UNC Jordan Lake Nutrient Management Study - Progress Report

Nutrient and light limitation of phytoplankton growth in Jordan Lake

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THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Overview

The UNC-Chapel Hill Collaboratory (https://collaboratory.unc.edu) ia undertaking a comprehensive study to understand underlying processes and propose management options to control the sources, transport and fate of nutrients and sediment from the watersheds contributing to water quality problems, including potentially toxic cyanobacterial blooms, in the Jordan Lake, NC drinking water reservoir (https://www.google.com/maps/place/Jordan+Lake/). Improvement of water quality in these vital freshwater sources for the North Carolina Triangle region is a critical need to assure continued economic growth and environmental health. This mandate requires a comprehensive understanding of the links between watershed economic and ecological conditions, the biological, chemical and physical functioning, and nutrient sensitivity of the two lakes. A process-based understanding of the linked watershed-lake system is required to efficiently develop and test innovative management practices, based on sound scientific theory and evidence, that will ensure long-term sustainability of these reservoirs for their basic

purposes; supplying safe drinking water, supporting recreational recreation activities and flood control.

Background and Objectives

Jordan Lake receives water input from the Haw River, Upper New Hope and Lower New Hope watersheds. Associated with these water inputs are nutrients, sediments and, in some cases, significant debris. The Haw River watershed is mixed agricultural, rural and urban while the Upper and Lower New Hope watersheds are principally urban. The primary outflow from the lake occurs over the Jordan Lake Dam and comprises the starting point of the Cape Fear River. The Haw River drains the Haw River watershed and discharges into the southern, Haw River arm of Jordan Lake approximately 5 miles upstream of the Jordan Lake Dam. The Haw River provides 70 – 90 percent of the annual flow into the lake. The Upper and Lower New Hope watersheds drain into the New Hope Creek arm of Jordan Lake which extends approximately 17 miles upstream from the Dam. The Haw River arm and the New Hope Creek arm are naturally separated by a narrow channel referred to as the "s-bends" or "narrows". The New Hope Creek arm is further subdivided by two causeways with relatively narrow bridge openings, one where NC Highway 64 crosses the lake and the other where Farrington Road crosses the lake.

Jordan Lake has been a highly productive reservoir since its creation, and the upper New Hope arm of the lake above the Highway 64 causeway consistently violates NC standards for chlorophyll a (>40 $\mu g\ L^{-1}$). High phytoplankton biomass levels threaten the quality of lake water for use by the city of Cary, and may also negatively impact aquatic life (e.g. due to hypoxia, poor water clarity etc.).

As part of the UNC Nutrient Management Study, we initiated a multi-part observational and experimental program in January, 2017 to help clarify the impacts of watershed input on key processes controlling water quality in Jordan Lake and to help inform management actions designed to improve water quality in the lake. This observational and experimental program was continued during project year 2 (July 2017 to June 2018) with three specific objectives

1.) **to identify water circulation and exchanges in the lake, in particular, the extent to which the large volume of nutrient and sediment laden Haw River water affects water quality of the New Hope Creek arm of the lake;**

2.) **to better quantify the response of important water quality parameters in the lake to a range of forcing conditions (variations in flow, seasonal variations of temperature and light, etc) via high frequency (e.g., hourly) in situ observations to complement the less frequent (e.g., monthly) sampling done by the NC Division of Environmental Quality; and**

3.) **to better quantify phytoplankton dynamics, including effects of nutrient and light limitation on the production of high phytoplankton biomass levels that are causing the lake to be out of compliance with state water quality standards.**

The Paerl laboratory focused on objective number three and utilized a series of bioassay experiments and laboratory analysis on Jordan Lake water to:

- **determine the limiting nutrient/s (N, P, or N and P) for phytoplankton growth**
- **determine the potential effectiveness of nutrient reduction (dilution) for reducing algal biomass / chlorophyll a in the lake**
- **provide laboratory validation of observations from in situ instrumentation and determine additional parameters such as depth profiles of nutrient concentrations in the lake**
  quantify phytoplankton productivity and the impact of light limitation on phytoplankton growth

Methods

A total of four nutrient addition/ nutrient dilution bioassay experiments have been conducted during project years 1 and 2. The first three experiments were conducted on water collected near NCDEQ station CPF086F on the upper New Hope R. arm in April, July, and October 2017. The fourth experiment was conducted on water from station CPF055C on the Haw R. arm of the lake in May 2018.

