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INTRODUCTION

Promoting increased sport fish production, both in number and size, is a key aspect of fisheries management. Regulating the number and size of fish harvested can help promote larger fish; however if the food base is lacking, gains in sport fish production may be slow, even with stiff harvest regulations. There are two main ways to promote the food base in lakes. First, sport fish diets can be supplemented by adding feeder fish to the lake. While this is a quick way to add forage to the lake being managed, adding feeder fish can cause strain on the lower levels of the food web, potentially leading to a collapse of the food web (O'connor and Donohue 2013). For this reason, the second option is to build up the basal resources within the food web through lake fertilization.

Lake fertilization works by adding nitrogen (N) and or phosphorus (P) to the lake, which in turn promotes increased algal production. The increased algal biomass is able to support more secondary production throughout the food web (Yper 2000; Ware and Thomson 2005). However, how you fertilize a lake is important. Algal growth is often constrained by the most limiting nutrient (Dzialowski et al. 2005). Algal growth in lakes can either be limited by P (Schindler 1977) or by N (Scott et al. 2008; Scott and Grantz 2013) independently or even co-limited by both (Müller and Mitrovic 2015); additionally, what lakes are limited by can change seasonally (Maberly et al. 2002). For these reasons, monitoring water quality and conducting experiments to determine whether N, P, or N and P are limiting algal growth prior to lake fertilization can be useful in managing a lake.

The United States Forest Service (USFS) currently manages over 241,000 km of streams and 1,012,00 ha of lakes across the national forests and grasslands (Witt 2017). The goal of this study was to understand which nutrients are limiting algal growth in three Arkansas lakes managed by the USFS. The specific objectives were to first, monitor nutrients, algal biomass, and water clarity in lakes Cove, Spring, and Wedington. Second, evaluate whether algal growth in each of the lakes was limited by N, P, or both N and P. This research was conducted to help USFS better manage lake fertilization to maximize algal growth and improve the fisheries within these lakes.

STUDY SITE DESCRIPTION

The lakes, Cove Lake, Spring Lake, and Lake Wedington, all managed by the USFS for fisheries, were selected for routine monitoring during the growing season (March 1 – October 31) from 2014 through 2017. During summer 2017, studies to evaluate the nutrient limitation of phytoplankton were conducted on all three lakes prior to and following lake fertilization.

Cove Lake is the deepest and largest of the three lakes with a maximum depth of 13 m, an average depth of 5 m (estimated from bathymetry data provided by M. Anderson 12/7/2017) and surface area of 65 ha and a watershed of approximately 2600 ha. The watershed for Cove Lake is mostly forested at 89%, with agriculture and urban land use making up a smaller portion of 5% and 4%, respectively. Cove Lake is in the larger Dardanelle Reservoir Watershed within the Arkansas River Valley Ecoregion. The USFS fertilized Cove Lake on June 19th, July 9th and 29th in 2014, June 22nd and September 8th in 2015, and July 27th of 2017 with an application rate of 9.4 L ha^{-1} of 34-0-0 (N:P:K) fertilizer and 2.0 L ha^{-1} of a 10-34-0 fertilizer. Cove Lake was also fertilized in 2016, but the dates could not be found.

Spring Lake is also in the Arkansas River Valley Ecoregion, and it is within the Petit Jean Watershed. Spring Lake is 11 m at its deepest, with an average depth of 4 m (estimated from bathymetry data provided by M. Anderson 12/7/2017), and has the smallest surface area of the three lakes of just 33 ha, but has the largest watershed of 4400 ha. The watershed is 93% forested, with only 4% agriculture and 3% urban. The USFS fertilized Spring Lake on June 19th, July 9th and 29th in 2014, June 22nd and September 8th in 2015, and July 27th of 2017 with an application rate of 9.4 L ha^{-1} of 34-0-0 (N:P:K) fertilizer and 2.0 L ha^{-1} of a 10-34-0 fertilizer. Spring Lake was also fertilized in 2016, but the dates could not be found.

