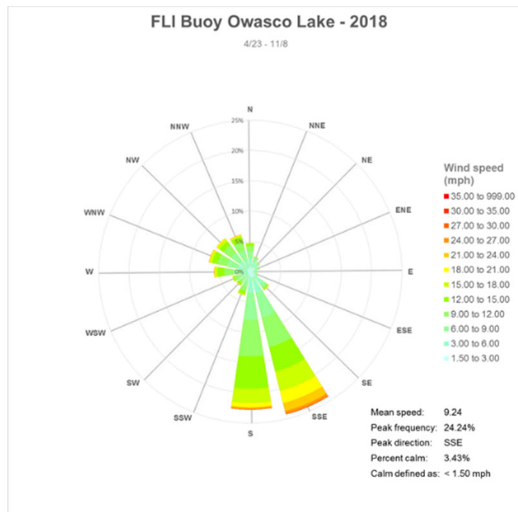

FLI Buoy Seneca Lake - 2016
4/14 - 10/26
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.45
Peak frequency: 16.08%
Peak direction: S
Percent calm: 4.47%
Calm defined as: < 1.50 mph

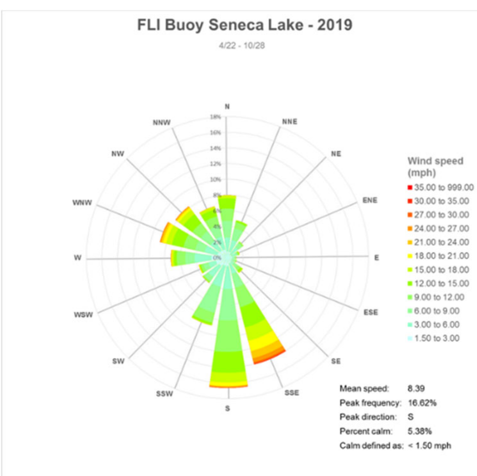

FLI Buoy Owasco Lake - 2016
4/23 - 10/25
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.87
Peak frequency: 29.15%
Peak direction: S
Percent calm: 4.54%
Calm defined as: < 1.50 mph


FLI Buoy Seneca Lake - 2017
4/11 - 11/4
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.64
Peak frequency: 18.57%
Peak direction: S
Percent calm: 4.04%
Calm defined as: < 1.50 mph


FLI Buoy Owasco Lake - 2017
4/12 - 11/3
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 9.13
Peak frequency: 33.38%
Peak direction: S
Percent calm: 4.28%
Calm defined as: < 1.50 mph


FLI Buoy Seneca Lake - 2018
4/7 - 10/26
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.96
Peak frequency: 22.08%
Peak direction: S
Percent calm: 4.02%
Calm defined as: < 1.50 mph


FLI Buoy Owasco Lake - 2018
4/23 - 11/8
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 9.24
Peak frequency: 24.24%
Peak direction: SSE
Percent calm: 3.43%
Calm defined as: < 1.50 mph


FLI Buoy Seneca Lake - 2019
4/22 - 10/28
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.39
Peak frequency: 16.62%
Peak direction: S
Percent calm: 5.38%
Calm defined as: < 1.50 mph

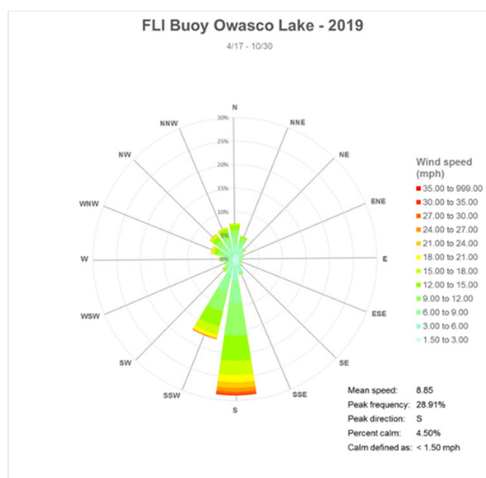
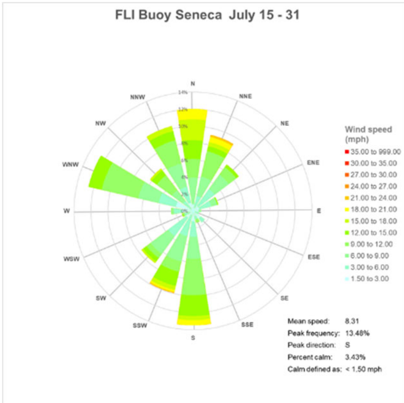
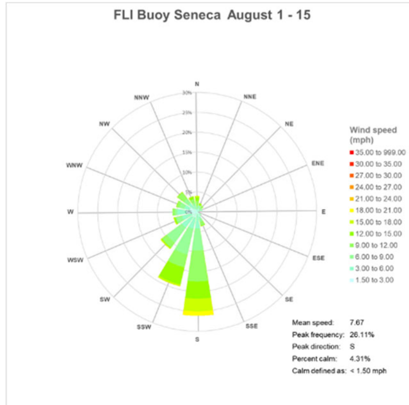

FLI Buoy Owasco Lake - 2019
4/17 - 10/30
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.85
Peak frequency: 28.91%
Peak direction: S
Percent calm: 4.50%
Calm defined as: < 1.50 mph

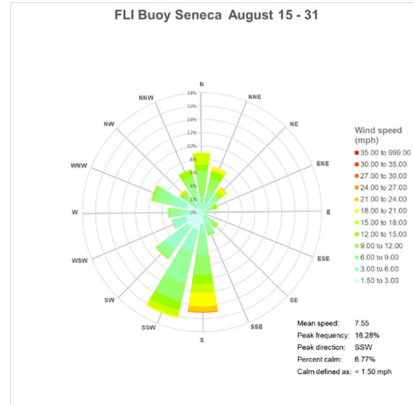
Fig. 19. Wind rose diagrams showing frequency of wind direction and speed during 2014 – 2021 at the Seneca Lake buoy (left) and Owasco buoy (right). Unfortunately, the USGS buoy did not record wind directions, and wind data from onshore meteorological stations do not mimic the lake buoy data.

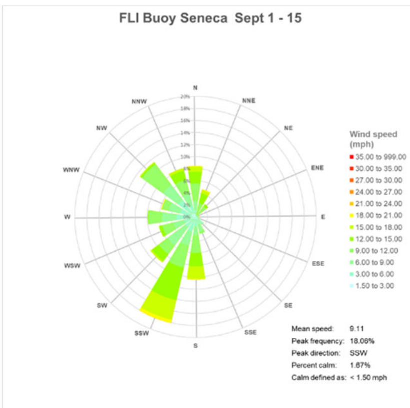
Previously, some scientists suggested that strong winds might push surface-floating cyanobacteria blooms towards the downwind shore. However, our direct observations noted the disruption of cyanobacteria blooms that formed on calm days after the development of even light winds. Apparently, wind and its vertical mixing of the water column by waves (gravity not capillary waves) were sufficient to overcome the buoyancy provided by the cyanobacteria gas vacuoles. Wind directions might still play a role in bloom genesis as dead macrophytes, *Cladophora* and other decaying organic matter would concentrate along the downwind shoreline. The nutrients released by bacterial decomposition of the accumulated organics could be an important nutrient source for cyanobacteria blooms.

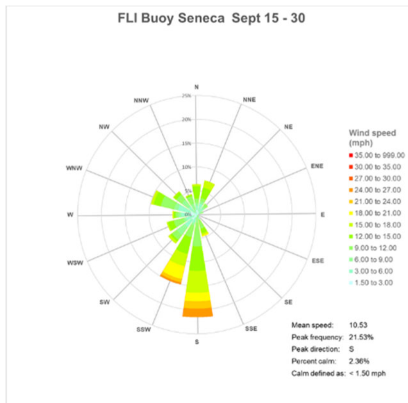
Seasonally, wind direction changed slightly at the Seneca Buoy in 2021 (Fig. 20). In late July, winds were light and from multiple directions. Subsequently, it was primarily from the south or SSW. Wind direction did not seasonally change at the Owasco Buoy during 2021 (Fig. 20).

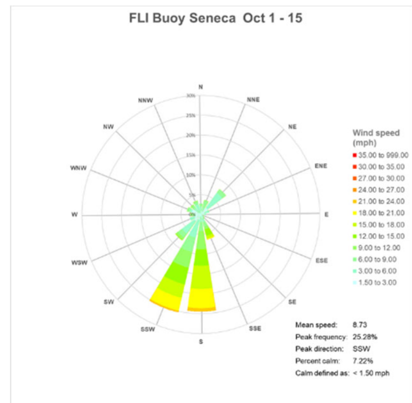

FLI Buoy Seneca July 15 - 31
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.31
Peak frequency: 13.48%
Peak direction: S
Percent calm: 3.43%
Calm defined as: < 1.50 mph

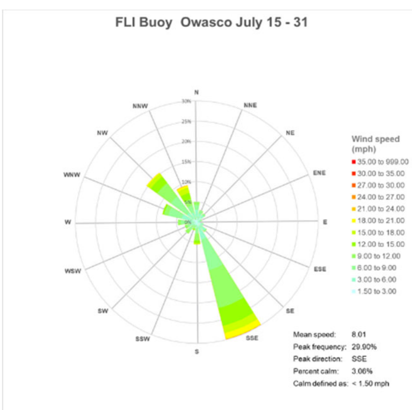

FLI Buoy Seneca August 1 - 15
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 7.67
Peak frequency: 26.11%
Peak direction: S
Percent calm: 4.31%
Calm defined as: < 1.50 mph

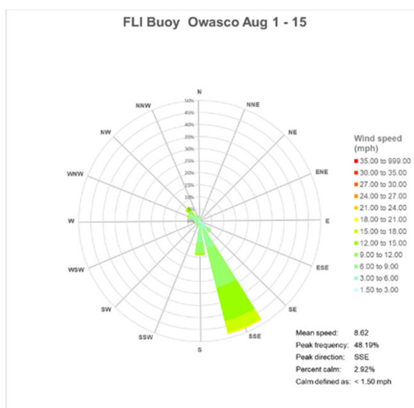

FLI Buoy Seneca August 15 - 31
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 7.55
Peak frequency: 16.28%
Peak direction: SSW
Percent calm: 6.77%
Calm defined as: < 1.50 mph

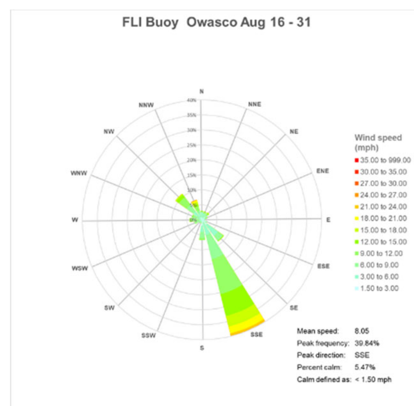

FLI Buoy Seneca Sept 1 - 15
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 9.11
Peak frequency: 18.08%
Peak direction: SSW
Percent calm: 1.67%
Calm defined as: < 1.50 mph


FLI Buoy Seneca Sept 15 - 30
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 10.53
Peak frequency: 21.53%
Peak direction: S
Percent calm: 2.36%
Calm defined as: < 1.50 mph


FLI Buoy Seneca Oct 1 - 15
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.73
Peak frequency: 25.28%
Peak direction: SSW
Percent calm: 7.22%
Calm defined as: < 1.50 mph


FLI Buoy Owasco July 15 - 31
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.01
Peak frequency: 29.90%
Peak direction: SSE
Percent calm: 3.06%
Calm defined as: < 1.50 mph


FLI Buoy Owasco Aug 1 - 15
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.62
Peak frequency: 48.19%
Peak direction: SSE
Percent calm: 2.92%
Calm defined as: < 1.50 mph


FLI Buoy Owasco Aug 16 - 31
Wind speed (mph)
35.00 to 999.00
30.00 to 35.00
27.00 to 30.00
24.00 to 27.00
21.00 to 24.00
18.00 to 21.00
15.00 to 18.00
12.00 to 15.00
9.00 to 12.00
6.00 to 9.00
3.00 to 6.00
1.50 to 3.00
Mean speed: 8.05
Peak frequency: 39.84%
Peak direction: SSE
Percent calm: 5.47%
Calm defined as: < 1.50 mph

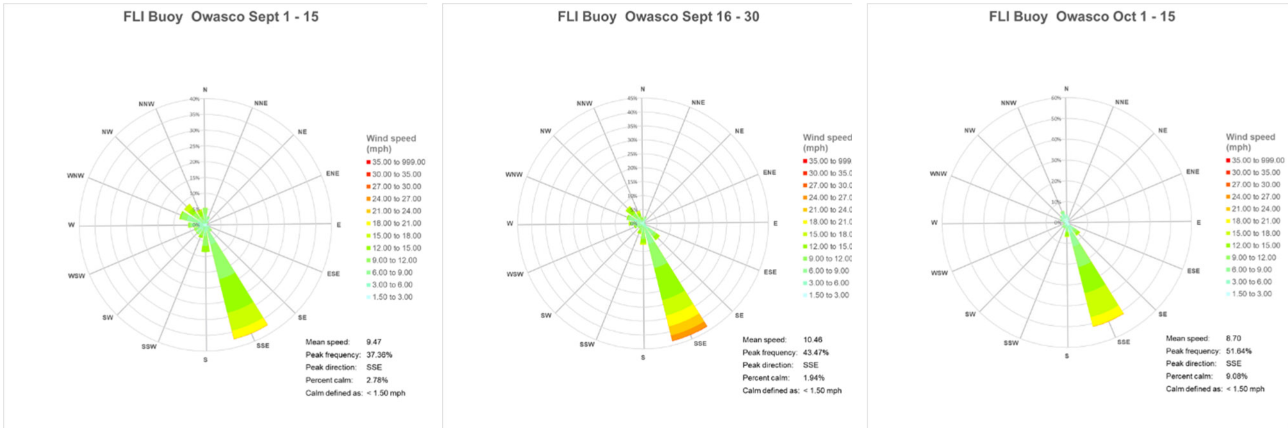
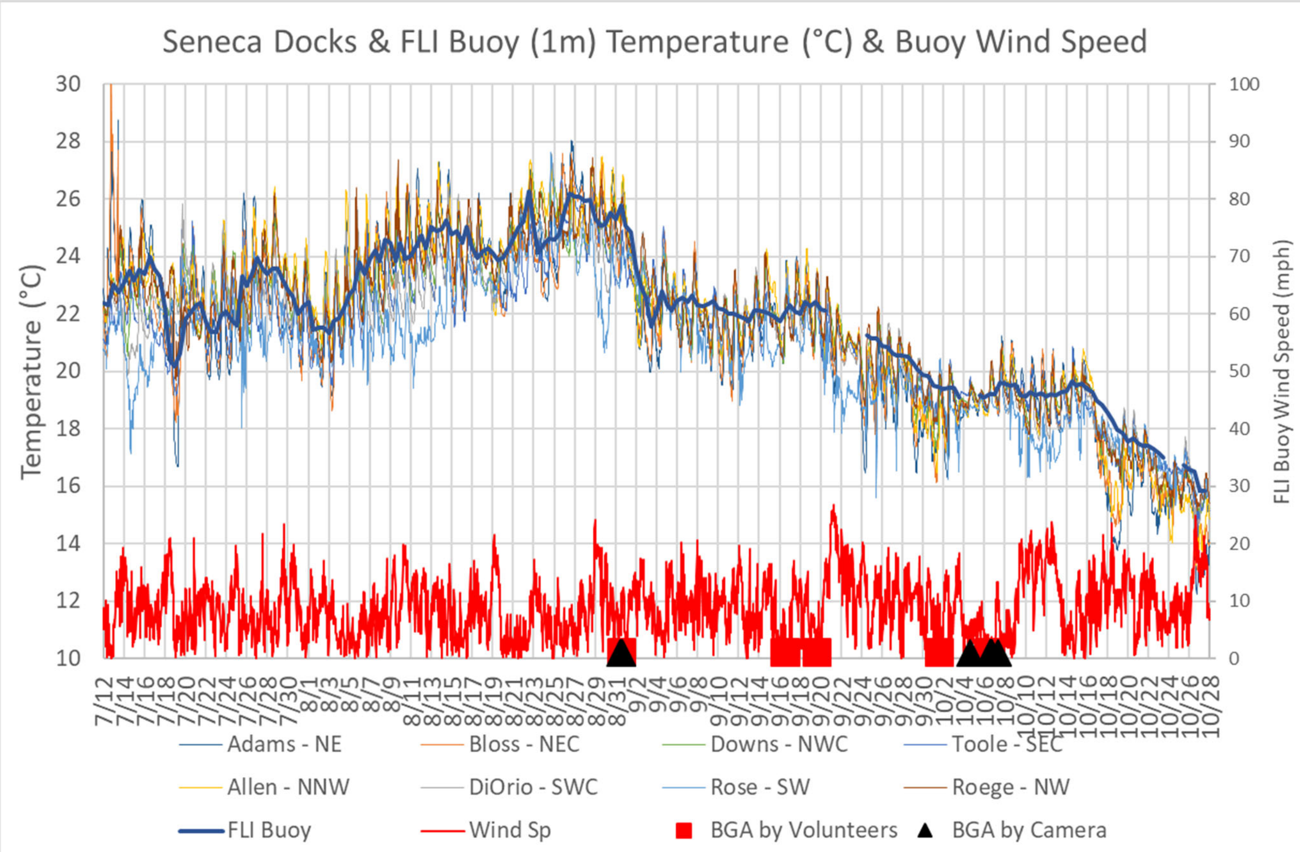


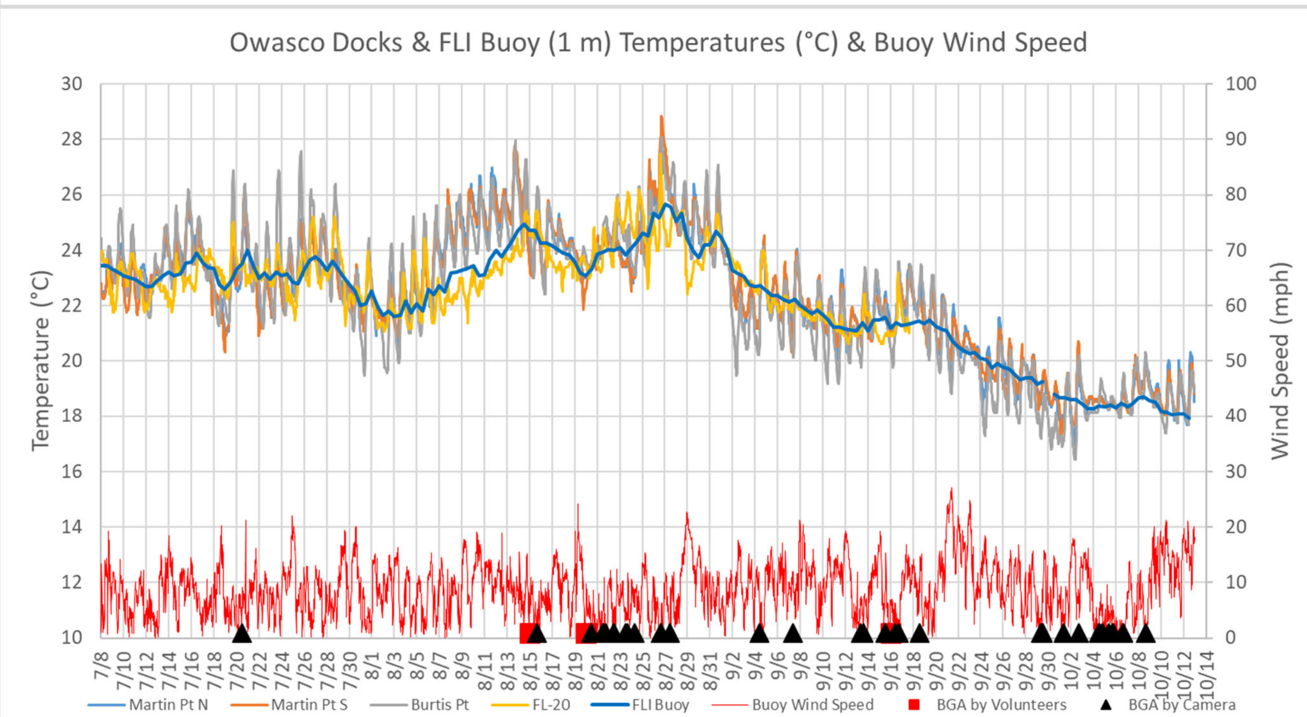
Fig. 20. Season variability in wind direction and speed at Seneca and Owasco Lakes recorded by the FLI buoy.