Water for the bioassays was collected using a diaphragm pump into ten - 20L polyethylene carboys. The carboys were quickly transferred to a darkened truck bed and transported to UNC-IMS. Upon arrival (approximately 14:30) the carboys were placed in the outdoor incubation ponds to maintain ambient temperature and light conditions. The following morning water from the carboys was homogenized in a 300L fiberglass tub prior to dispersing into 4L Cubitainers and performing experimental nutrient addition and dilution treatments.

Nutrient additions consisted of a full factorial design of N and P additions, including a control with no nutrients added, an N treatment (0.63 mg L^{-1} $N\text{-}NO_3^-$ plus 0.07 mg L^{-1} $N\text{-}NH_4^+$), a P treatment (0.155 mg L^{-1} $P\text{-}PO_4^{-3}$) and a N plus P treatment (0.63 mg L^{-1} $N\text{-}NO_3^-$ plus 0.07 mg L^{-1} $N\text{-}NH_4^+$ plus 0.155 mg L^{-1} $P\text{-}PO_4^{-3}$). Addition treatments were made to whole lake water as well as to lake water diluted by 10, 30, and 50 percent with a major ion solution that contained all the major salts of Jordan Lake water less N and P.

Phytoplankton growth in the nutrient addition and dilution bioassays was tracked by measurements of chlorophyll a and accessory photopigments on day 0, day 1, day 3, and day 6 of the experiment. Analyses for chlorophyll *a* (Chl *a*), representing total phytoplankton biomass,

are completed while accessory photopigment data are still being analyzed. Phytoplankton growth rates (μ in units d^{-1}) at each time point during the experiment were calculated as:

$$\mu = ln(C_t/C_0)/t$$

where *ln* is the natural logarithm, t is the length of time elapsed since the beginning of the experiment, C_t is the *Chl a* concentration at time t, and C_0 is the initial Chl *a* concentration. Using growth rates rather than biomass allows determination of the phytoplankton growth response that is not impacted by the reduction of biomass in the dilution treatments. Growth expressed in this manner is also consistent with the phytoplankton growth rates in many eutrophication models and therefore will facilitate incorporation of experimental results into such models. At each time point in the experiment, the effects of treatments on phytoplankton growth rates were analyzed using a three way ANOVA with dilution treated as a continuous variable and the addition or omission of N or P treated as categorical variables.

Water collected for each bioassay as well as water collected during a trip to maintain the AVPs on 8 September 2017 was used to measure the relationship between light availability and phytoplankton photosynthesis. Immediately upon delivery of lake water to UNC-IMS (~ 4.5 hours after collection), aliquots of water were dispensed into 20 mL borosilicate glass incubation vials. Photosynthesis was measured by $^{14}CO_2$ incorporation at 42 different light levels that span the range of light levels known to limit phytoplankton photosynthesis. The light gradient was produced by a photosynthetron which consists of a white light source, and a range of light reducing filters, and an aluminum heat sink that surrounds each vial to control temperature (Figure 7). Light delivery to water samples within each vial was measured using a Biospherical Instruments Model QSL-100 irradiance meter with a QSL-101 4 π sensor. Water was circulated through the heat sink to a temperature controlled water bath to maintain the water temperature present at the time of collection (17-30 °C). Samples were incubated in the photosynthetron for 1 hour and photosynthesis was determined by the amount of $^{14}CO_2$ incorporated according to standard methods. Photosynthesis was normalized by Chl *a* to express observed productivity in units of carbon produced per unit of phytoplankton biomass. Photosynthesis and light measurements were fit to a hyperbolic tangeant model developed by Jassby and Platt (1976)

Figure 1. Photosynthetron set up for measuring the light vs. photosynthesis relationship. Note light increases from left to right within rows and also varies within columns.

$$P^b = P^b_{max} \tanh(\alpha I / P^b_{max})$$

where P^b is the biomass normalized photosynthetic rate, P^b_{max} is the light-saturated photosynthetic rate, α is the initial light limited slope, and I is irradiance. This is a common formulation for expressing light dependence of photosynthesis and the resultant parameters P^b_{max} and □ will be necessary for accurately characterizing the light dependence of photosynthesis within the coupled circulation/ water quality model that will be produced by James Bowen and Daniel Obenour's labs during project year 3.