Lake Wedington is found within the Ozark Highlands Ecoregion, within the Illinois River Watershed. Lake Wedington is only 6 m at its deepest and has an average depth of 3 m (personal communication, M. Lark 12/7/2017). It has the second largest surface area (41 ha) and smallest watershed (1000 ha) of the three lakes. Like the other two lakes, Lake Wedington is in a primarily forested watershed (73%); however, agriculture and urban land use take up a greater percentage of the total watershed area than for the other two lakes at 20% and 5%, respectively. Lake Wedington was fertilized by the USFS in late July of 2014, on August 1st 2015, July 19th 2016, and July 6th 2017 with an application rate of 9.4 L ha^{-1} 10-34-0 (N:P:K) fertilizer.

METHODS

Routine Monitoring

Each lake was sampled approximately two times per month during the growing season in 2014 through 2016; sampling was reduced to monthly during 2017. Sample and data collection occurred at a single site near the dam of each lake. During each sampling event a YSI 600 XLM multi-parameter data-sonde was used to collect in-situ measurements of water temperature, specific conductance, dissolved oxygen (DO), and pH. A Secchi disc was used to measure water transparency, and a LiCor Quantum sensor was used to estimate photic depth, by lowering the sensor through the water column until the measured irradiance was 1% of the surface irradiance.

The photic depth was divided into 4 equal proportions; each proportion was sampled with an alpha sampler and then composited into a single sample, providing an average photic zone sample. In addition to the photic zone sample, a water sample was collected from ~1 m above the lake bottom representing a hypolimnion sample. Water samples were stored in dark bottles on ice until returning to the lab.

Once returned to the Arkansas Water Resources Center's Water Quality Lab, water samples were split, filtered, and acidified as needed for each specific analysis. Photic zone samples were analyzed for total nitrogen (TN) and total phosphorus (TP), nitrate plus nitrite as nitrogen (hear after NO3-N), soluble reactive phosphorus (SRP), and chlorophyll a (CHL-a) following standard methods (Table 1). Water samples from the hypolimnion were analyzed for all parameters except for CHL-a.

Data were compiled for each the lakes into a single database "DR-WQ-MSCxxx". Nutrient concentrations, phytoplankton biomass as CHL-a and Secchi transparency were graphically examined for temporal variability. Additionally, Pearson correlations of log transformed data were used to evaluate the log-log linear relationships of phytoplankton biomass with nutrients and secchi depth.

Nutrient Limitation Experiments

Nutrient limitation experiments were conducted on three occasions for each lake, once in May and June prior to lake fertilization by USFS, and once within two days of the first lake fertilization for each of the lakes. For each event a minimum of 20 1-L cubitainers were randomly filled from the lake surface at the deepest point of each lake, and then returned to the greenhouse for experimental setup.

Cubitainers were evenly divided into 4 groups: the control, nitrogen (+N), phosphorus (+P), and nitrogen and phosphorus (+N+P). Phosphorus treatments (+P and +N+P) were amended with KH_2PO_4 to a final concentration of 0.5 mg P L^{-1}, while N treatments (+N and +N+P) were amended with $NaNO_3$ to a final concentration of 5 mg N L^{-1}. Cubitainers were incubated in water baths in the greenhouse for 4 to 8 days to allow for algal growth. During the incubation period, the cubitainers were vented to allow for the exchange of gasses.

At the end of the 4 to 8 day incubation period cubitainers were moved into the lab for processing. For processing, cubitainers were shaken vigorously to insure contents were thoroughly mixed, and then

Table 1: Laboratory parameters with specific EPA approved analytical procedures.