DOCK SITE RESULTS

Water Temperatures: Surface water temperatures revealed nearly consistent fluctuations in temperature among the dock temperature loggers (deployed at 1-m depth) as surface water (1 m) temperatures detected offshore by the buoy within and between both lakes (Fig. 21). In Seneca Lake, the most northern sites, NNW (Allen) and NNE (Adams) experienced the warmest water (a few tenths of a degree) through mid-September. Both sites are more protected from the offshore southerly winds and have larger shallow water areas directly offshore. The southwestern site, SW (Rose) was a few tenths of degree cooler than the northern sites and the monitoring buoy. This site also experienced an occasional and unique spike to cooler water temperatures (up to 5°C) than the other sites, most notably after a wind event. The lake floor at this site descends quickly into very deep water without an extended nearshore shelf observed at the other nearshore sites. Perhaps internal seiche activity induced by these wind events more easily brought colder hypolimnetic (bottom) water to this southern site. Similar cooling episodes were not observed in 2021 at the southeastern site (SSE, Toole) as it was in the past. Perhaps more winds from the S and SSW prevented upwelling of hypolimnetic water along the eastern side (Toole's site) of the lake in 2021.



Seneca Docks & FLI Buoy (1m) Temperature (°C) & Buoy Wind Speed
Temperature (°C)
FLI Buoy Wind Speed (mph)
Adams - NE
Bloss - NEC
Downs - NWC
Toole - SEC
Allen - NNW
DiOrio - SWC
Rose - SW
Roege - NW
FLI Buoy
Wind Sp
BGA by Volunteers
BGA by Camera



Owasco Docks & FLI Buoy (1 m) Temperatures (°C) & Buoy Wind Speed
Temperature (°C)
Wind Speed (mph)
Martin Pt N
Martin Pt S
Burtis Pt
FL-20
FLI Buoy
Buoy Wind Speed
BGA by Volunteers
BGA by Camera

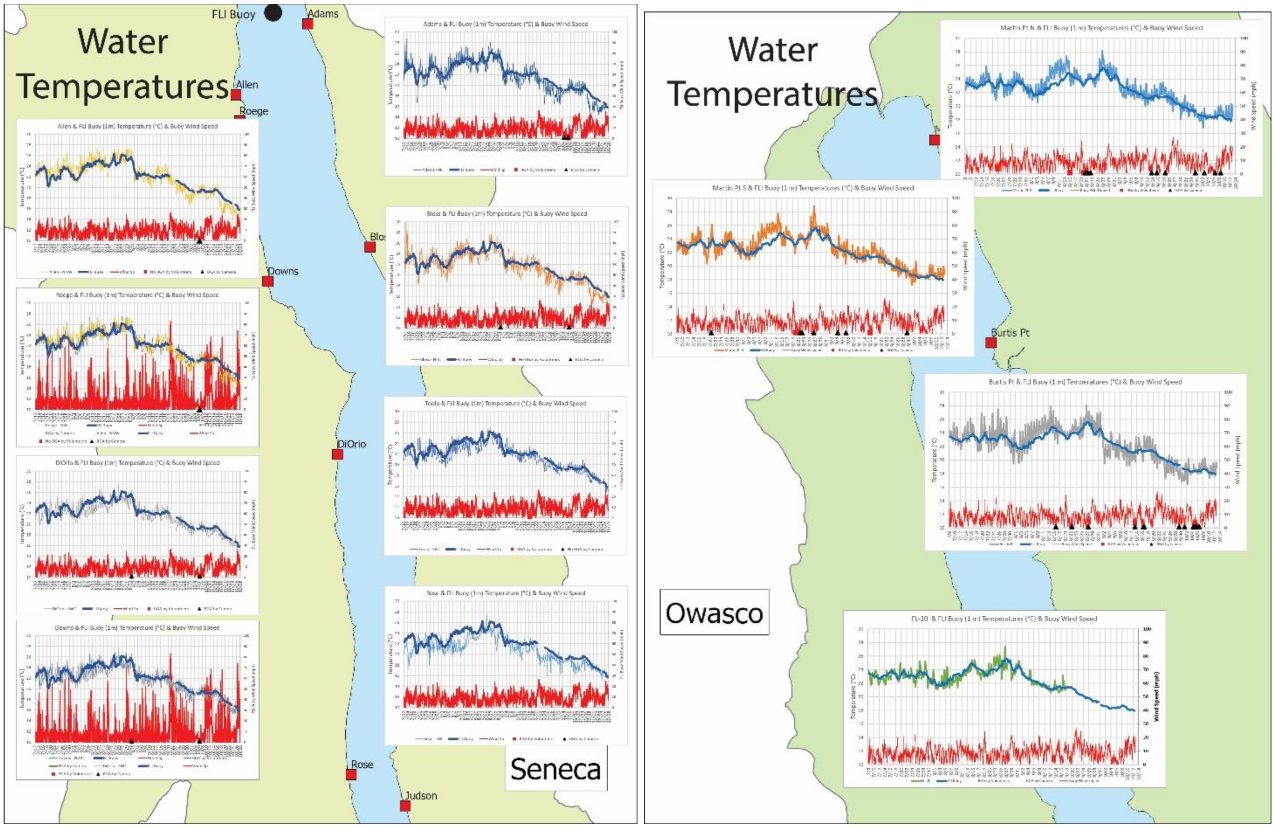


Fig. 21. Dock and buoy surface water temperatures, nearshore cyanobacteria blooms and mean daily wind speeds measured in Seneca (above), Owasco (middle) Lake and every site (below).

Daily fluctuations in surface water temperatures were observed in Seneca Lake, with a mean amplitude (daily maximum – minimum) of 0.9 to 3°C over the course of the study. The oscillations were smaller in 2021 than 2020 perhaps reflecting cloudier weather and less direct sun in 2021. No spatial patterns were observed in the amplitude of the oscillations, other than the smallest oscillations were detected at the buoy sites (< 1°C). The daily oscillations are interpreted to reflect the daily warming of the lake by the sun and radiative heat loss and evaporitic cooling of the lake at night, the heat transfer happening at the lake's surface. The differences in magnitude are expected, as shallow water masses are easier to warm (or cool) than deeper water masses during sunny (or cloudy) days and the differences observed here are probably related to the extent of the shallow water shelf at each site. The daily oscillations were subdued or absent when the wind was blowing onshore, as the circular water motions induced by waves mixed the water column at the shoreline.

In Owasco Lake, daily cycles in surface water temperature also ranged from 0.1 to 3°C. The oscillations were smaller in 2021 than 2020 again reflecting cloudier weather and less direct sun in 2021. The largest fluctuations were detected at the more isolated Burtis Pt location (mean amplitude of 3.3°C), and smallest at the southern Fire Lane 20 site (mean amplitude 1.5°C). Burtis Pt site is more protected from mixing events by a point of land and has an extensive shallow shelf, whereas the Fire Lane 20 site quickly descends to very deep water much closer to shore. The FLI buoy on Owasco Lake did not detect daily oscillations. Yet, it would be challenging to detect with only two samples / day. Occasional cooler spikes in water temperature were not observed in Owasco like Seneca, however only one site was located in the southern margin of the lake. The lack of cooler spikes might also reflect the smaller size of Owasco Lake. Consistent conclusions were drawn from the deployment of surface thermistors and the observed buildup and breakdown of thermal stratification along the shoreline in previous years.

The 2021 August and early September shoreline cyanobacteria blooms were typically preceded by a lake-wide decrease (up to 5°C) in temperature in both lakes like previous years. Unlike previous years, the 2021 dips in temperature were not as pronounced. Lake-wide temperature declines in the surface water may reflect cooler air, cloudier conditions, and/or wind/storm events that generate surface waves and internal seiche activity ultimately mixing some colder hypolimnetic water into the epilimnion. These same events could have also introduced nutrient-rich hypolimnetic waters to the nearshore areas and released nutrients buried in nearshore sediments from decaying macrophytes, mussel poop, and other sources of organic matter. This suggests that waves and internal seiche activity might be important mechanisms to release nearshore nutrient sources and propagate cyanobacteria blooms.

Dips in temperature observed in July and early August did not result in cyanobacteria blooms. The delay to late summer probably reflected the time required for bacteria to increase the nutrient concentrations in the hypolimnion and nearshore sediments to promote cyanobacteria blooms. The bacteria in turn must wait for the macrophytes and other attached plants like *Cladophora* to grow, mature and die. Once they die or get uprooted by wind events, their biomass, once decayed, probably contributed to the nutrient pool in nearshore areas.

Lake-wide surface water temperature dips preceded blooms but every dip did not generate a bloom and some blooms were not preceded by a dip in water temperature.

Automated Cameras: The Brinno cameras recorded ~2 x 3 meter images of the lake's surface from 7/11 through 10/27, a 108 day deployment in Seneca Lake; and 7/7 through 10/13, a 98 day deployment at Owasco Lake in 2021. Positioning the camera closer to shore in 2020 and 2021 compared to 2019 detected blooms within a meter of the shoreline that would have been missed in 2019. Consistently positioning the camera to collect images towards the north in 2020 and 2021 minimized glare from the sun, and suggests that careful camera orientation corrected a glare issue that hampered image analysis in 2019. Camera power or memory issues in 2021 hampered image recovery at the Rose (35 days missed), Toole (32), DiOrio (19), and Downs (15) sites in Seneca Lake and Fire Lane 20 (26) and Martin Pt S (19) sites in Owasco Lake. Unfortunately, blooms may have been missed at these sites because blooms were detected elsewhere during the malfunctioning episodes. Water has occasionally found its way into the camera housing and slowly degraded the electronics over time. It suggests that these cameras have a short useful lifetime in harsh environments.

The cameras detected from 0 to 3 cyanobacteria blooms at the Seneca Lake sites and from 3 to 10 blooms at the Owasco Lake sites (Table 2, Fig. 22, photo by photo logs are summarized in the data repository). The cameras detected slightly fewer blooms in Seneca than Owasco in 2021 but the decline was not as severe as recorded in 2020. Blooms were detected throughout the day with more blooms in the afternoon, especially at Seneca Lake (Fig. 22).

Table 2. Brinno Automated Camera Results Seneca & Owasco Lakes

Camera Results (in days)	NNW Allen	NW Roege	NWC Downs	SWC DiOrio	SW Rose	NE Adams	NEC Bloss	SEC Toole
Blooms Detected (unknown conc.)	1	1	2	2	1	3	2	0
Turbid Water (lake floor invisible)	39	57	22	66	20	49	62	42
Clear Water (lake floor visible)	71	52	68	25	54	52	46	34
Glare Impacted Image	0	0	0	0	0	0	0	0
Camera Malfunctioned*	0	0	15	19	35	0	0	32
SLPWA Volunteers (#Blooms)	0	2	2	1	3	1	0	1
Calm Winds (<1 mph average)	35	16	85	40	29	30	8	25
Rainy Days (> 0 in)	37	28	30	42	49	34	45	42
Sunny Skies (> 130 W/m^2)	43	45	47	18	103	9	48	96

Camera Results (in days)	Martin Pt N	Martin Pt S	Burtis Pt	Fire Lane 20
Blooms Detected (unknown conc.)	10	7	10	3
Turbid Water (lake floor invisible)	21	7	8	12
Clear Water (lake floor visible)	70	68	85	57
Glare Impacted Image	0	0	0	0
Camera Malfunctioned*	0	19	0	26
OWLA Volunteers (#Blooms)	2	2	1	0
Calm Winds (<1 mph average)	26	15	16	20
Rainy Days (> 0 in)	39	27	45	34
Sunny Skies (> 130 W/m^2)	40	40	48	47

*faulty camera or power issues. Cameras might have gotten wet early in the field season. A few cameras drained batteries quickly.

Each bloom lasted 1.3 to 7.5 hours on any given day and averaged 3.2 hours in Seneca Lake and 0.2 to 12 hours on any given day and averaged 4.4 hours in Owasco Lake. Dockside cyanobacteria concentrations were measured by FluoroProbe in Owasco Lake during the dock visits, but no blooms were observed on these visit dates. Even though the imaged blooms lacked concurrent water samples, the images revealed similar surface appearances/algal densities to those at or above the 25 µg/L cyanobacteria concentration threshold for blooms in previous years, and thus suggests that the imaged cyanobacteria blooms were concentrated enough to be a confirmed bloom.

Typically, bloom events were random in both space and time. However, two dates in 2021 were noteworthy exceptions. Blooms were detected at 3 of 4 sites on August 20 – 22 in the northern end of Owasco Lake. This date was just after the heaviest rainfall of the season, when 10" of rain was dumped over the northeastern corner of the Owasco watershed, and lake levels rose a few feet to near flood stage. The August 18th event also input over 50% of the annual total phosphorus load to Owasco Lake.[15] It suggests that blooms occur after a major rain/wind event on the next calm and sunny day. Interestingly, more blooms were not detected at Seneca Lake during this time. Rainfall events would impact Owasco to a greater extent than Seneca due to its larger watershed to lake surface area ratio.

Is this a sign of the future? More intense, more localized and larger rain events are becoming the norm as we move into a global warming world[16]. Extremely large events have been observed in

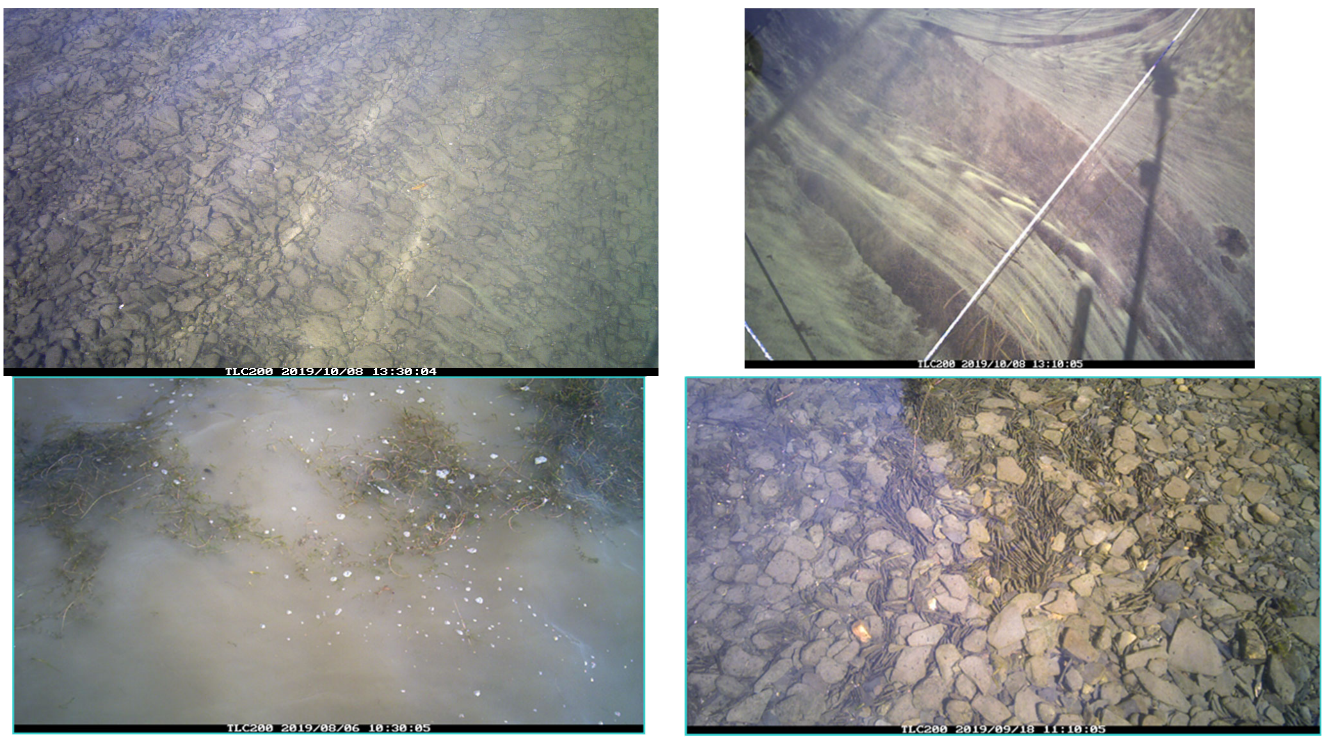
[15] Halfman, J.D., et al., 2022. The 2021 water quality monitoring report Owasco Lake, NY. Finger Lakes Institute, Hobart and William Smith Colleges. 54 pg.

[16] Easterling, D., et al., 2917. Precipitation change in the United States. In: Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program [Wuebbles, D.J., D.W. Fahey, K.A.

the Finger Lakes region in the recent past. For example, extremely large events have already been experienced over the southern end of nearby Skaneateles Lake (2017), and over Lodi and the southeastern edge of Seneca Lake (2018).

In Seneca Lake, blooms were detected at 6 of the 8 sites on October 6th. The two southernmost sites did not detect a bloom. Blooms were also detected on this date at over 20 zones in Seneca Lake by the SLPWA shoreline volunteers, typically reporting multiple blooms in each zone. These detections were mostly along the northern and western shorelines, but were also detected in the open water, and at 2 of 4 sites in Owasco Lake as well on this date. This date was the first major calm and nearly sunny (overcast) day after a string of windy days. The timing fits our observations that blooms occur after a wind event on the next calm and sunny (and apparently overcast) day.

Cyanobacteria blooms are typically localized in space and time. Two exceptions were noted in 2021 when a flood (Owasco) and a lake wide calm event after sustained lake wide wind events (Seneca & Owasco) presumably added sufficient nutrients to the nearshore environment.



Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA (2017), pp. 301-335.