Depth profiles of important water quality parameters were collected at the time and location of the bioassay water samples and during servicing of the *in situ* moorings. In each case, temperature, conductivity, pH, dissolved oxygen, in vivo fluorescence, and PAR were measured at 0.5 m depth intervals. Discrete water samples were also collected at 1 m depth intervals during the bioassay sampling and at surface, mid-depth and near bottom during the servicing trips. Upon return to IMS, these were analyzed in the laboratory for dissolved nutrients and chlorophyll *a*.

Results

Nutrient limitation: The initial growth rate response from the first to the second day of the experiments is likely most representative of the in situ nutrient limitation status of the phytoplankton community in Jordan Lake. The initial growth response of all nutrient addition bioassays clearly indicated that N was the primary nutrient limiting phytoplankton growth during the spring through fall in Jordan Lake. In the absence of N addition, growth was negative during all three experiments conducted in 2017. Addition of nitrogen prevented biomass loss but did not

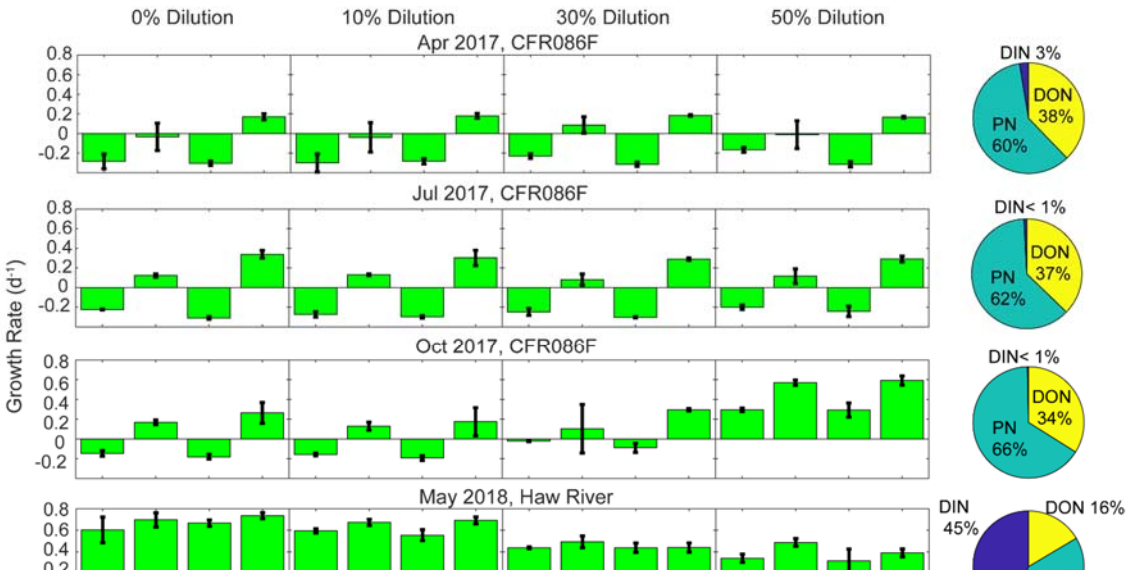

Figure 2. Phytoplankton growth responses to nutrient addition and dilution treatments in four bioassays. C = control. N = N addition, P = P addition, N + P = both N and P addition. Bars and error bars are means and standard deviations of triplicate values.

allow biomass to increase without also adding P. In treatments with only P additions, biomass declined at a similar rate to the controls that received no nutrient additions.