Parameter	Method	Units	RL	MDL
NO_3-N	EPA 353.2	mg L^{-1}	0.05	0.02
SRP	EPA 365.1	mg L^{-1}	0.01	0.004
TP	APHA 4500PJ	mg L^{-1}	0.02	0.005
TN	APHA 4500PJ	mg L^{-1}	0.05	0.03
Chl *a*	APHA 10200 H1&2C	µg L^{-1}	--	--

a 100 ml sub-sample was filtered through a 25 mm glass fiber filter (Whatman GF/F 1.0 µm pore size). Filters containing algal samples were placed into 15 ml conical centrifuge tubes with 7 ml of 90% acetone and then stored at -20 °C in the dark for at least 24 hr to allow the CHL-a to be extracted from the filters. Samples were analyzed for CHL-a fluorometrically following EPA method 445.0 sans tissue grinding (Arar and Collins 1997).

Chlorophyll a data was log transformed to insure the data was normally distributed prior to cross comparisons of treatments for each experiment. A single factor analysis of variance (ANOVA) was used to compare treatment means and then least square differences (LSD) was used to assess where differences in treatment means were if they existed. From this analysis, limitation of algal growth by either N or P or both N and P (co-limitation) would be suggested by treatment groups being significantly greater than the control ($p<0.05$). If treatment groups were not statistically different or less than the control, then this suggests no-limitation.

Lake Fertilization Calculator

A lake fertilization calculator, previously developed to help determine when and how to fertilize the lakes in Bella Vista, AR, was modified for use in these three lakes (Scott 2016). The calculator uses measured and target Secchi transparencies and the month in the growing season (3-10; March-October), to determine the P-fertilizer application rate needed to achieve the target Secchi transparency. The N-fertilizer application rate is calculated based on achieving an N:P ratio of 10:1 by mass, so the added N should be 10 times greater than the P added. The AWRC report MSC-379 provides a more detailed description on how the calculator was developed and how to use it (Scott 2016; https://arkansas-water-center.uark.edu/publications/msc.php; accessed 9/26/2018). Before the calculator can be used for other lakes, a few components need to be updated to tailor the calculator to a specific lake, including:

- Bathymetry data (i.e., surface area, depth, etc.) needs to be changed to reflect the specific lake.
- Data should be collected to either verify or update the model used to predict photic depth from Secchi transparency.
- Data should be collected to either verify or update the model used to predict CHL-a from Secchi transparency.
- Data should be collected to either verify or update the model used to predict TP from CHL-a.

With these models and variables updated to fit the lake being managed, the calculator should be applicable to the specific lake and maybe across a broad range of small lakes and reservoirs.

RESULTS

General Limnological Trends

Phosphorus

The availability of SRP in the water column (both photic zone and near bottom) was relatively low across the three lakes. Soluble reactive P in the water samples collected across the three lakes ranged from below detection (MDL=0.004 mg L^{-1}) to 0.030 mg L^{-1} during the 2016 and 2017 growing seasons, and 70% of the measured concentrations were less than the MDL (Figure 1). The greatest SRP concentrations were measured early in the growing season and following lake fertilization for each lake both years, where SRP was between 20% and 90% of TP. However, most of the time SRP concentrations were less than 10% of the measured TP in water samples from each lake.

During the 2015 through 2017 growing seasons, TP concentrations in the water samples (both from the photic zone and near the bottom) ranged from 0.01 to 0.14 mg L^{-1} across all three lakes; however, 93% of the samples collected had TP concentrations below 0.065 mg L^{-1} (Figure 2). The TP concentrations in the photic zone increased throughout the growing season each year in these lakes, except in 2016 at Cove and Wedington Lakes. The opposite occurred in these two lakes where TP concentrations peaked early (~0.06 mg L^{-1}) and then decreased in subsequent water samples (~0.02 mg L^{-1}) collected during the growing season.