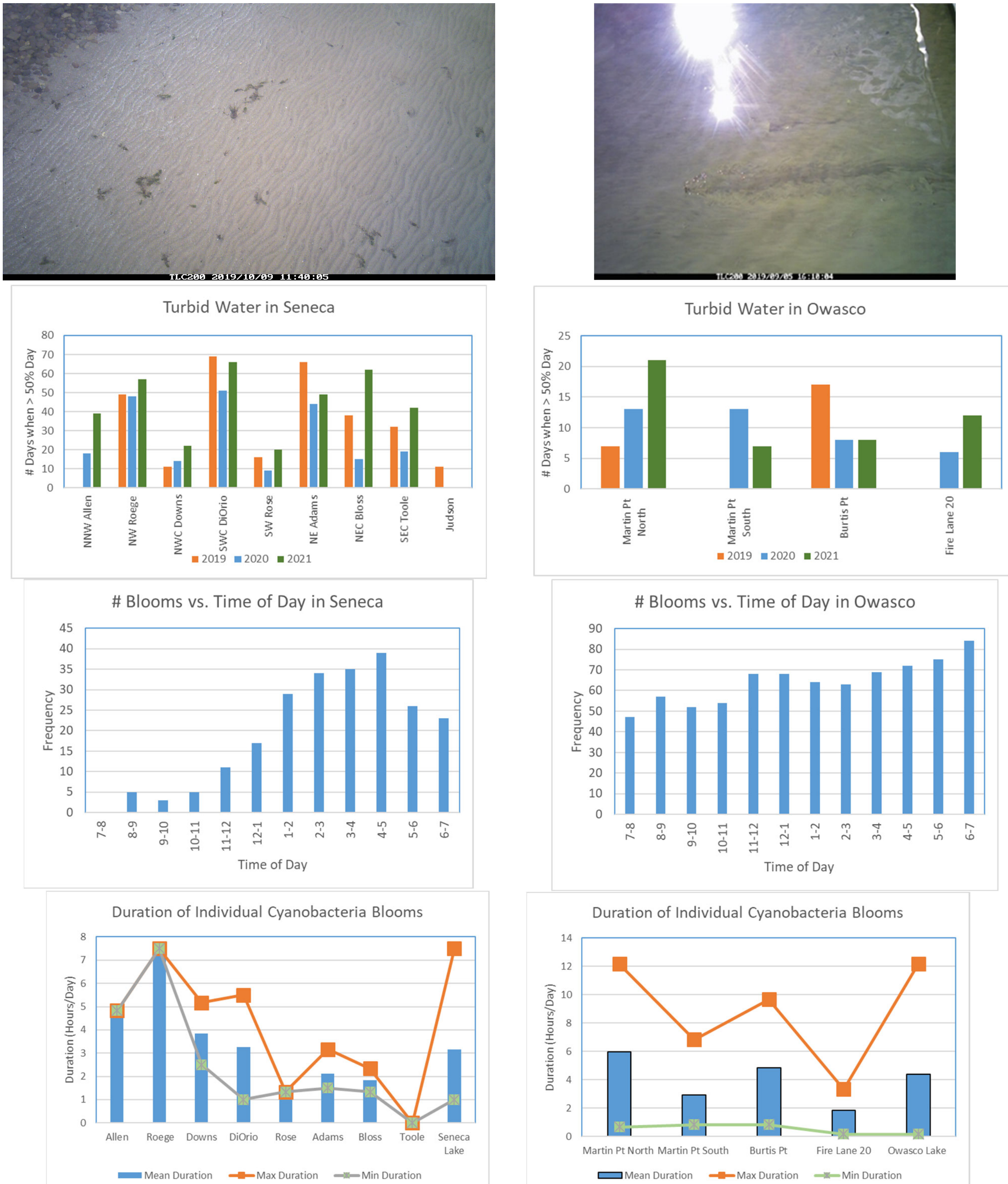


Fig. 22. Example camera images from 2019 revealing cyanobacteria appearances (top), turbid and clear conditions (2nd row), a sandy bottom subsequently covered by leaves and organic debris (3rd row). Similar images were collected in 2020 and 2021. The frequency of turbid days in 2019 through 2021 at Seneca and Owasco Lakes (4th row). A tally of bloom frequency and duration detected in Seneca and Owasco images (bottom).

Seneca Lake Pure Waters Association HABs volunteers detected a similar number of blooms in the surveillance "zones" adjacent to the camera, but like earlier years, blooms were typically detected on different dates by the different methods. Owasco HABs volunteers detected slightly fewer blooms at the camera sites. Perhaps the volunteers missed blooms that happened during other times of the day, other days of the week (likely as volunteer surveys were only once a week), and/or they focused their surveys outside of the camera's field of view.

The images also differentiated between turbid (lake floor invisible) and clear water (lake floor visible), and occasionally detected fish, ducks, waders, swimmers, kayakers, and other animals (daily logs are tabulated in the data repository). Days with turbid and clear water also varied from site to site across the lake, and paralleled when the wind was blowing onshore (turbid) or not (clear). In Owasco Lake, a twig influenced the shoreline parallel northward migration of the bloom at Martin N in 2019 (lower right photo, Fig. 22). Migrating blooms were also noted by HABs volunteers. Although current meters are expensive, perhaps nearshore currents should be measured at selected sites in the future.

The number of days with turbid water in 2021 increased at all of the sites above previous years, except at the DiOrio site (Fig. 22). The increase may reflect winds blowing onshore more often, and more certainly, more rainfall in 2021.

One set of images collected in 2020 from the Martin N site were informative on bloom development (Fig. 23). As small, cm-high, waves with relatively clear water lapped onto the organic debris littering the shoreline, the receding water was full of cyanobacteria. It suggests that the cyanobacteria originated from within the shoreline pile of debris, and is consistent with this material providing a source of nutrients for cyanobacteria blooms. Cell phone images from just south of the Burtis Pt site on 9/9/20, revealed more cyanobacteria adjacent to larger piles of accumulating organic debris along the shoreline than small piles or no macrophytes along the shoreline (Fig. 23).

Decaying organic matter probably provided an important nutrient source for nearshore cyanobacteria blooms.

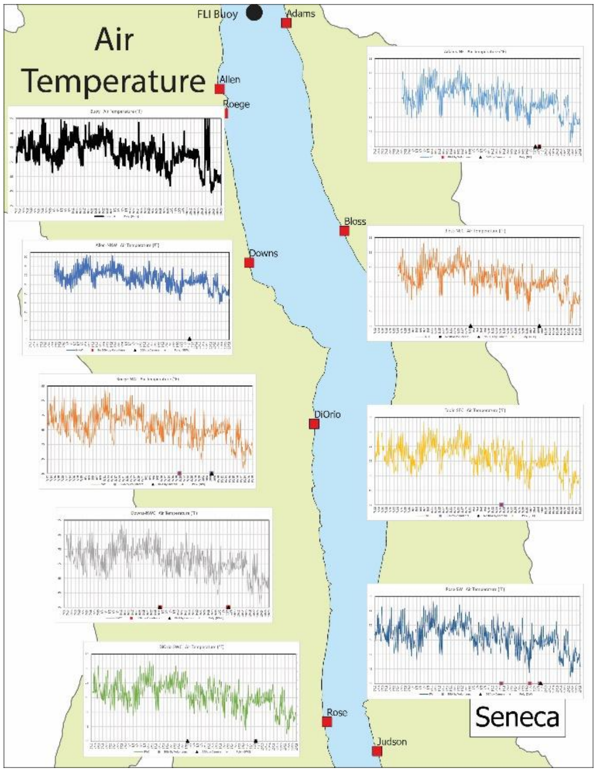
 

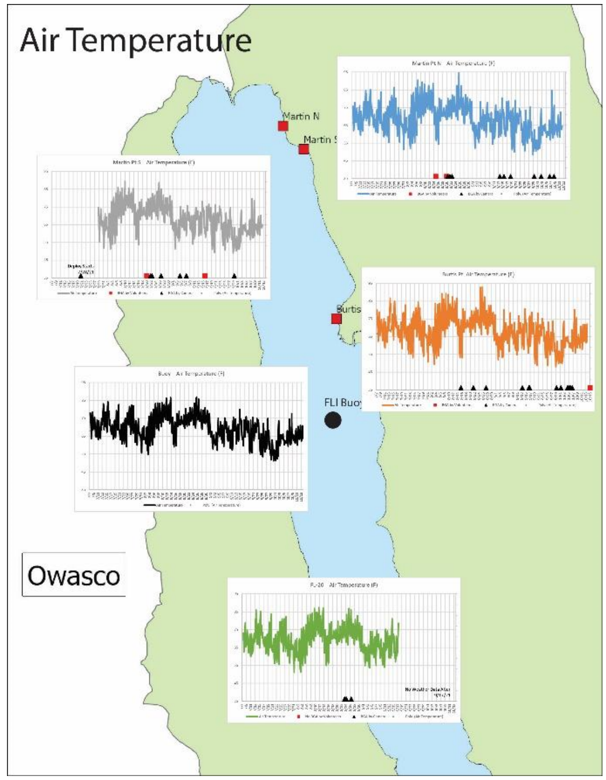
Fig. 23. Cyanobacteria were more abundant in the back wash moving away from shore (above left) than waves lapping onto (above right) a macrophyte covered shoreline. Larger cyanobacteria concentrations (below right) were detected adjacent to larger piles of macrophytes than smaller piles or no macrophytes (below left) along the shoreline.

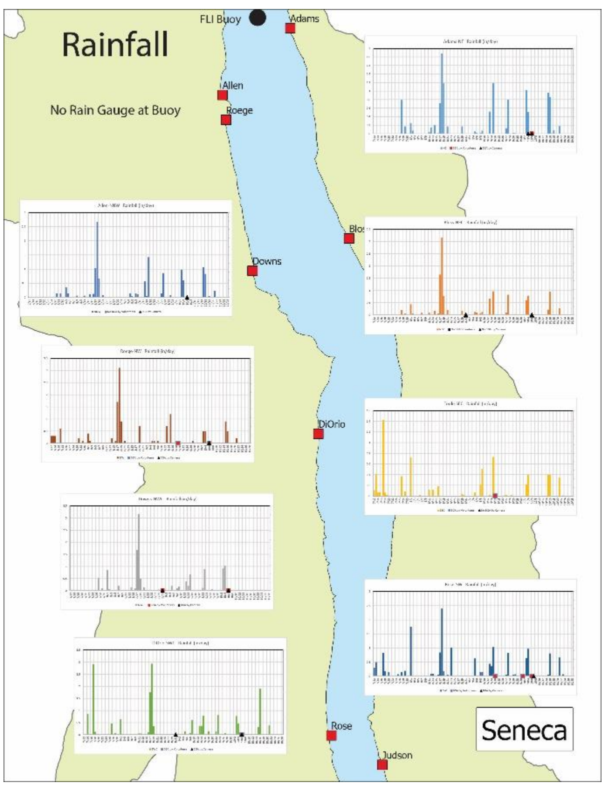
Nearshore Weather: Air temperature, rainfall, solar radiation, wind speed and wind direction data are consistent with cyanobacteria blooms occurring after a wind/rain event on the concurrent or following calm or nearly calm sunny (or apparently overcast) day. Weather data from the NW site (Roege) in Seneca Lake and Martin N site in Owasco Lake are shown (Fig. 24). The data repository has larger plots. A few issues were noted. A few weather stations initialized with the wrong date & time (e.g., Jan 1, 2017) but the timing was correctable. Some blew over in strong gusts of wind or during the flood event but the homeowner quickly fixed these issues. A few sites, Adams, Bloss, and Martin S started later in the deployment than the others (7/26, 7/24, & 7/28, respectively) but these late starts did not overlap with bloom detections and thus were inconsequential.

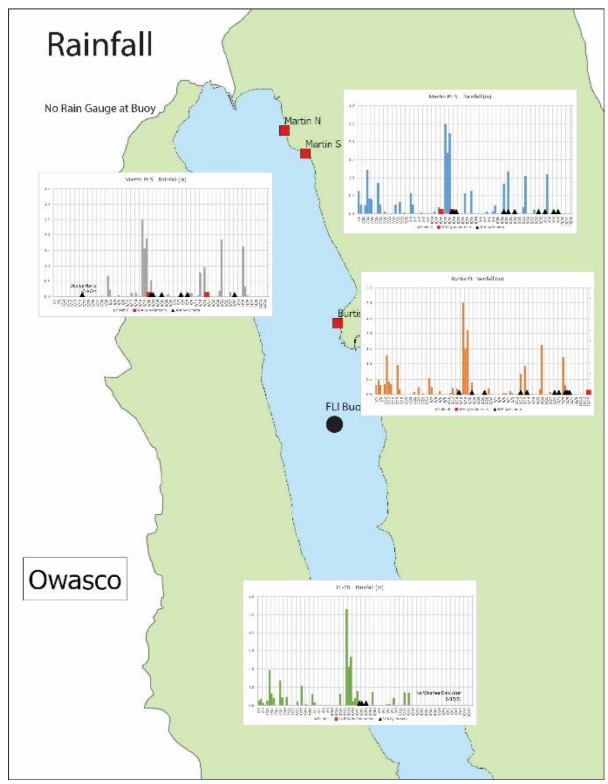
In both lakes, warmer air temperatures, cloudier skies, windier conditions and rain preceded most cyanobacteria appearances at the sites. The blooms occurred on the next sunny (or apparently overcast), calm or nearly calm day. For example, the mean wind speed during blooms was slower than the mean wind speed for the entire deployment at every site (Fig. 25, Table 3).

Open water solar intensities were typically larger at the offshore buoy site than the dock sites. The dock sensors were occasionally in the shade of nearby buildings, steep topography and trees.


Air
Temperature
FLI Buoy
Adams
Allen
Roege
Bloss
Downs
DiOrio
Rose
Judson
Seneca


Air Temperature
Martin N
Martin S
Burtis
FLI Buoy
Owasco


Rainfall
FLI Buoy
Adams
Allen
No Rain Gauge at Buoy
Roege
Downs
DiOrio
Rose
Judson
Seneca


Rainfall
No Rain Gauge at Buoy
Martin N
Martin S
FLI Buoy
Owasco

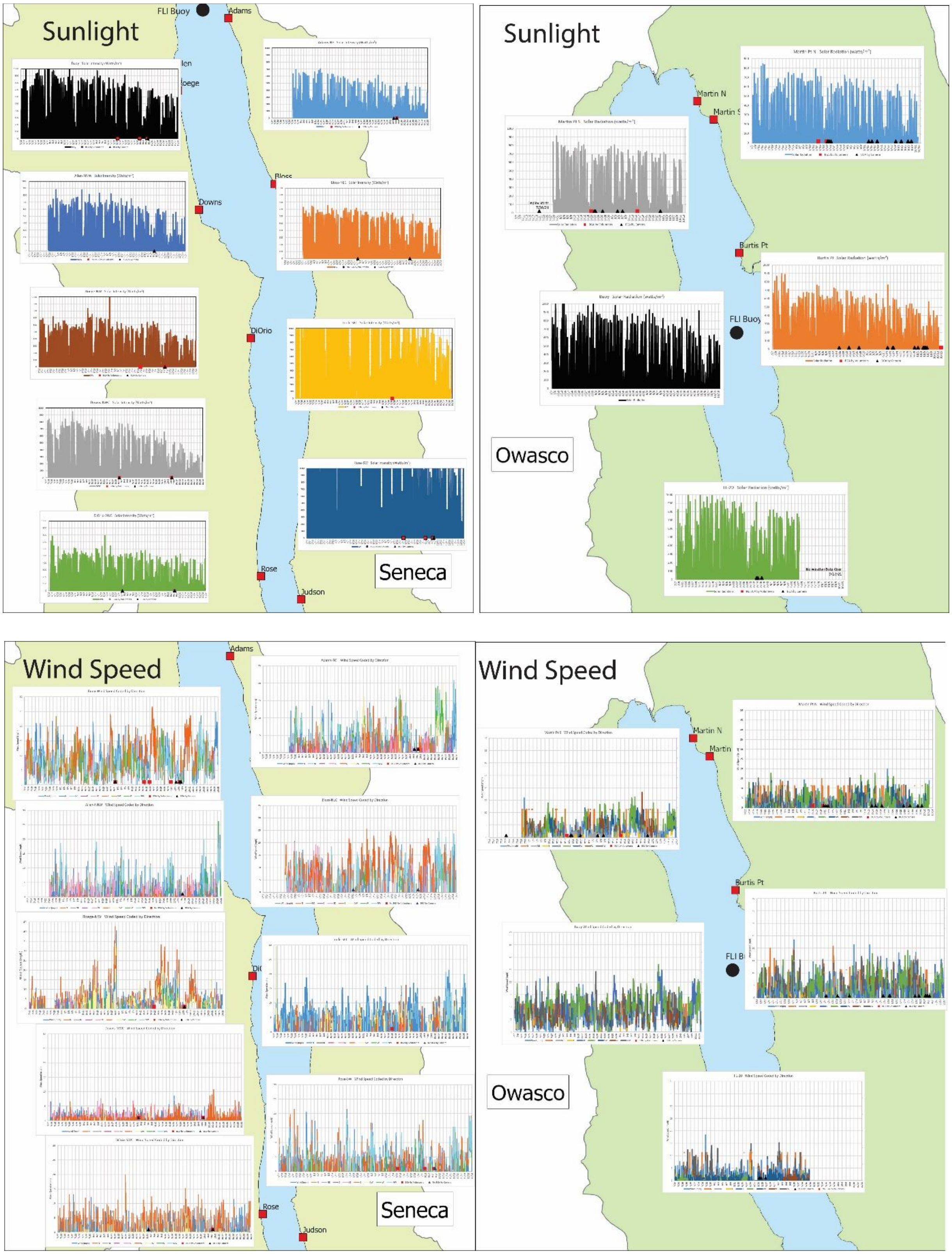
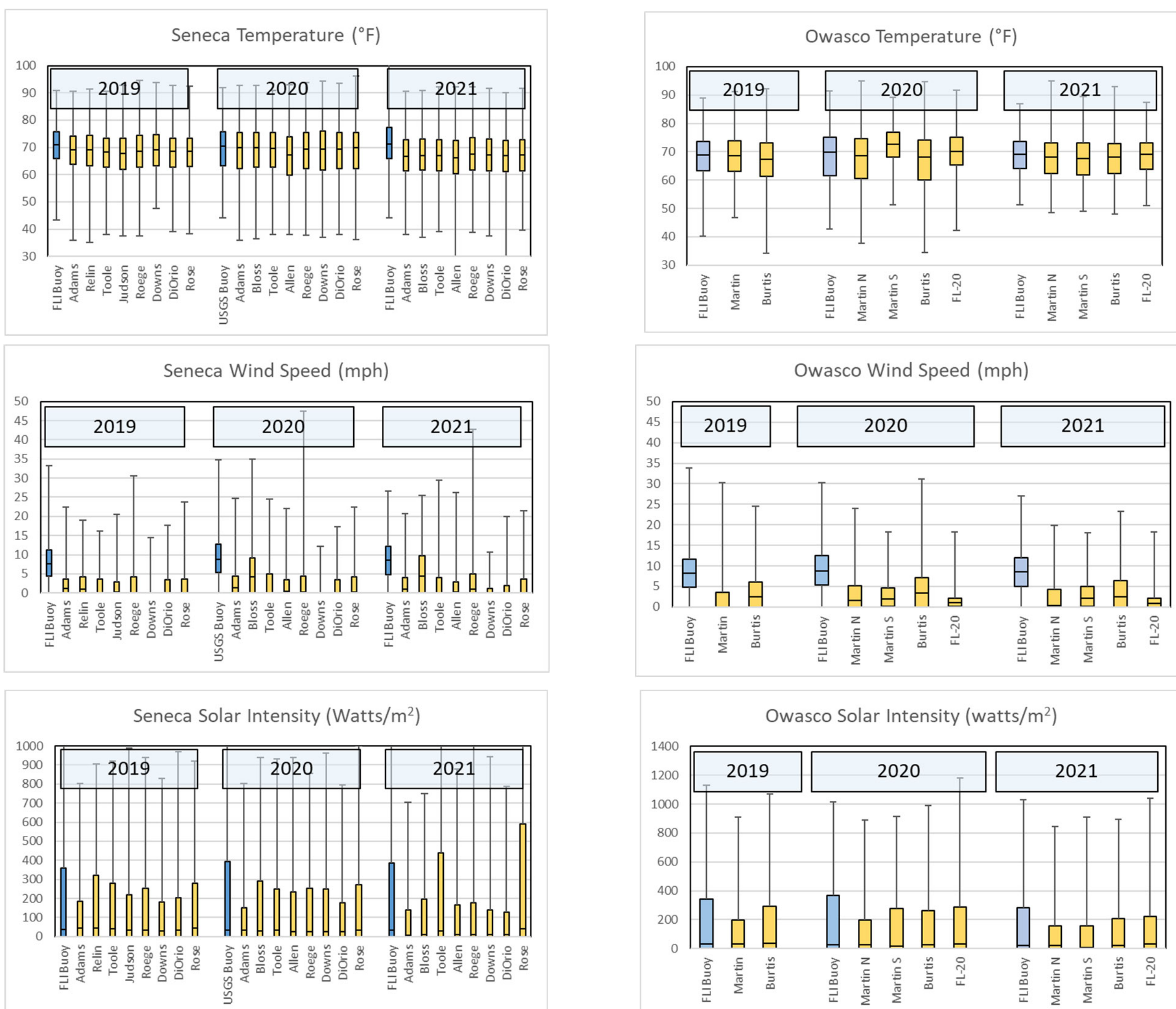


Fig. 24. Dockside air temperature, daily rainfall, solar intensity and wind speed data. Wind speed is color coded by its direction. The red squares mark dates when cyanobacteria were observed by the HABs volunteers, the

black triangles mark dates when cyanobacteria were imaged by the camera.