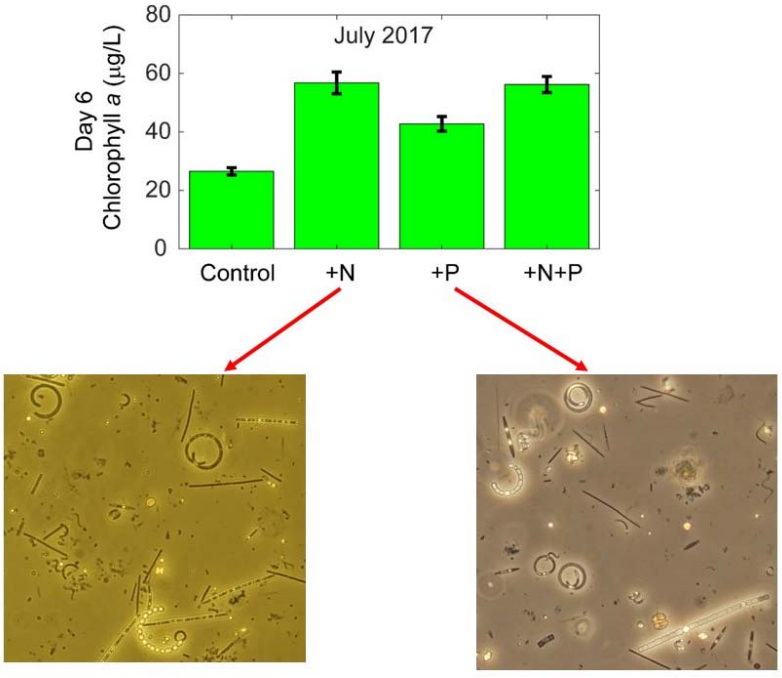

Figure 3. Results from the July 2017 nutrient addition experiment after 6 days of incubation. Note the stimulation of chlorophyll a in the P only addition. Photomicrographs below show the high density of heterocystous cyanobacteria in the P only treatment.

Although N was the primary nutrient limiting in situ growth, after a period of six days, P additions did increase the phytoplankton growth rate in the July 2017 experiment (Figure X). Stimulation by P alone can occur when P additions stimulate the growth of cyanobacteria that are capable of using atmospheric nitrogen via the process of N_2-fixation. Although N_2-fixation was not measured during the July 2017 experiment, microscopic examination of samples from the experiment did indicate that P addition had stimulated N-fixing, cyanobacteria with obvious heterocysts (specialized non-photosynthetic cells for N_2-fixation). Experiments conducted in project year 3 will include measurements of N_2 fixation (acetylene reduction) to determine the potential for N_2-fixation to alleviate potential N_2 limitation due to reducing external N loads.

The lack of a significant response to nutrient dilution during the 2017 experiments was likely because at the time and location in the lake during those experiments the vast majority of nutrients were contained within the phytoplankton or as recalcitrant dissolved organic forms rather than in bioavailable dissolved forms within the water. Nutrient concentrations measured at the beginning of the 2017 experiments confirmed that dissolved inorganic nitrogen (DIN) levels were low (~0.1 mg/L) and phosphate concentrations were below the limits of detection. Greater than 97-99 % of nitrogen was either in the particulate pool, likely as phytoplankton, or in the dissolved organic N pool with only 1-3% of nitrogen as bioavailable dissolved inorganic nitrogen. Such low nutrient but high phytoplankton biomass conditions are typical of long residence time water bodies with high nutrient loads such as the upper New Hope River arm of Jordan Lake. The primary source of nutrients sustaining phytoplankton growth was likely

remineralization which can at best maintain constant biomass levels over time, and cannot by definition result in increased biomass. Despite very low initial phosphate concentrations, it appeared that the supply of recycled N exerted a primary control on phytoplankton growth. This is not uncommon due to the capacity of phytoplankton to strongly modulate their internal stores of P in response to decreases in availability, and due to the relatively faster rates of cycling of P compared to N. The lack of a positive growth response to N additions alone indicates that the phytoplankton growth requirements for N and P were very close to being balanced (i.e., N and P co-limitation). By adding N, the phytoplankton were forced to P limitation. This is consistent with the strong positive growth achieved in the N plus P treatments, and is common for the growth phytoplankton communities fueled by internal nutrient cycling.