Nitrogen

During the 2014 through 2017 growing seasons, NO_3-N concentrations ranged from 0.01 to 0.17 mg L^{-1} in both the photic zone and near the bottom across all three lakes; however, 95% of all the water samples had concentrations at or below 0.02 mg L^{-1} (Figure 3). As with SRP, NO_3-N concentrations tended to be greatest early in the growing season and following lake fertilization events and NO_3-N was 10-20% of TN at these times. NO_3-N concentrations generally made up less than 5% of the TN measured in water samples within each of the lakes.

Total nitrogen concentrations ranged from 0.16 to 1.70 mg L^{-1} in water samples collected from the photic zone of the lakes, whereas TN concentrations near the bottom of the lakes ranged from 0.05 to 2.77 mg L^{-1} (Figure 4). The TN concentrations overall were relatively low, and 84% of all samples collected (both in the photic zone and near bottom) had concentrations below 1.00 mg L^{-1}. The greatest concentrations were measured in Lake Wedington in the photic zone (1.7 mg L^{-1}) and bottom waters (2.8 mg L^{-1}). Like TP, TN increased throughout the growing season for all three lakes during the 2015 through 2017.

Secchi Transparency

From 2015 through 2017, secchi transparency

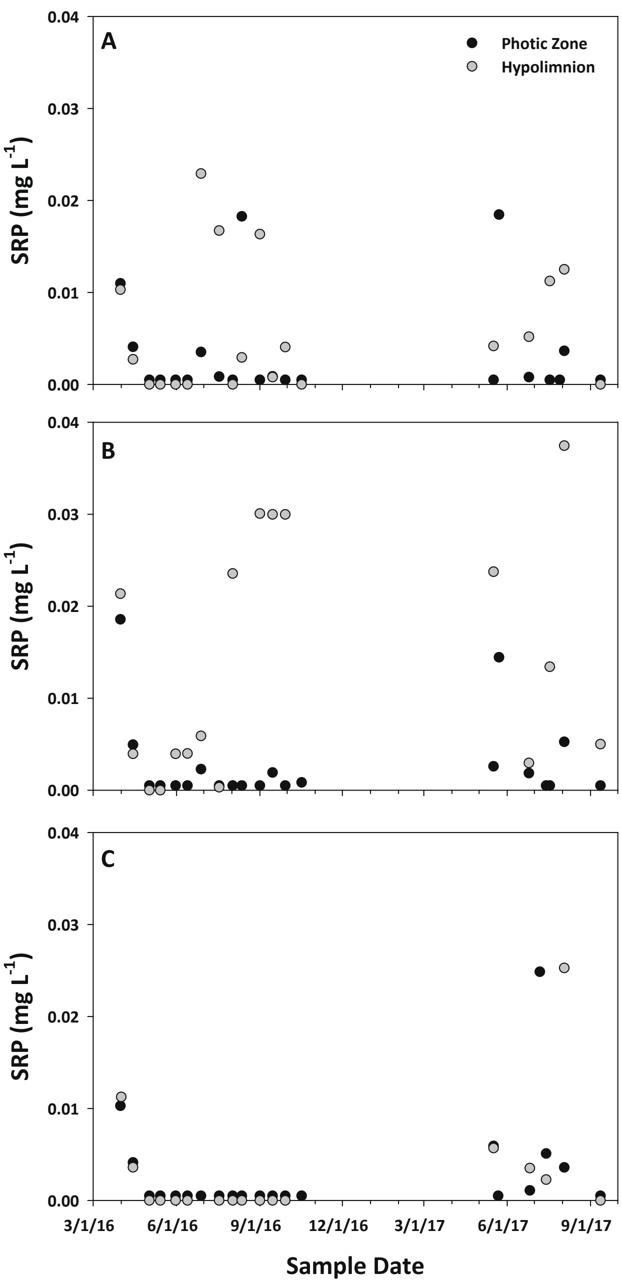

Figure 1. Measured soluble reactive phosphorus (SRP) concentrations for the Forest Service Lakes during the 2016-2017 growing seasons. Black circles represent photic zone samples and gray circles represent hypolimnion samples.