Wind Speed & Direction: Like previous years, the mean wind velocities were significantly slower at all the dock sites than the mid-lake buoy site (Fig 25). The shoreline provides some protection from the winds, especially winds not blowing directly onto shore. Wind speeds were also slower during bloom events in both lakes (Fig. 26) indicative that blooms prefer calm days. Seasonal variability was also detected in wind speed at each dock site in both lakes with faster winds during late September and late October and slower winds during July, early September and early October (Fig. 27). The majority of the blooms occurred in September and early October. Apparently, when wind speeds decreased long enough and/or were slow enough in both lakes during the September – October HABs season, it proliferated bloom development.

Enough calm or nearly calm days and a seasonal decrease in wind speeds fostered a bumper crop of blooms in both lakes.



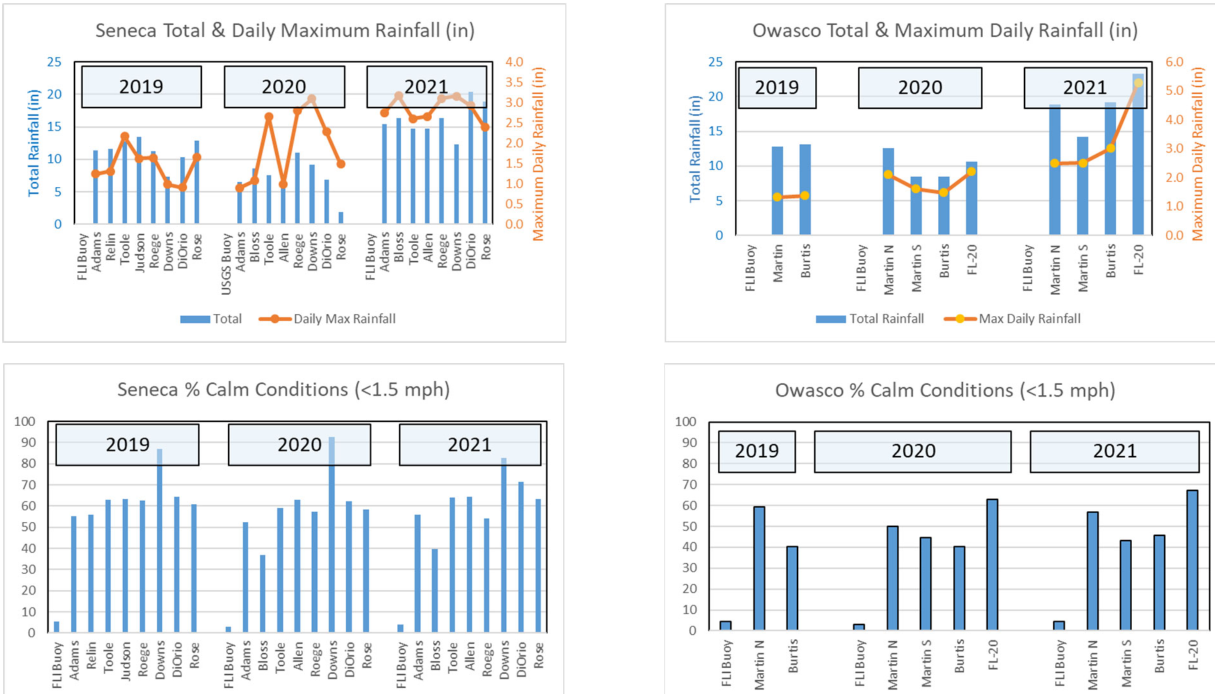


Fig. 25. Box and whisker or bar/line plots of air temperature (top), wind speed (2nd row), solar intensity (3rd row) rainfall (4th row), and % calm (<1.5 mph) conditions (bottom) at the eight Seneca sites (left) and the four Owasco sites (right) in 2019 through 2021. The buoy data (USGS in Seneca during 2020) are included for comparison, the buoys did not detect rainfall.

Table 3. Mean wind speeds (mph) during cyanobacteria blooms and over the entire field season.

Site	Cyanobacteria Blooms	Season	Site	Cyanobacteria Blooms	Season
Seneca					
NNW Allen	0.4	2.0	SW-Rose	0.7	2.2
NW-Roege	0.0	3.3	NE-Adams	1.1	2.6
NWC-Downs	0.7	0.7	NEC-Bloss	0.3	5.7
SWC-DiOrio	0.5	1.4	SEC-Toole	0.0	3.3
Owasco					
Martin N	1.4	2.4	Burtis Pt	1.3	3.6
Martin S	1.3	3.0	Fire Lane 20	1.0	1.7

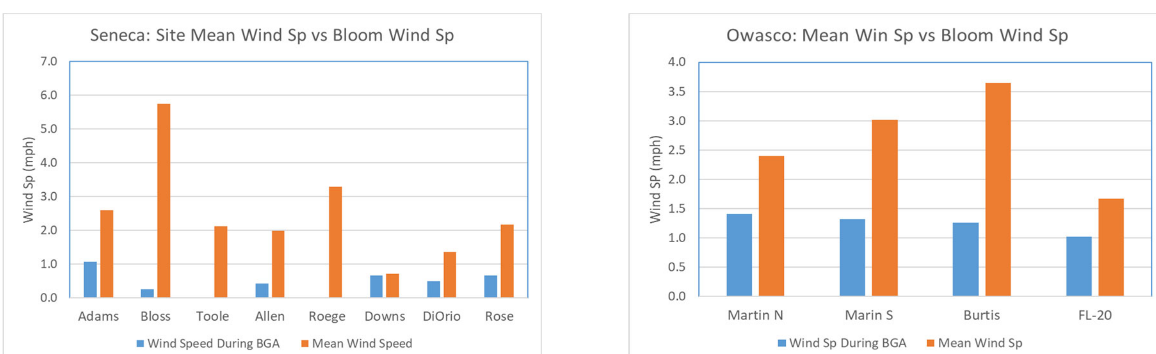


Fig. 26. Mean wind speed during detected blooms and over the entire field season at each site, Seneca left, Owasco right.

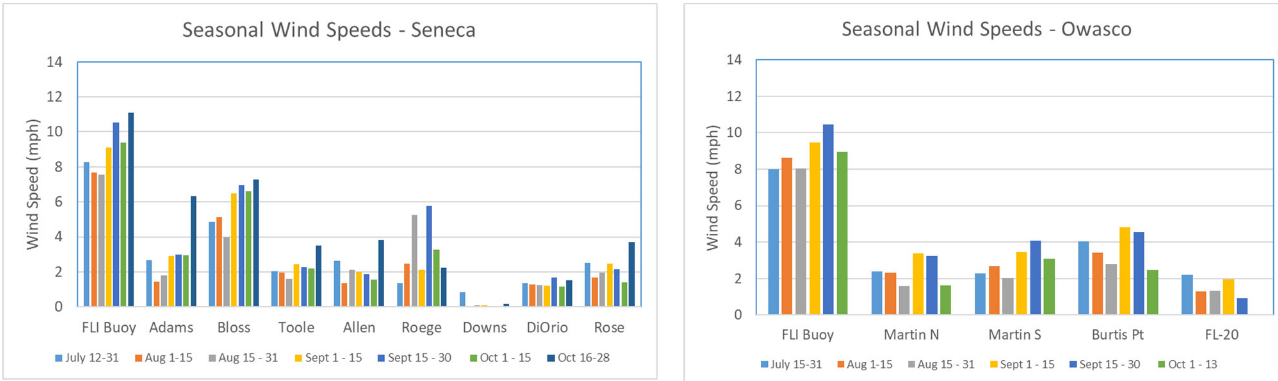


Fig. 27. The 2021 seasonal mean wind speeds at the buoy and dock sites in Seneca (left) and Owasco (right) Lakes.

The most frequent wind direction detected at each dock varied between sites in both lakes as well (Fig. 28). Wind roses from the previous years can be found in the data depository. Even sites in close proximity, e.g., north and south Kashong Point sites, and north and south Martin Point sites revealed significantly different wind speeds and directions over the course of the study. Differences are explained by the unique shoreline orientations at each site. Occasionally light breezes originated from land, especially during the early evening hours at sites with agricultural or grassy fields inland. The timing and speed suggest that these breezes originate from the differential heating and cooling of land/water surfaces. Even though variability was detected between sites, each site's season long dominant wind direction(s) were usually consistent since 2019. It reaffirms that the shoreline orientation at each site modified wind directions and wind speeds, and may dictate which shoreline locations experienced winds and which did not. Onshore winds clearly impact water clarity, i.e., turbid *vs.* clear water, as mentioned above and suggested in the earlier reports. The local variability in winds provide a plausible explanation why the water column can be turbid (windy) at some sites but clear (calm) at other sites on the same day. More importantly, if one shoreline is experiencing calm and sunny conditions, and a bloom appears, the other shorelines may not develop a bloom because those sites may be experiencing onshore winds. It may explain why cyanobacteria blooms appear along different segments of shoreline on different days.

Shoreline orientation and its impact on the regional winds can explain the seeming random nature of blooms in both space and time.

In Seneca Lake, the dominant wind directions detected at the Roege, DiOrio, Toole and the Buoy sites were more aligned with a S or SSW direction in 2021. The other sites were from the S and SSE. Mean annual wind speeds were also faster at these four sites and the Bloss site than the other sites in Seneca Lake. It suggests that their shoreline orientations were more exposed to the open water winds, and thus faster and more frequent winds retarded significant bloom development at these sites than elsewhere in the lake. These wind field patterns did not parallel the number of detected blooms at these sites.

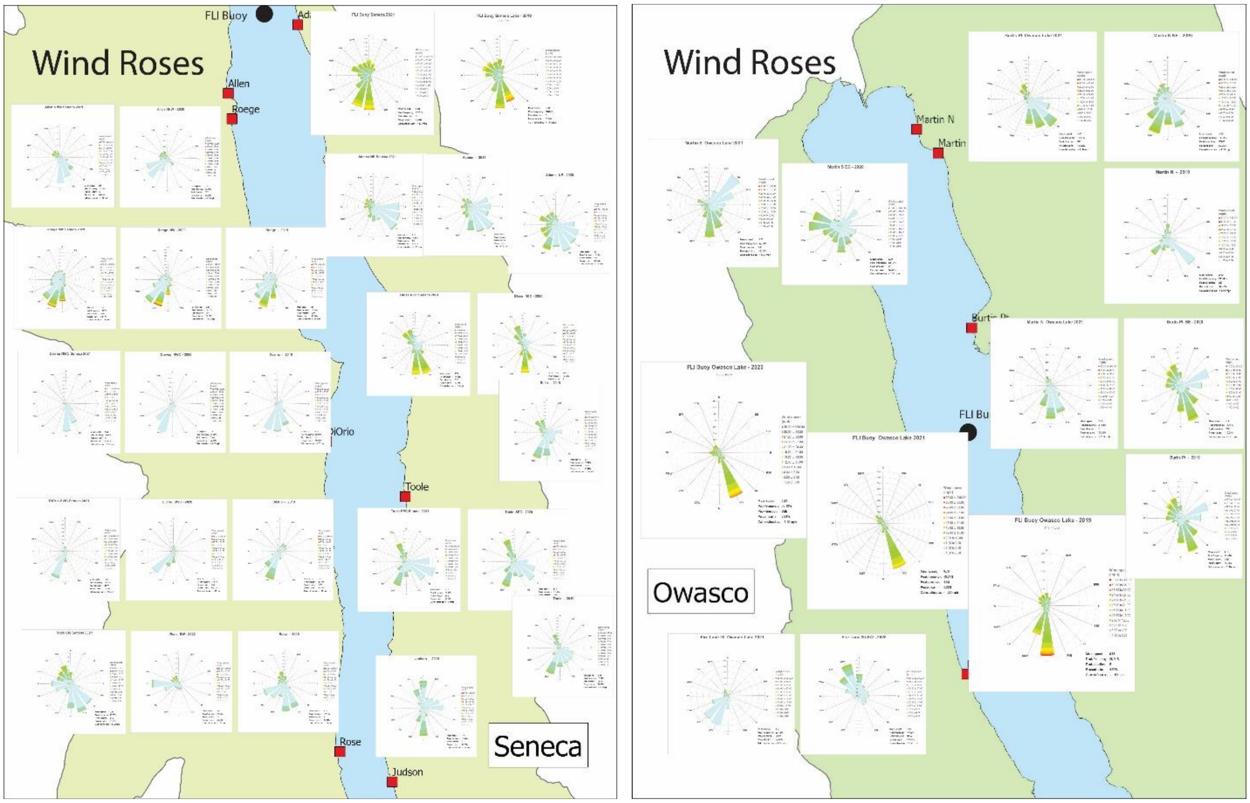


Fig. 28. Rose diagrams of wind speed and direction at the Seneca, Owasco dock sites, and the offshore buoys.

Minor seasonal variability in wind direction was detected at the dock sites (not shown).

Based on the slowest recorded wind speeds and greatest amount of % calm weather recorded at each site, Downs (NWC) in Seneca Lake and Fire Lane 20 in Owasco Lake should have experienced more blooms in 2021 and previous years. Perhaps the winds were sufficiently faster in the daytime and thus more easily mixed blooms into the water column., and/or these sites lack sufficient nutrients to stimulate adjacent blooms. In 2021, the mean wind speeds increased (from 0.7 to 1.1 m/s at Downs and from 1.9 to 2.8 at Fire Lane 20) and percentage of calm recordings decreased (from 92 to 85% at Downs and from 63 to 41% at Fire Lane 20) if the dataset isolated daytime (7 am to 7 pm) winds, i.e., the sites experienced faster winds and fewer calm periods during the daylight hours. However, the increase in wind speed and decrease in the %Calm was probably not sufficient enough to influence bloom numbers as the increased winds speeds impacting the shoreline were still smaller than winds experienced at the other sites. Alternatively, the lack of fast winds at these two sites may have hampered nutrient release from the nearshore sediments to support bloom activity. Finally, biomass was insufficient adjacent to the Fire Lane 20 site as it has a very narrow nearshore shelf and revealed limited DO daily oscillations.

Even with the "correct" meteorological "calm and sunny" conditions, some sites revealed fewer blooms. It suggests that these sites lacked sufficient nutrients to support blooms.

Rainfall: Like previous years, rainfall totals, both seasonal and daily accumulations, varied from site to site (Fig. 29). Daily variability was significant, from no rain at a number of sites to over 3 inches of rain at another site. More sites detected rainfall when daily rain accumulations were larger. More importantly, rainfall totals were significantly larger in 2021 than 2019 and 2020 at every dock site, and neighboring national weather stations, e.g., Geneva, Penn Yan and Ithaca (Fig. 30). The large events in August and October induced floods in the Owasco watershed, near flood-stage lake levels and shallower water table depths during the 2021 HABs season (Fig. 31).

The larger rainfall and runoff provided a source of nutrients to the shoreline and thus stimulated bloom development. For example, the Owasco watershed experienced a number of significant intense storm events in 2021. The Aug 18 event dumped over 10” of rain in the northeastern part of the watershed over a 3-day period, and contributed over 50% of the nutrient loads from fluvial sources to Owasco Lake.[17] It preceded a record number of blooms over the next few days. This rain event was less severe over Seneca Lake, and it experienced fewer blooms. It indicates that the runoff from large precipitation events can deliver sufficient nutrients to the nearshore regions to stimulate cyanobacteria blooms. These intense events are localized, and only impact an individual lake or a portion of a lake that experiences the blooms. Unfortunately, not all rainfall events stimulated blooms, and some blooms lacked a preceding rain event.

Rainfall and its associated runoff of nonpoint source nutrients from very large rain events was an important source of nutrients for bloom development.