In contrast, during the May 2018 experiment nearly half of the N was in the form of bioavailable, dissolved inorganic N. These nutrient conditions are also typical of the rapidly flushed Haw River arm, particularly after a strong river pulse as occurred in May 2018. Growth rates were strongly positive regardless of whether or not nutrients were added, and it was the only experiment where growth was negatively impacted by diluting the ambient nutrient pool. Diluting the ambient nutrients by 50% resulted in an approximate 40% decrease in growth within the control treatments where no nutrients were added. Nutrient limitation imposed by the 50 % dilution was partially alleviated by N addition which indicates again that N was the primary growth limiting nutrient.

Overall, the three 2017 experiments and the spring 2018 bioassay experiment indicated that N was the primary limiting nutrient with secondary co-limitation by P, a condition observed in numerous eutrophic freshwater lakes and reservoirs (Elser et al. 2007; Paerl et al., 2016). Both N and P should be considered when developing nutrient reduction strategies to reduce phytoplankton biomass of Jordan Lake. The May 2018 nutrient dilution experiment indicated that reductions in the range 30-50% will likely be required to control phytoplankton growth.

Light limitation: Photosynthesis vs irradiance measurements produced remarkably consistent results. For all of the measurements except for 30-Apr-2018, the maximum, light saturated photosynthetic rate (P^b_{max} varied by less than 20% from ~4.3 to ~5 g C/ g chl a/h. The lower Pbmax of ~1.5 g C/ g chl a/h was possibly caused by low water temperature (~17 C) compared to 22-30 C for the other measurements. The slope of the light limited portion of the curve (a) varied from 0.05 to 0.11 and average 0.088. All of these P^b_{max} and a values are within the expected range for freshwater phytoplankton communities.

Photosynthesis increased rapidly as PAR increased up to about 50 µmol photons/ m^2/s and began to saturate at higher values, Figure 19. The value of P^b_{max} divided by α, known as I_k , provides the irradiance at which photosynthesis is nearly saturated. In this case I_k ranged from 20 to 82 and average 47 which are all relatively low values for phytoplankton assemblages. The Jordan Lake Nutrient Response Model developed by TetraTech (https://ncdenr.s3.amazonaws.com/s3fs-

public/Water%20Quality/Planning/TMDL/FINAL%20TMDLS/Cape%20Fear/Jordan%20Related/JordanLakeNRMFinal.pdf) is based on the Water Quality Analysis and Simulation Program (WASP) and assumes an I_k near 500 µmol photons/ m^2/s. Therefore, the current water quality model has strongly overestimated the degree of light limitation experienced by phytoplankton in Jordan Lake.

The close agreement between productivity vs. light response measurements across the five time points and at two different locations indicates that the derived model parameters (P^b_{max} and □) can be used with confidence in the water quality modeling efforts (Bowen and Obenour's groups). Using parameter values that are specific to the phytoplankton community of Jordan Lake will provide a much more accurate representation of light limitation of phytoplankton growth than the literature values used in the current water quality model. Our work in project year 3 will extend the temperature range of measurements to determine the extent to which temperature affects the photosynthetic response to light, particularly the light saturated photosynthetic rate.