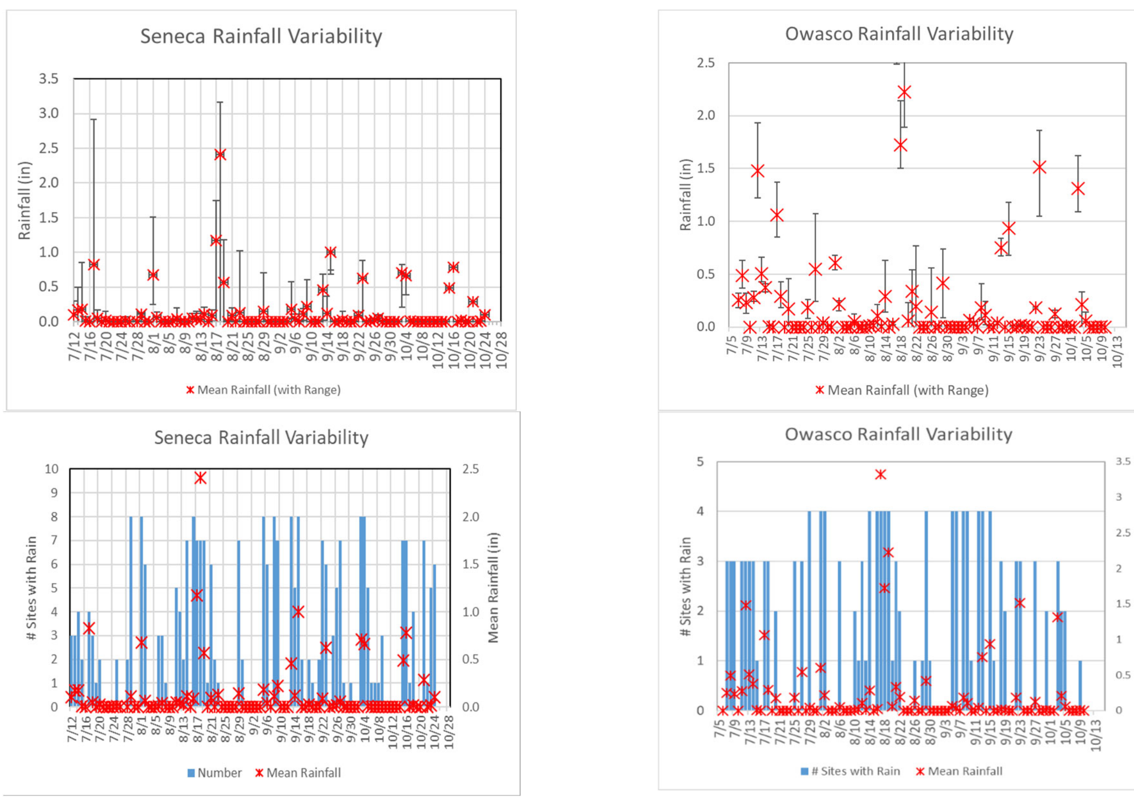


Fig. 29. Rainfall variability between sites Seneca (left) and Owasco (right). The mean, and minimum and maximum range for rainfall on any given day (above), and the mean rainfall and number of sites with any rain on any given day (below)

[17] Halfman, J.D., et al., 2022. The 2021 water quality monitoring report Owasco Lake, NY. Finger Lakes Institute, Hobart and William Smith Colleges. 54 pg.

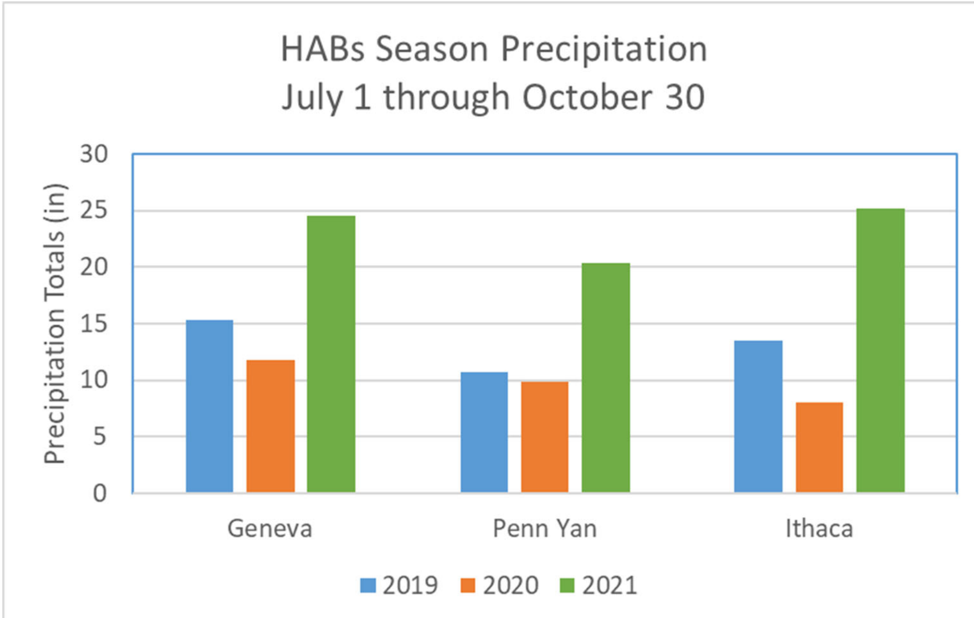
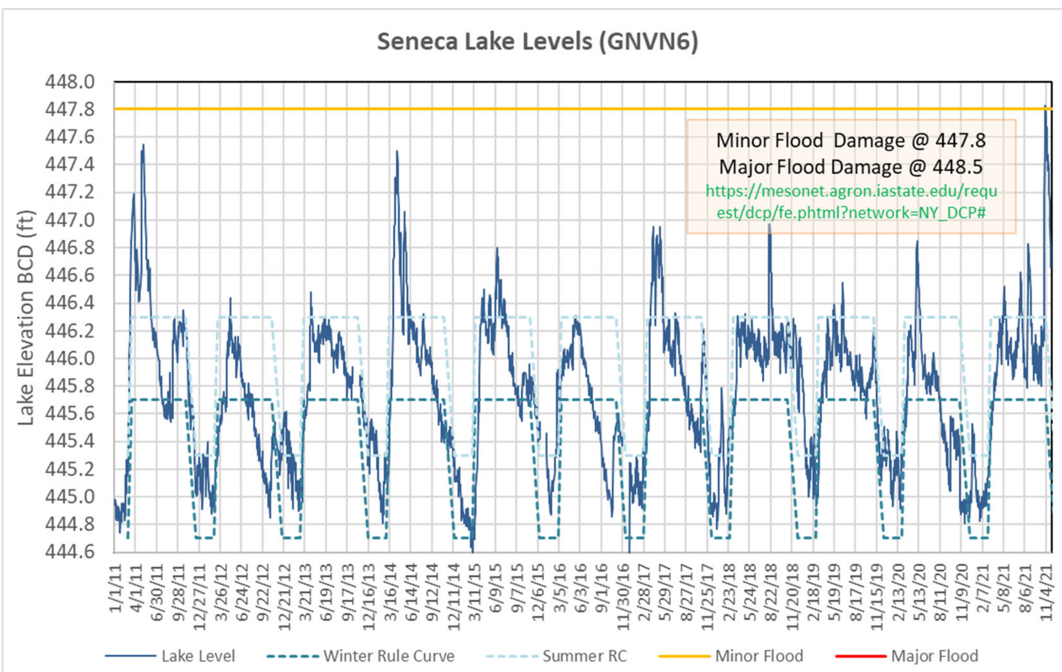
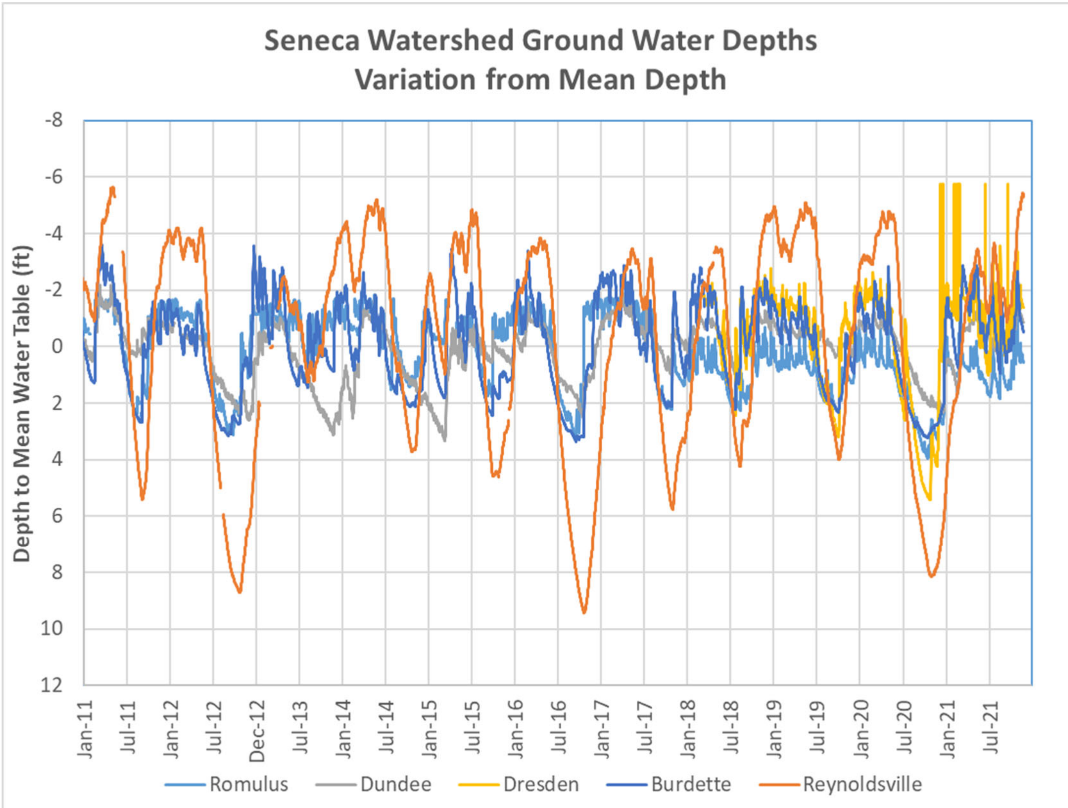


Fig. 30. HABs season precipitation totals for Geneva, Penn Yan and Ithaca, NY.




Seneca Watershed Ground Water Depths
Variation from Mean Depth
Depth to Mean Water Table (ft)
-8
-6
-4
-2
0
2
4
6
8
10
12
Jan-11
Jul-11
Jan-12
Jul-12
Dec-12
Jul-13
Jan-14
Jul-14
Jan-15
Jul-15
Jan-16
Jul-16
Jan-17
Jul-17
Jan-18
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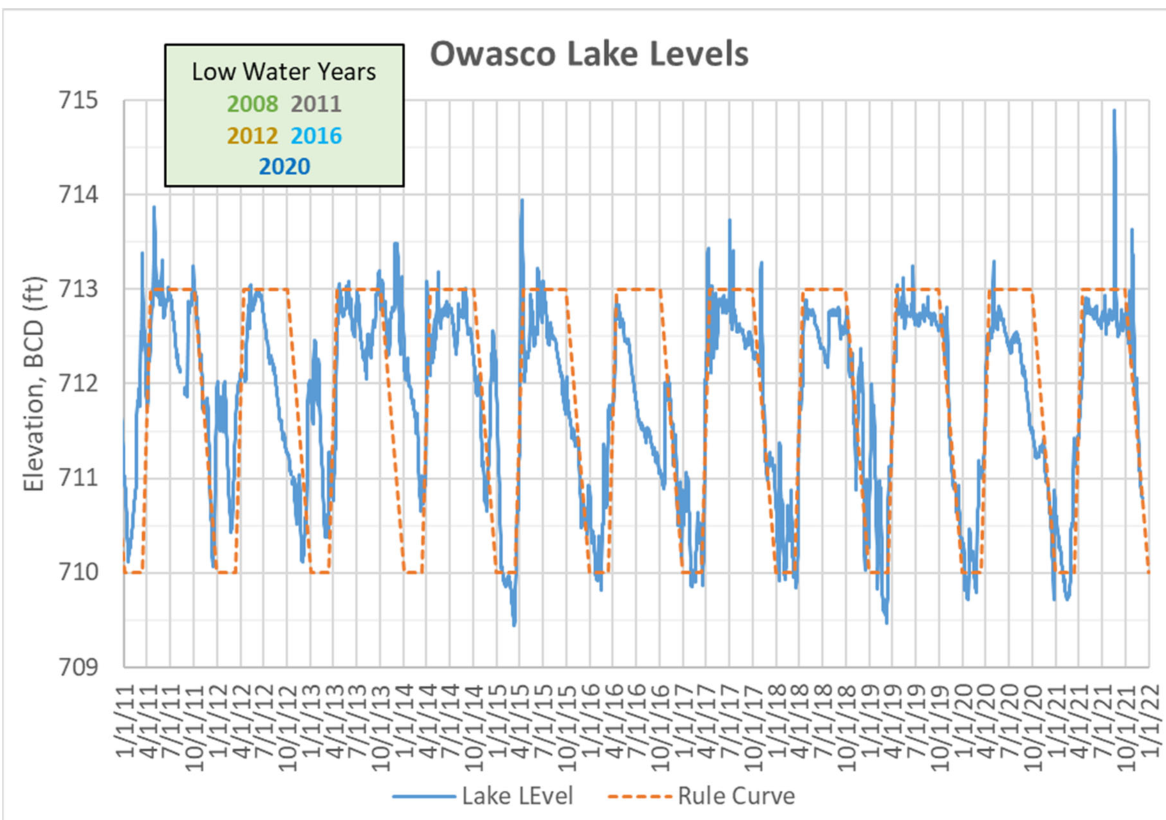
Dundee
Dresden
Burdette
Reynoldsville


Owasco Lake Levels
Low Water Years
2008 2011
2012 2016
2020
Elevation, BCD (ft)
715
714
713
712
711
710
709
1/1/11
4/1/11
7/1/11
10/1/11
1/1/12
4/1/12
7/1/12
10/1/12
1/1/13
4/1/13
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Lake LEvel
Rule Curve

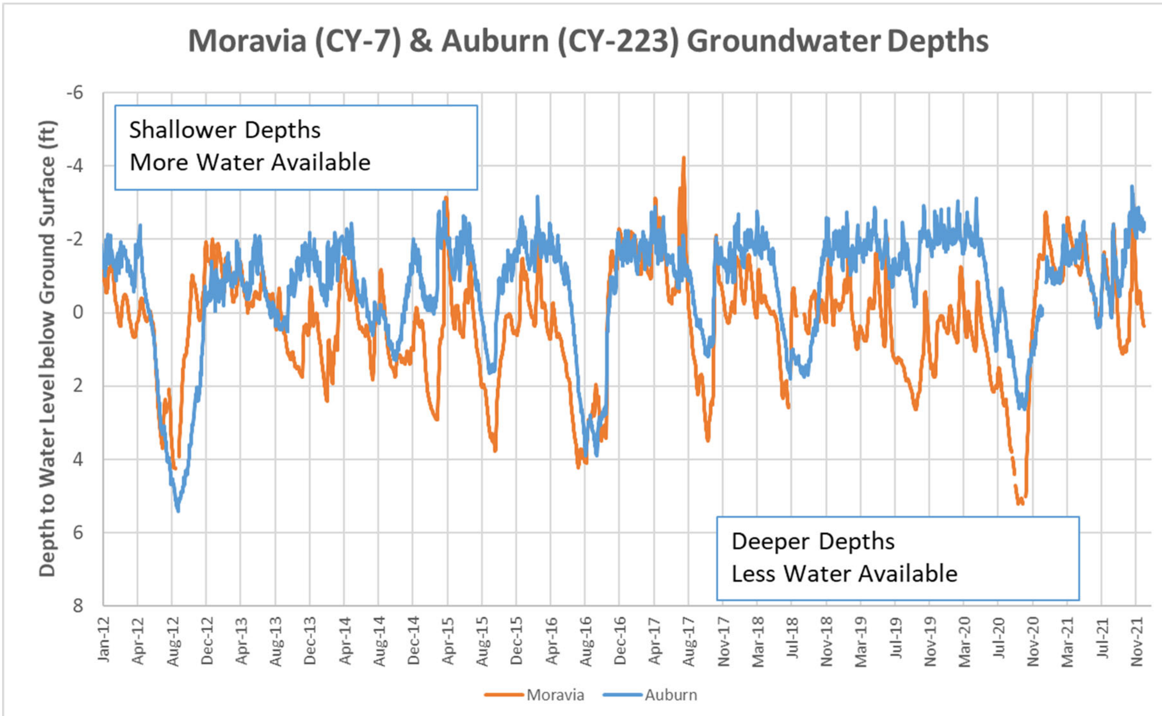


Fig. 31. Lake level at Seneca and Owasco Lakes and water table depths at USGS monitoring wells in the Seneca and Owasco Watersheds. Owasco Lake flood stage is 715 ft; and Seneca Lake flood stage is 447.8 ft.

Statistical Analysis of the Meteorological Data: Statistical analysis of selected daily average meteorological and water temperature data was performed to determine which parameter(s) consistently correlated to bloom events (Fig. 32). Each year's data from each site were analyzed separately for a total of 24 separate statistical tests (Seneca Lake 2020 data and Fire Lane 20 data from Owasco Lake were not analyzed due to the limited number of HABs events). Air temperature, rainfall, rainfall on the preceding day, solar intensity, water temperature, water temperature on the preceding day, wind direction, wind speed, and the percentage of calm (<1.5 mph) weather were compared to days with blooms and days without blooms. Days with blooms statistically ($p < 0.05$, 22 of 24 results) correlated to days with less rainfall, less rainfall on the preceding day, and days with smaller wind speeds than with air temperature and solar intensity ($p < 0.05$ less than 10 of 24 results). The parameters with less significant results also revealed less consistent trends, i.e., a mixed bag of warmer or cooler water during a day with a bloom. Take these results with a word of caution. Daily averages could bias the results, e.g., a short-lived calm episode with a bloom might happen on an otherwise windy day. However, a subset of 24 analyses (Owasco 2021 rain, rain previous day and wind speed) was rerun using the 30-minute interval data, and the results revealed an increase in the level of significance of the correlations. These statistical findings are consistent with the bloom-parameter observations mentioned in this report.

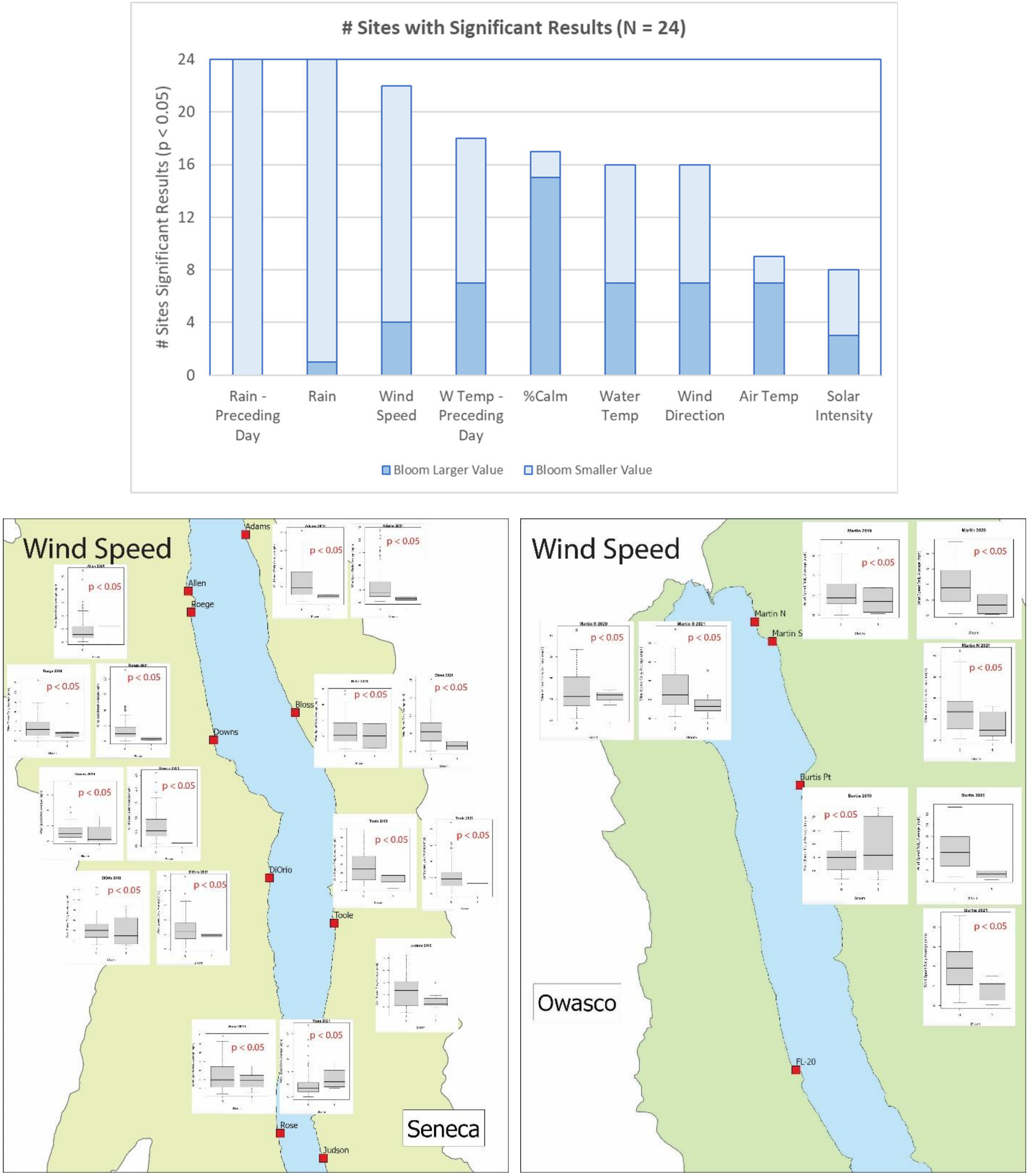


Fig. 32. Number of sites with significant results from the statistical analysis of selected meteorological and water temperature data (above). Each year's data from each site were analyzed separately for a total of 24 separate statistical tests. The light blue bars tally when the bloom correlated to warmer/larger values, and dark blue bars to cooler/smaller values, out of all of the significant results ($p < 0.05$) for each parameter. For example, 18 of the 22 significant results revealed slower wind speeds, and 4 faster wind speeds, during a bloom event (below).

Water Quality Sonde Data (Owasco Only): Water quality (WQ) sondes were redeployed at the four Owasco dock sites to measure temperature, salinity, and fluorescence, both total fluorescence and cyanobacteria-PC fluorescence at approximately 1-m below the lake's surface inside a PVC pipe.

The sonde temperatures revealed similar long term and daily oscillations in temperature as the 1-m temperature loggers at each site (Fig. 33). The salinity data was also uneventful and paralleled open water concentrations (Fig. 33). Like 2020, it decreased by ~10 µS/cm each night at Burtis Pt. The reasons for these daily changes are unclear and may reflect the sensor's temperature sensitivity. Salinity increased by 50 to 100 µS/cm on a few occasions in July at Martin S and Martin N, and in mid-August and early October at Burtis Pt for unknown reasons. Perhaps the sensor was temporarily fouled with organic matter or mussels. The salinity increases at Burtis Pt were concurrent with low dissolved oxygen and high chlorophyll concentrations. The changes were similar to the clogging event at Martin S in 2020. It suggests that the deployment pipe was temporarily clogged with organics, and their decay decreased oxygen concentrations in the pipe.

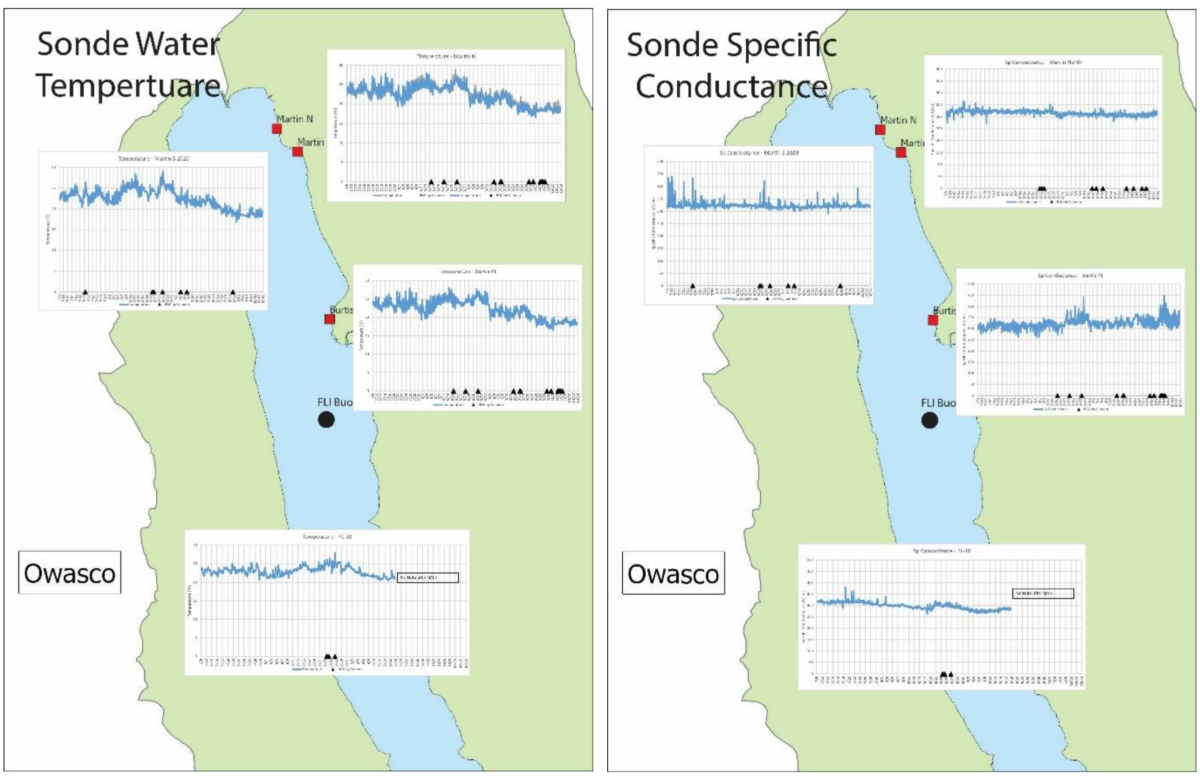


Fig. 33. Surface water temperatures and salinity measured by the WQ sondes at the dock sites in Owasco Lake. The long-term and daily temperature oscillations were identical to the temperature loggers, and the salinity trends similar to the offshore data.

The dissolved oxygen (DO) concentrations again revealed daily oscillations that co-varied with water temperature (Fig. 34). The daily variations were again largest at Burtis Pt and smallest at Fire Lane 20. Two parameters control DO concentrations in water, water temperature and biological activity. Water temperature inversely controls saturated dissolved oxygen concentrations. The covariance in water temperature and dissolved oxygen concentrations in Owasco Lake indicates that water temperature and the diffusion of oxygen between the water and the atmosphere did not control the observed daily variability in dissolved oxygen concentrations. Instead, photosynthesis and respiration by macrophytes and other organisms affected the DO concentrations. When biological activity is intense enough, oxygen is produced during the daylight hours through photosynthesis; oxygen is removed from the water column through respiration by all organisms, and the decline in DO is most noticeable at night. The covariance between the temperature and DO fluctuations indicates that biological activity had a major but variable impact on nearshore dissolved oxygen concentrations. The sites with the largest DO fluctuations recorded the largest number of blooms. This suggests that nearshore bacterial decay could be a (or the) source of nutrients for nearshore cyanobacteria blooms.

The magnitude of the daily oscillations parallels the amount of macrophyte biomass at its site, as visual inspection suggests that Burtis Pt had the most and Fire Lane 20 had the least. Martin N and Martin S have rocky lake floors but still experienced DO fluctuations. It highlights the importance of biological activity in a variety of lakeshore settings. It confirms the importance of photosynthesis and respiration in the nearshore portions of the lake, and suggests the organic debris, e.g., macrophytes and *Cladophora*, might provide a viable source of nutrients for cyanobacteria blooms.

Dissolved oxygen decreased to anoxic conditions at the Burtis Pt site in early October. It suggests that the deployment pipe was temporarily clogged with macrophytes and other organic debris (Fig. 34). Bacterial respiration of the organic material inside the pipe could have depleted the dissolved oxygen in the water within the pipe. This respiration would have released dissolved nutrients and other ions, increasing the salinity inside the pipe.

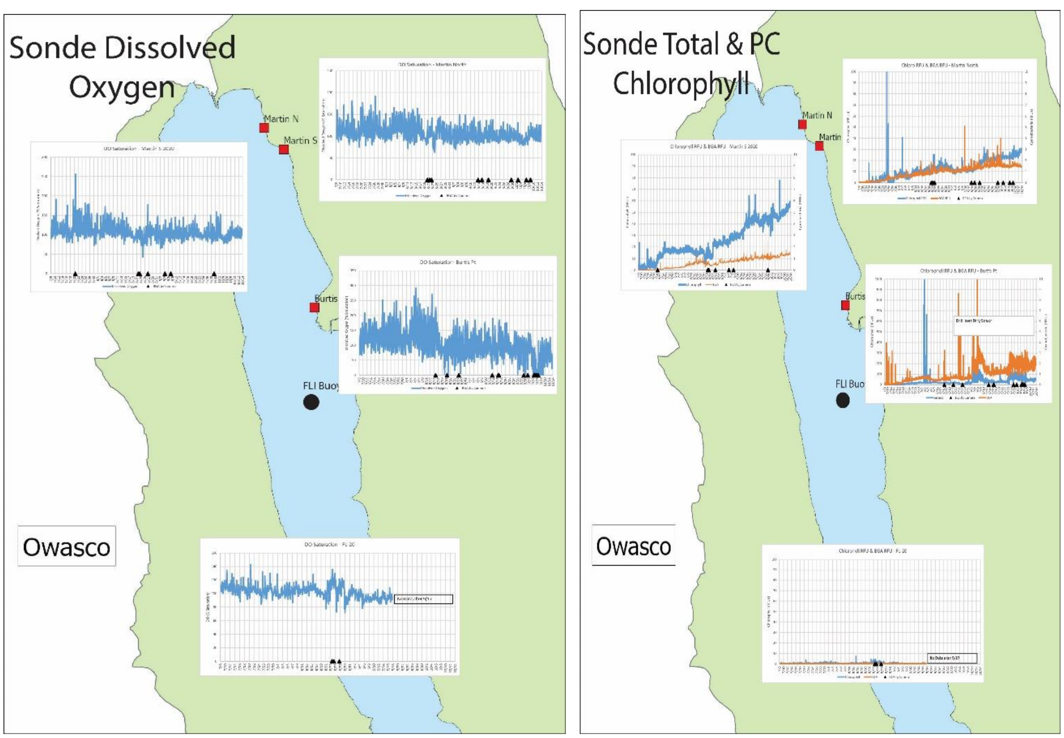


Fig. 34. WQ sonde dissolved oxygen, total chlorophyll and cyanobacteria-chlorophyll concentrations. Non-synchronous blooms were detected at all the sites. Significant deviations in August, September and October at the Burtis Pt site were probably induced by the decay of organic debris, e.g., macrophytes and *Cladophora*, clogging the deployment pipe. Note the scale change for the Burtis chlorophyll plot.

The WQ sonde total fluorescence (chlorophyll) revealed a baseline increase in fluorescence at Martin S, Martin N, and Burtis Pt over the duration of the deployment (Fig. 34). It is interpreted to reflect the decreased effectiveness of the wiper to clean biofouling organic films off of the *In Situ* Aqua Troll 600 sensor over time. It appears that the wiper on the YSI/Xylem EXO2 sonde kept its sensor clean (Fire Lane 20 site). These Aqua Troll wipers should be replaced before the next deployment.

Rising above the baseline trend were hour to day long, and seemingly random spikes of increased in fluorescence at all four sites (Fig. 34). They were more frequent at the northern sites. Like last year, these brief spikes in fluorescence were not synchronous in time between sites, nor synchronous with peaks in the cyanobacteria-PC fluorescence. Cyanobacteria blooms were not imaged at the site during these spikes in fluorescence as well. They were however, synchronous with increased water turbidity (detected by the camera). It suggests that wave action that induced the nearshore turbidity also suspended benthic (lake floor) algae into the water column. It highlights a robust algal community st the lake floor even along the rocky shorelines at Martin N and S. The algae, after their decay, potentially provide yet another source of nutrients for cyanobacteria blooms. Interestingly, every time the Burtis Pt pipe was clogged, the total fluorescence increased for a few days (most notable deviations starting at 8/3, 9/4 and 9/27). We speculate that the sensor detected the chlorophyll released by the decaying plant debris. The decay in chlorophyll over the next few days is consistent with bacterial decay and eventual degradation of the plant chlorophyll and other easily degradable parts, and/or the flushing of the debris from the pipe with fresh lake water. This scenario is consistent with the salinity and dissolved oxygen variability.

Finally, the WQ sonde cyanobacteria-PC fluorescence sensors also revealed a baseline increase in PC-fluorescence at Martin S, Martin N, and Burtis Pt over the duration of the deployment (Fig. 34). It is again interpreted to reflect the decreased effectiveness of the wiper to clean organic films off of the In Situ Aqua Troll 600 sensor.

Rising above this baseline trend were hour to day long, and seemingly random peaks in cyanobacteria at all of the sites (Fig. 34). They were more frequent at the northern sites. Like the total fluorescence data, these blooms were not synchronous in time between sites, nor synchronous with peaks in the total fluorescence. Cyanobacteria blooms were not imaged at these sites during these PC-fluorescence events. They were however, synchronous with increased water turbidity detected by the cameras. It suggests that wave action, that induced the nearshore turbidity, also suspended cyanobacteria in the sediments into the water column, and a robust lake floor cyanobacteria community exists in the nearshore area even along rocky shorelines. It is unclear why these cyanobacteria-PC detections were asynchronous with the other forms of benthic (lake floor) algae. The cyanobacteria, after their decay, provide yet another source of nutrient for additional cyanobacteria blooms.

Like the total fluorescence results, cyanobacteria-PC concentrations were rarely elevated during obvious cyanobacteria blooms detected by the camera. It highlights the surface floating character of cyanobacteria blooms, where the camera images detect them, in contrast to a WQ sonde sensor deployed at ~0.5 m below the surface.

Interestingly, once the Burtis Pt pipe was clogged, the cyanobacteria-PC fluorescence increased for a few hours after the initial detection. Just like last year at Martin S, we speculate that the sensor detected the development of cyanobacteria within the pipe, supported by the release of nutrients from the decay of organic matter that clogged the deployment pipe, and decaying macrophytes are a viable source of nutrients for cyanobacteria blooms (see above).

The WQ sonde at the Burtis Pt site, when clogged with dead plant matter, provided valuable information. The nearshore region has a robust plant community, and once decayed may provide a critical nutrient source for cyanobacteria blooms.

NUTRIENTS, SEDIMENTS, MUSSELS & MACROPHYTES

Mesocosm Experiments: For the June incubations, the starting chlorophyll concentration for the incubation, or T_0, was 5.8 µg/L (Fig. 35). After seven days, the average chlorophyll concentration for the three controls was 6.6 µg/L. The chlorophyll concentration for the nitrogen treatment was not statistically different than the control. However, the phosphorus only treatment was significantly higher than the nitrogen only treatment. Finally, the nitrogen plus phosphorus treatment was statistically higher than all three treatments. This likely indicates a serial limitation for phosphorus for June in Owasco Lake water meaning that phosphorus is limiting, but the addition of nitrogen further enhances productivity as demonstrated by higher chlorophyll concentrations. The phytoplankton community remained consistently dominated by green algae and diatoms although the phytoplankton in single nutrient treatments were only green algae (Fig. 36).

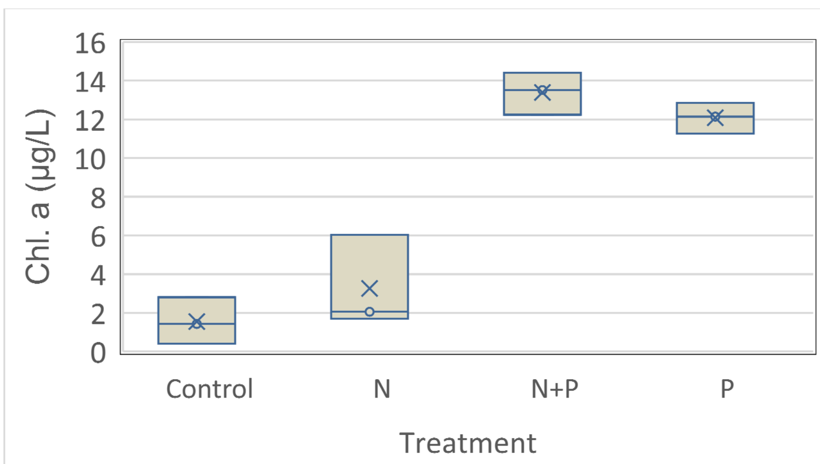


Fig.35. Results from June mesocosm experiments. The P as well as the N+P treatments resulted in higher Chl. a concentrations at the end of the experiments.

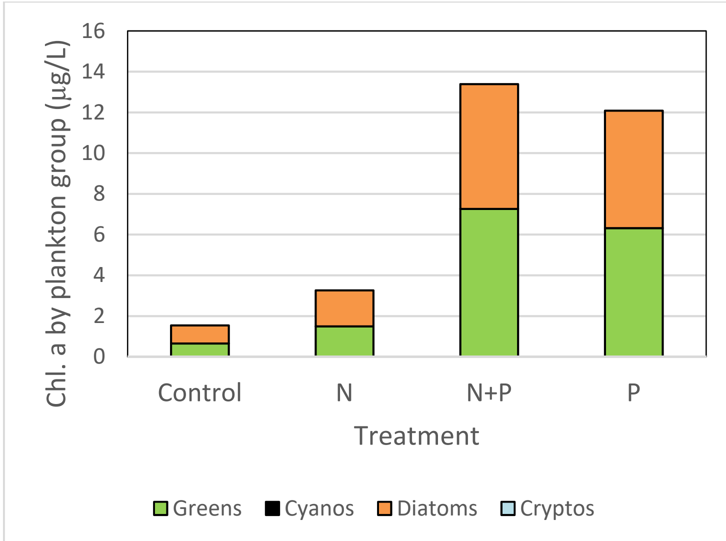


Fig. 36. Average FluoroProbe chlorophyll concentrations from June mesocosm experiments showing major algal groups present. Key: Greens = green algae, Cyanos= cyanobacteria, Diatoms = diatoms, Cryptos = cryptophytes.

In July, a similar finding was observed but with higher overall chlorophyll concentrations likely due to the warmer temperatures observed in July (Fig. 37). For this trial, we tested the addition of single N treatments by themselves and in combination with P. This time the phosphorus only treatment was statistically higher than the control and nitrogen treatments. Owasco Lake is therefore, P limited in July. The phytoplankton community was once again dominated by green algae and diatoms at the end of the five-day incubation period although cyanobacteria and cryptophytes were also detected (Fig. 38).