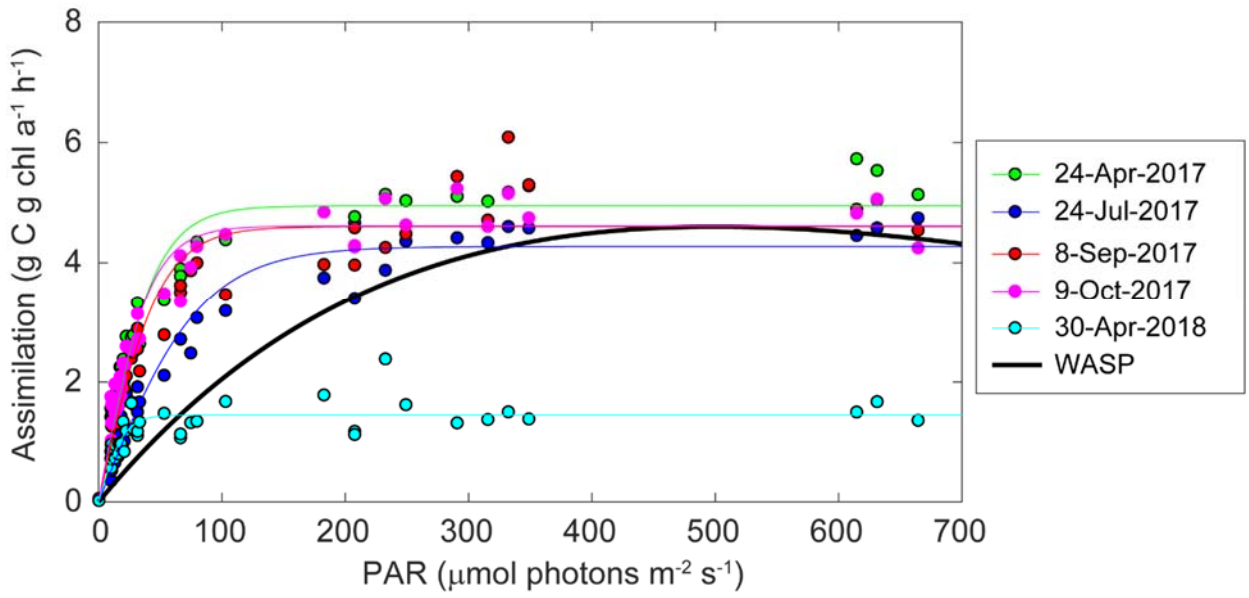

Figure 4. Productivity versus irradiance measured by a photosynthetron from Jordan Lake water collected at NC DEQ station CPF086F except for the collection on 30-Apr-2018 at station CPF055C on the Haw River arm. The bold black curve represents the assumed relationship within the current WASP based water quality model for Jordan Lake.

Important management implications of our work during project year 2 include:

- nutrient addition bioassays indicate that phytoplankton in the upper New Hope Creek arm of the lake and the Haw arm are primarily N limited from spring through fall. Additionaly stimulation by P was common, and during summer stimulation by P alone is possible due to stimulation of N-fixing cyanobacterialikely co-limited by N and P. This suggests that efforts to reduce phytoplankton biomass will need to address both N and P input reductions. The degree to which N-fixation may alleviate N-limitation due to N load reductions is a focus for project year 3.

- the Jordan Lake Nutrient Response Model assumed that light limitation is a significantly greater impediment to phytoplankton growth than was measured on five occasions from spring through fall and in both the New Hope and Haw River arms of Jordan Lake. Jordan Lake phytoplankton are much better adapted to growing in low light than represented by the current Jordan Lake Nutrient Response Model. The robust parameterization of the light versus photosynthesis relationship will greatly improve water quality modeling efforts during project year 3 and enable more robust predictions of questions such as how fast can phytoplankton respond to pulses of nutrients from the tributaries given that such pulses are also associated with high loads of suspended particulates and color. Measurements of the photosynthesis versus irradiance relationship during winter and early spring will be a focus during project year 3.

References cited

Elser, J. J., M. E. S. Bracken, E. E. Cleland, D. S. Gruner, W. S. Harpole, H. Hillebrand, J. T. Bgai, E. W. Seabloom, J. B. Shurin, and J. E. Smith. 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecol Lett 10**:** 1124-1134.

Paerl, H. W., J.T. Scott, M.J. McCarthy, S.E. Newell, W.S. Gardner, K.E. Havens, D.K. Hoffman, S.W. Wilhelm and W.A. Wurtsbaugh. 2016. It takes two to tango: When and where dual nutrient (N & P) reductions are needed to protect lakes and downstream ecosystems. Environmental Science & Technology 50: 10805−10813.