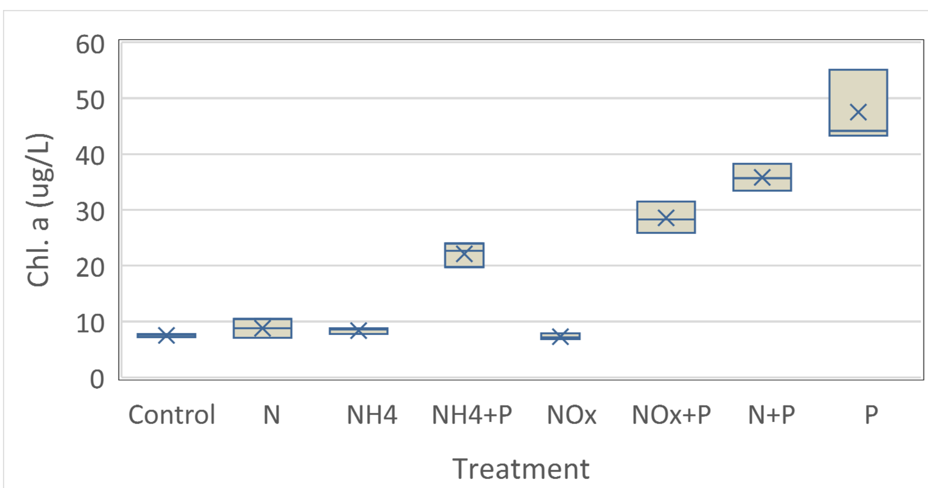


Fig.37. Results from July mesocosm experiments. The P treatment yielded the highest average chlorophyll concentrations showing that Owasco Lake is P limited during July. The N+P treatments were higher than the controls, but not as high as P by itself.

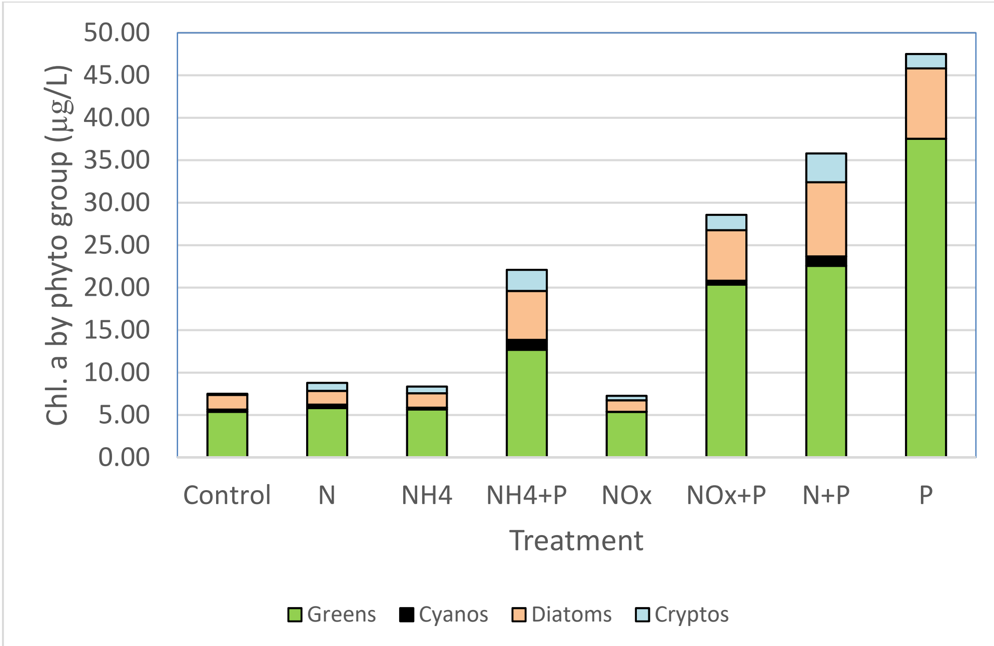


Fig. 38. FluoroProbe chlorophyll concentrations from July mesocosm experiments showing major algal groups present. Key: Greens = green algae, Cyanos= cyanobacteria, Diatoms = diatoms, Cryptos = cryptophytes.

For August, starting chlorophyll concentrations were higher (Fig. 39), but the phytoplankton community again exhibited P limitation although the N+P treatment was not statistically different from the P only treatment. The phytoplankton community was dominated by green algae and diatoms; this did not change during the incubations (Fig. 40).

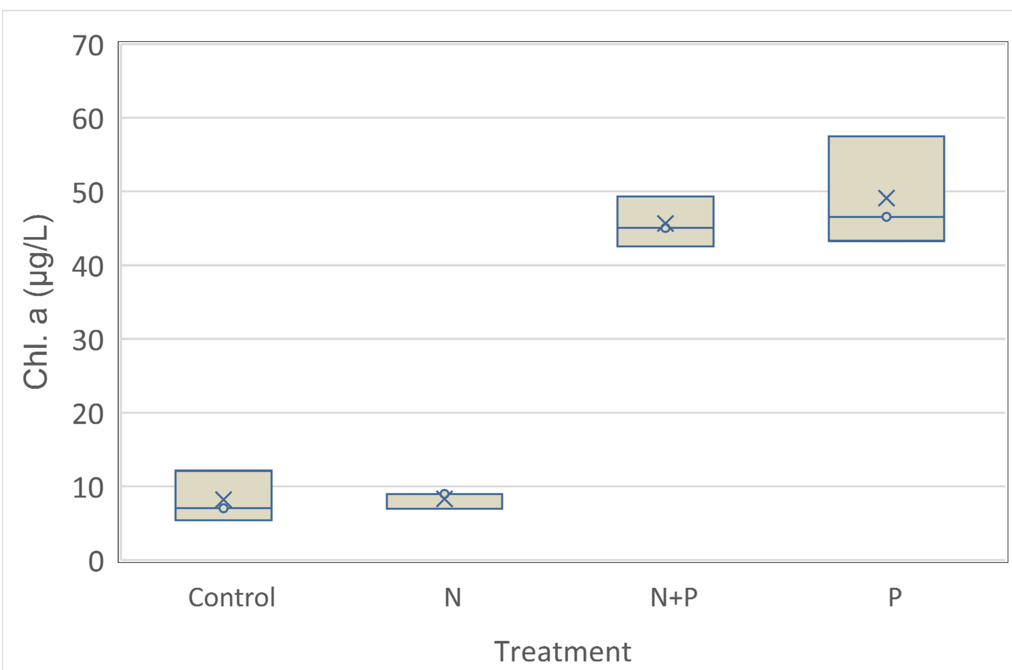


Fig. 39. Results from August mesocosm experiments. The P as well as the N+P treatments resulted in higher Chl. a concentrations at the end of the experiments demonstrating serial P limitation.

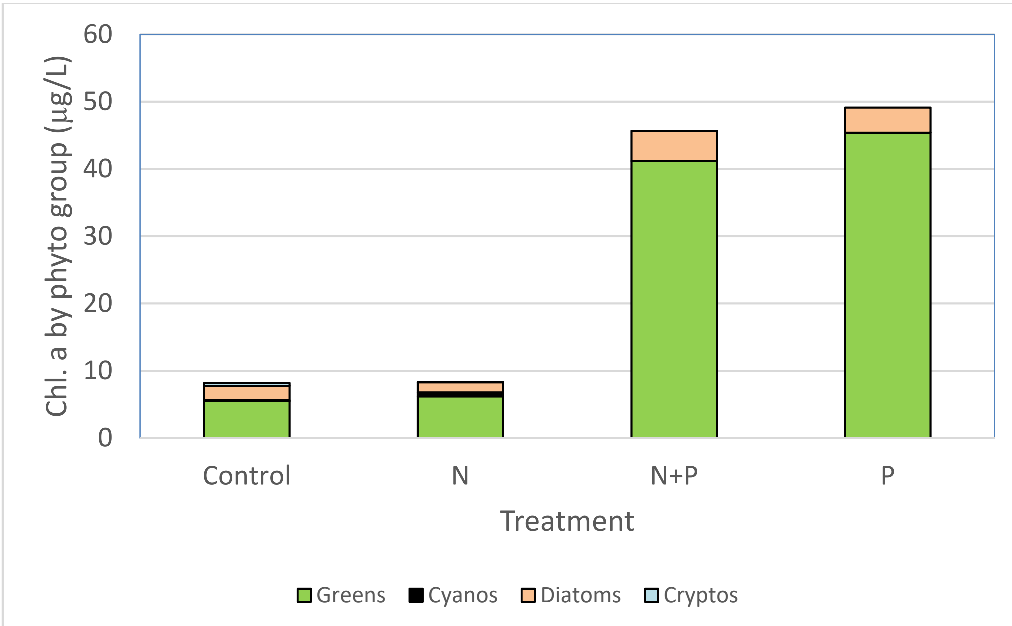


Fig. 40. FluoroProbe chlorophyll concentrations from August mesocosm experiments showing major algal groups present. Key: Greens = green algae, Cyanos= cyanobacteria, Diatoms = diatoms, Cryptos = cryptophytes.

In September, the average chlorophyll concentrations for all treatments were not statistically significantly different (Fig. 41). A major reason for this is that there was a large variation in the chlorophyll concentrations for the incubation replicates and this was seen in September 2020 as well. On average, the P only had the highest concentration after five days with an approximately 75% increase compared to the controls. The phytoplankton community remained consistent across the treatments (Fig. 42) and the diversity of the phytoplankton community may be responsible for the variability among the chlorophyll concentrations in the three replicates for each treatment.

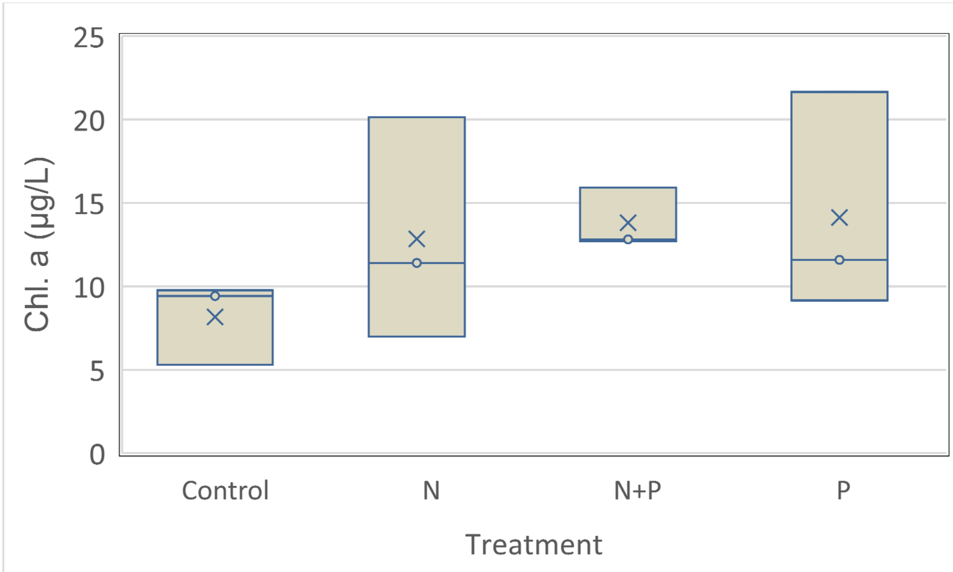


Fig. 41. Results from September mesocosm experiments. No significant differences in final chlorophyll concentrations among treatments were observed.

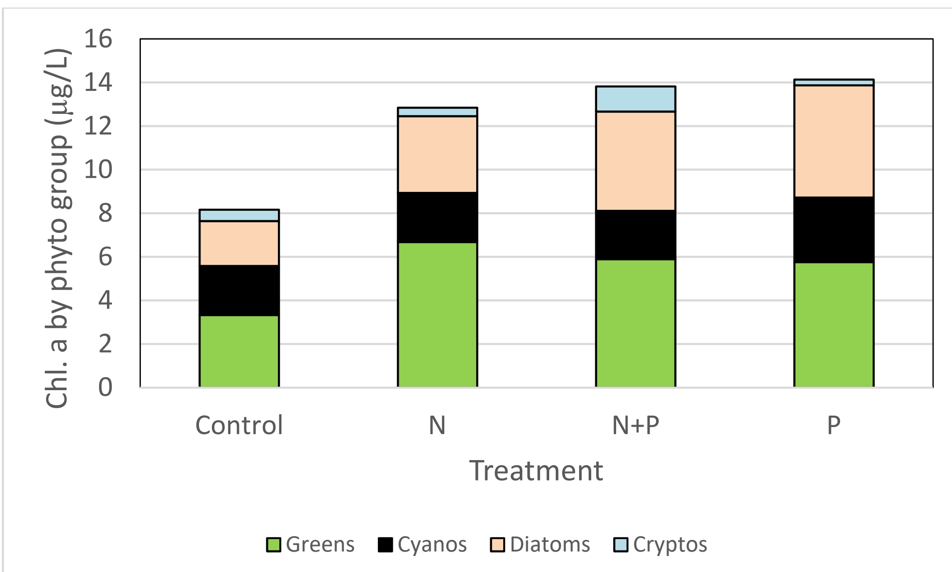


Fig. 42. FluoroProbe chlorophyll concentrations from September mesocosm experiments showing major algal groups present. Key: Greens = green algae, Cyanos= cyanobacteria, Diatoms = diatoms, Cryptos = cryptophytes.

Conclusions: Compared to other Finger Lakes tested in 2021 including Cayuga, Canandaigua, and Honeoye, Owasco Lake was the only lake to show serial P or P-only limitation. As explained in Lewis et al.[18], serial limitation could be due to a number of factors. For instance, additional nutrients can enable phytoplankton cell to obtain nutrients that were previously not accessible.

[18] Abigail S. L. Lewis, Brian S. Kim, Hailee L. Edwards, Heather L. Wander, Claire M. Garfield, Heather E. Murphy, Noah D. Poulin, Sarah D. Princiotta, Kevin C. Rose, Alex E. Taylor, Kathleen C. Weathers, Courtney R. Wigdahl-Perry, Kiyoko Yokota, David C. Richardson & Denise A. Bruesewitz (2020) Prevalence of phytoplankton limitation by both nitrogen and phosphorus related to nutrient stoichiometry, land use, and primary producer biomass across the northeastern United States, Inland Waters, 10:1, 42-50, DOI: 10.1080/20442041.2019.1664233.

An example of this could be the production of amino acids spurred by the addition of nitrogen that may enable the production of enzymes to consume additional sources of phosphorus. In 2022, we plan to continue experiments different nutrient concentration amendments, particularly for P. We will also plan to do more the of the single N treatment combinations with P in August and September when HAB events are typically observed.

Sediment Flux Experiments: Results from the sediment incubation show that the uptake and efflux of nutrients from sediments vary in magnitude across treatment groups.

Concentrations of SRP averaged ~3 µg/L while TP averaged 8.76 µg/L. Concentrations of NO_3 were constant while NH_4 concentrations in the inflow water increased over time, especially at the 72 hr collection. The concentrations of nutrients from the T_0 water collected in the field as well as the concentrations of the inflow water collected every 24 hr can be found in Table 4.

Table 4. Nutrient concentrations of inflow water for sediment core incubations over time.

Time	SRP (µg/L)	TP (µg/L)	NO_3 (mg/L)	NH_4 (mg/L)
T-0	2.71	8.6	0.706	0.096
T-24hr	4.47	7.64	0.687	0.051
T-48 hr	3.13	11.12	0.701	0.083
T-72hr	1.58	7.69	0.720	0.186

For phosphorus species (Fig. 44), the control cores showed the largest flux or release of TP from the sediments over the three-day incubation period; and SRP flux was ~20% of the TP flux. The nitrogen only amended cores showed that SRP was taken up by the sediments while modest TP efflux was observed. For the SRP amendments (NP, P), the flux of TP across the 72 hr period was similar. The P only treatment however, showed that most of the efflux from the sediment was SRP when compared to TP.

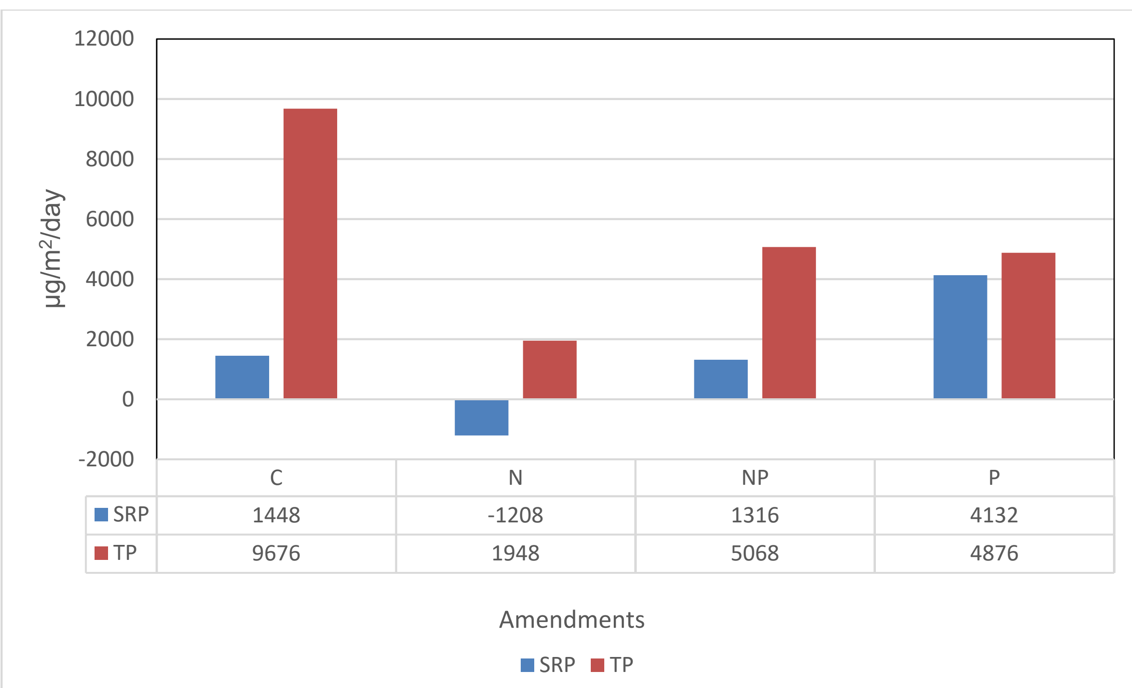


Fig. 44. Daily flux of SRP and TP from sediment cores over 72 hrs.

The average daily flux for SRP and TP across the amendments are listed in Table 5 and shown in Fig. 45. These results demonstrate that nitrogen amendments prevent the release of SRP from sediments, but these results are counteracted by modest additions of SRP in the inflow water as seen in the P and N+P amendments. These daily flux rates are comparable to others reported across the literature.

Table 5. Daily fluxes of phosphorus from Owasco sediments.

Amendment	**SRP (mg/m^2)**	**TP (mg/m^2)**
Control	0.48	3.23
N	-0.40	0.65
N+P	0.44	1.69
P	1.38	1.63

For nitrogen, nitrate from the surface water was taken up by the sediments in the control and nitrogen only treatments. Please note that the flux rates for the nitrogen species are in mg compared to µg for phosphorus. With the addition of SRP in the N+P and P treatments, nitrate was released from the sediments into the overlying water. In contrast, ammonium was released across all treatments and the control. The control cores had the highest flux of ammonium.

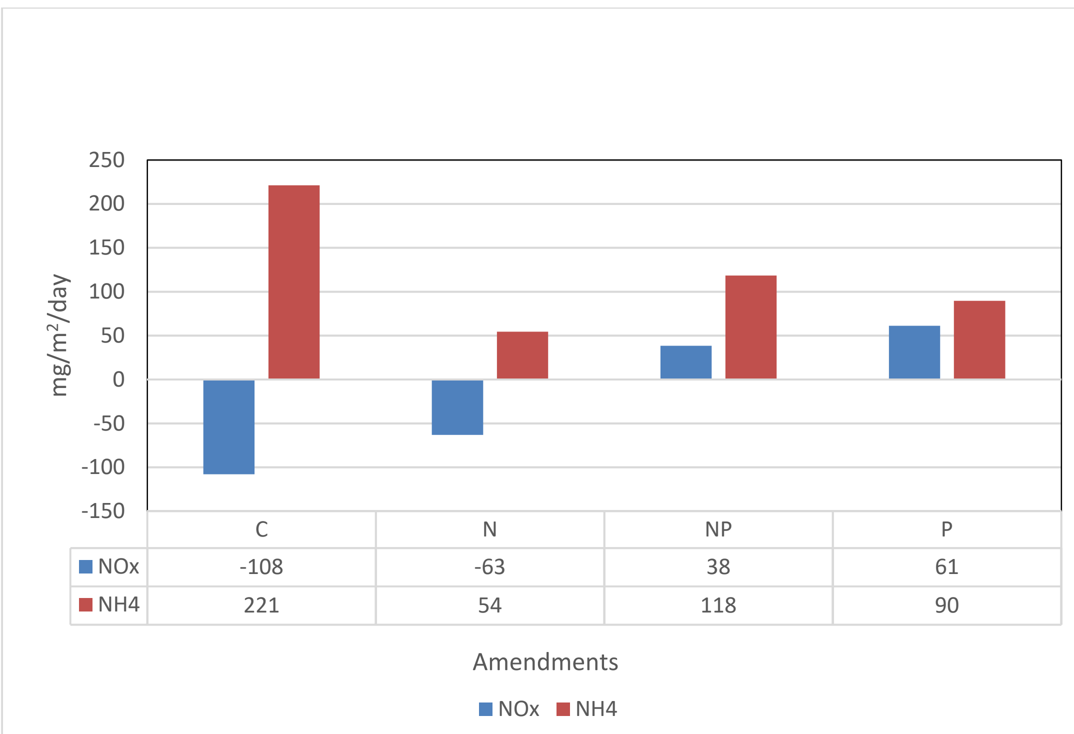


Fig. 45. Daily flux of nitrate and ammonium from sediment cores over 72 hrs.

Summary and future plans: Sediment cores showed an uptake of NO_x from the sediments and a positive efflux of SRP, TP, and NH_4 regardless of the external nutrient amendments. The phosphorous treatment group (P) showed the highest efflux of SRP among all treatment groups and time intervals while the control group (C) showed the highest efflux of TP. The control group also showed the highest efflux of NH_4 from sediments and uptake of NO_x into sediments relative to other treatment groups.

These results suggest that increased external phosphorous loading may stimulate the additional release of SRP from sediments while increased NO_x loads show decreased rates of NO_x uptake and NH_4 efflux when compared to ambient sediment interface interactions. This could indicate that the rate of NO_x uptake and nitrogen cycling by microbial interactions may not have more capacity for this time period and that additional nutrient loads may inhibit the efficiency of this interaction and increase the total nitrogen availability in the system.

The Site D (Burtis Point) sediment cores showed an average organic composition of 1.1% determined via ash free dry weight. Observed elevated efflux of NH_4 in control groups compared to NO_x treatment groups suggests that the primary driver of N cycling for this system may be via microbial activity in sediments. Further studies should explore temporal variations in denitrification rates and additional nitrogen pathways in response to seasonal nutrient loading and microbial activity in the ambient system.

Thus, future work will focus on more sediment core experiments during different times of the season including late spring, summer and fall. We will also include the measurement of nitrite, an intermediary between nitrate and ammonium, to better understand nitrogen transformations. Finally, as a borderline oligotrophic/mesotrophic lake, Owasco has moderate levels of nutrients including nitrogen and phosphorus species. Since SRP and ammonium are the most bioavailable forms of these nutrients for cyanobacteria growth, it is critical to better understand the efflux of these nutrients from sediments into the water column in nearshore areas.

Mussel & Macrophyte Results: Sorted mussel and macrophyte totals showed differences in attachment frequency and community composition among sampling sites. Zebra mussel attachment rates were higher per gram of macrophyte for all plant species except Southern Naiad and Brittle Naiad (Fig. 46).

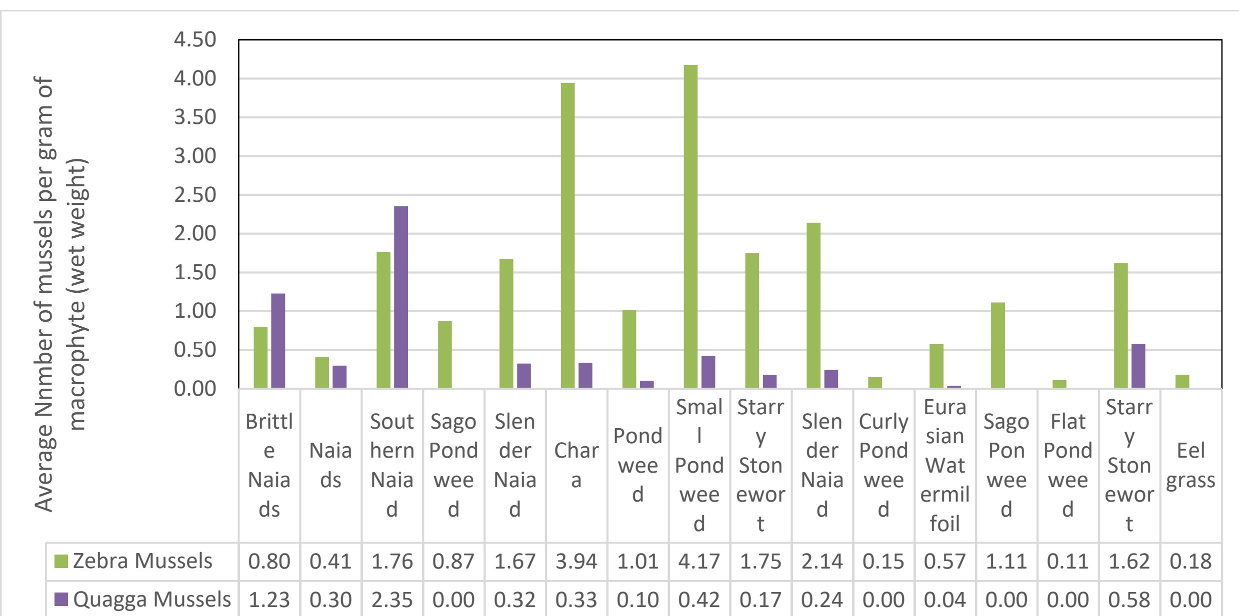


Fig. 46. Mussel attachment frequency for each macrophyte species detected for all sites.

The ratio of zebra to quagga mussel attachment across all species of macrophytes was 3.67:1 with an average amount of zebra attachment of 1.32 mussels per gram of macrophyte compared to 0.36 mussels per gram of macrophyte for quaggas.

Sorting mussels by size class showed that all of the sample sites were dominated by small zebra mussels (Fig. 47). The total mussels collected were comprised of 68% small zebra mussels. In comparison the total number of quagga mussels collected made up only 16% of mussel totals.

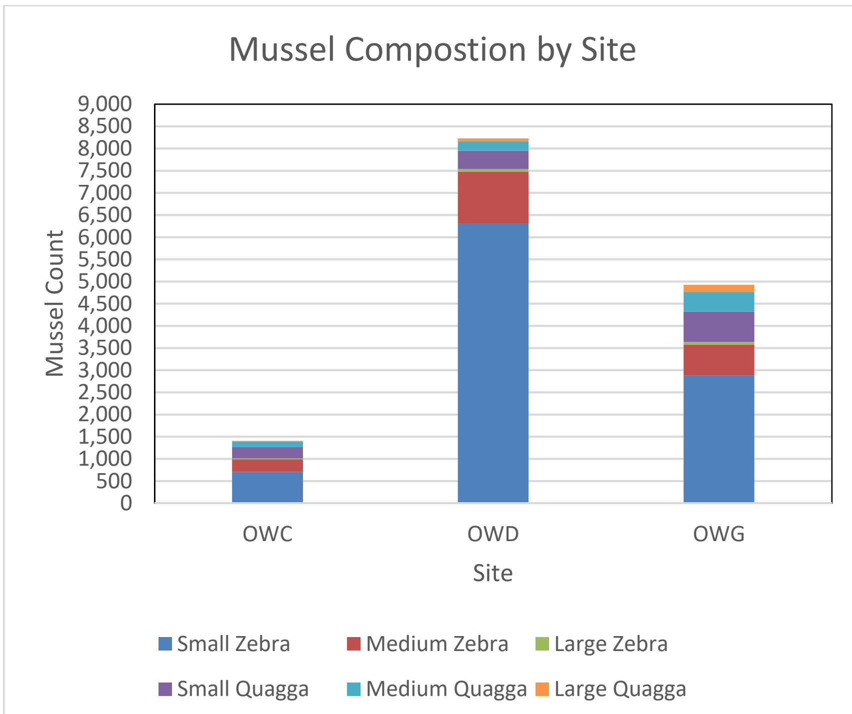


Fig. 47. Counts of mussels sampled at sites C, D and G by species and size.

Mussel totals were positively correlated with macrophyte wet weights for all sample sites meaning that if more plant biomass was found at a site, more mussels were present (Fig. 48). Similar to the mussels, site D had the most macrophyte biomass.

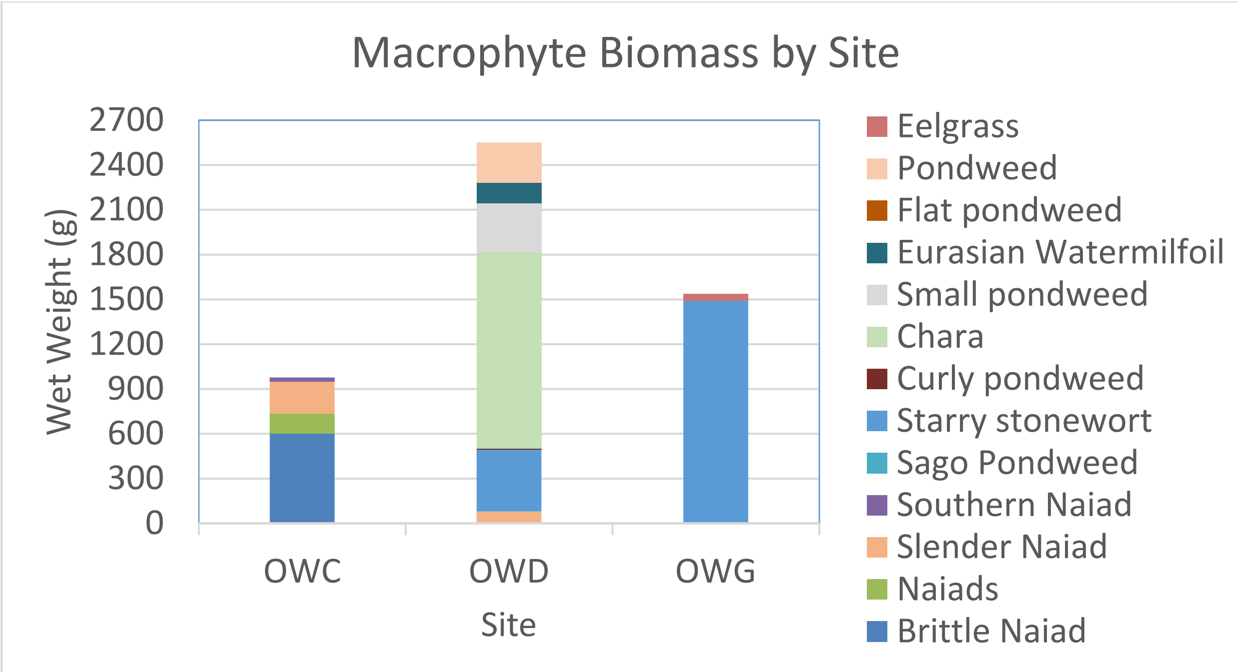
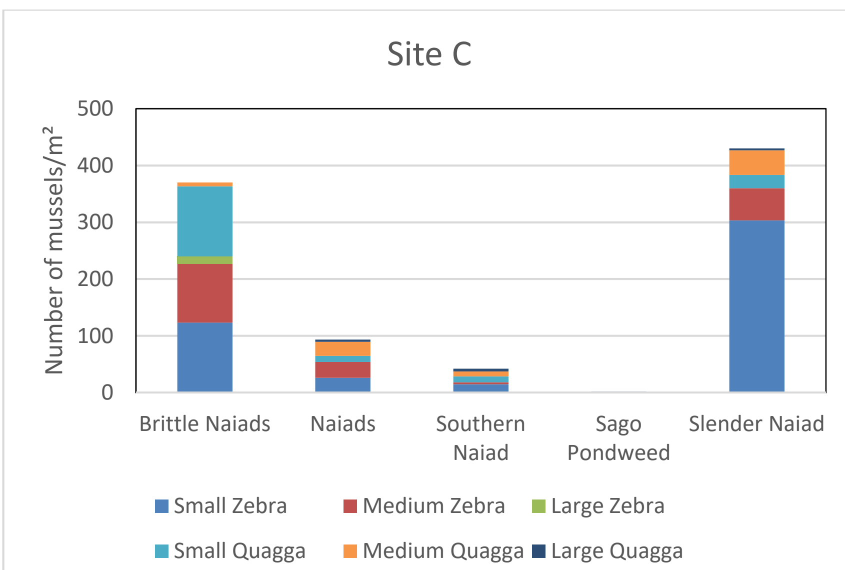
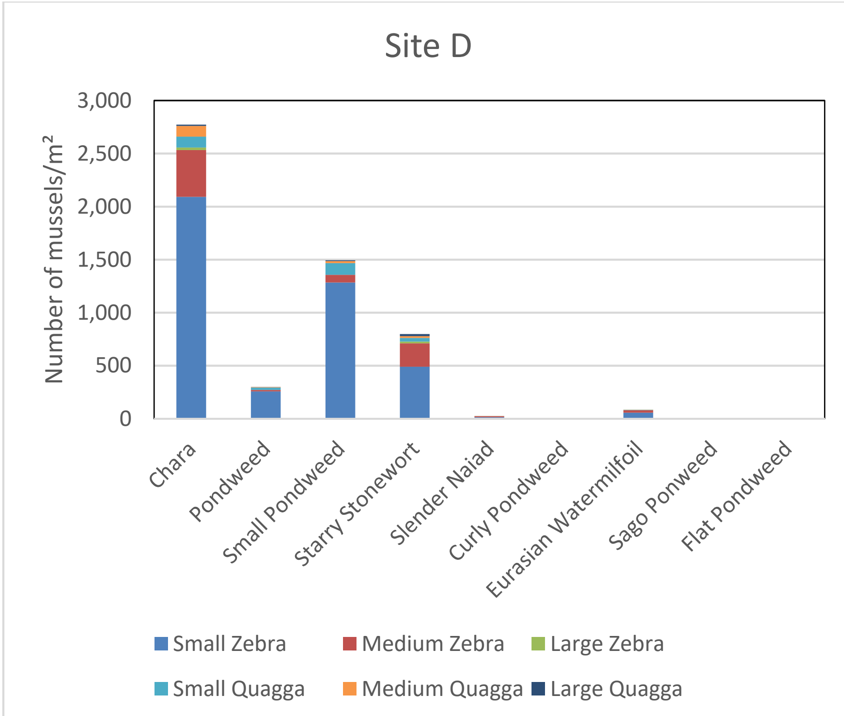


Fig. 48. Macrophyte biomass for all sites (**Ow**asco **C, D & G**) by species.

On an areal basis, site C (western shore) had the lowest number of both zebra and quagga mussels, with an average of 194 zebra mussels/m² and 103 quagga mussels/m². Site D (Burtis Point) had the highest total number of zebra and quagga mussels with 1,479 zebras/m² and 296 quagga/ m². Site G (Yacht Club) had 411 zebras/m² and 147 quagga/m² (Fig. 49).





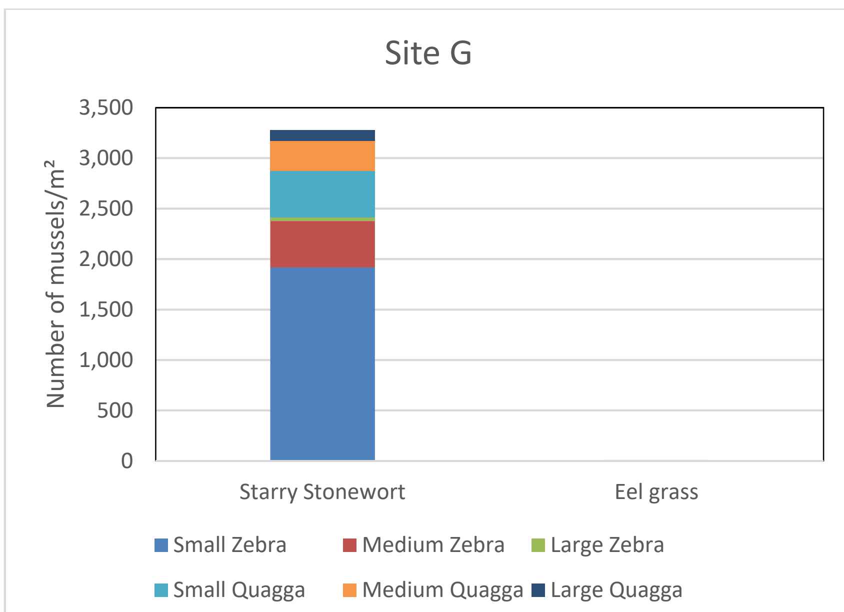


Fig. 49. Comparison of mussel types and sizes for different macrophyte across sampling sites.

Site D (Burtis Point) was dominated by Chara, and had both the most macrophytes and mussels sampled across all sites. Sites C (western shore) and G (Yacht Club) showed similar macrophyte biomass while site G had significantly more mussels present. Site C was characterized by several native Naiad species while site G was dominated by invasive Starry Stonewort (Fig. 49).

Across the sites, Chara had the highest number of mussels attached of all macrophyte species and Starry Stonewort showed the fourth highest mussel attachment rate. This suggests that sites dominated by single species like Starry Stonewort may serve as superior substrate for mussel attachment compared with native species. As the presence of Starry Stonewort increases and species richness decreases, the total mussel attachment may also increase due to the increased substrate provided by the Starry Stonewort habit. Site G, adjacent to Owasco Yacht Club, demonstrates this relationship as two total species were detected at this site across all three quadrats collected with the dominant species present in each quadrat being Starry Stonewort. In comparison, both sites C and D showed more macrophyte species variability among quadrat replicates (Fig. 49).

Decreased species richness through the spread of invasive macrophyte species could further increase zebra and quagga mussel densities. Future work should continue to monitor changes in macrophyte and mussel communities in response to the spread of invasive species like Starry Stonewort. These community changes could alter nutrient cycling and availability in the water column throughout the season which has been linked to harmful algal blooms.