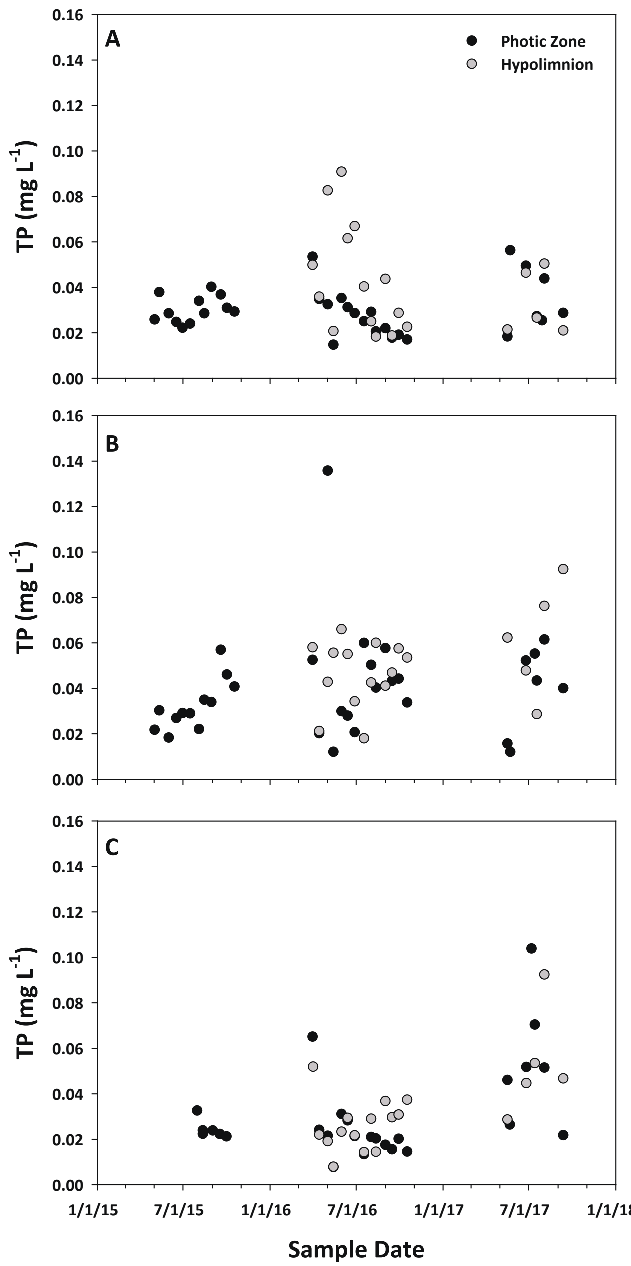

Figure 2. Measured total phosphorus (TP) concentrations for the Forest Service Lakes during the 2015-2017 growing seasons. Black circles represent photic zone samples and gray circles represent hypolimnion samples.

ranged from 0.5 to 4.4 m across all three lakes. In 2015 and 2016, Lake Wedington typically had the greatest water clarity with ~75% of secchi readings greater than 2.0 m, while ~85% of secchi readings in Cove and Spring Lakes during the same time frame were below 2.0 m. Secchi transparency in Lake Wedington was less in 2017 than in previous years, and Secchi depth was not different across all three lakes in 2017 ($F_{16,2}$=1.12, p=0.352).

In Cove Lake, secchi transparency at the beginning of the growing season was typically 1 m or less and increased to 2.0 to 2.5 m by the end of the growing season. Whereas, secchi transparency in Spring and Wedington Lakes was typically greater early in the growing season (Spring: 2 to 3 m; Wedington: 4.5 m) and then fluctuated from 0.5 to 2 m in Spring Lake, and 1.6 to 4 m in Lake Wedington. Although in 2017, Lake Wedington secchi transparency followed

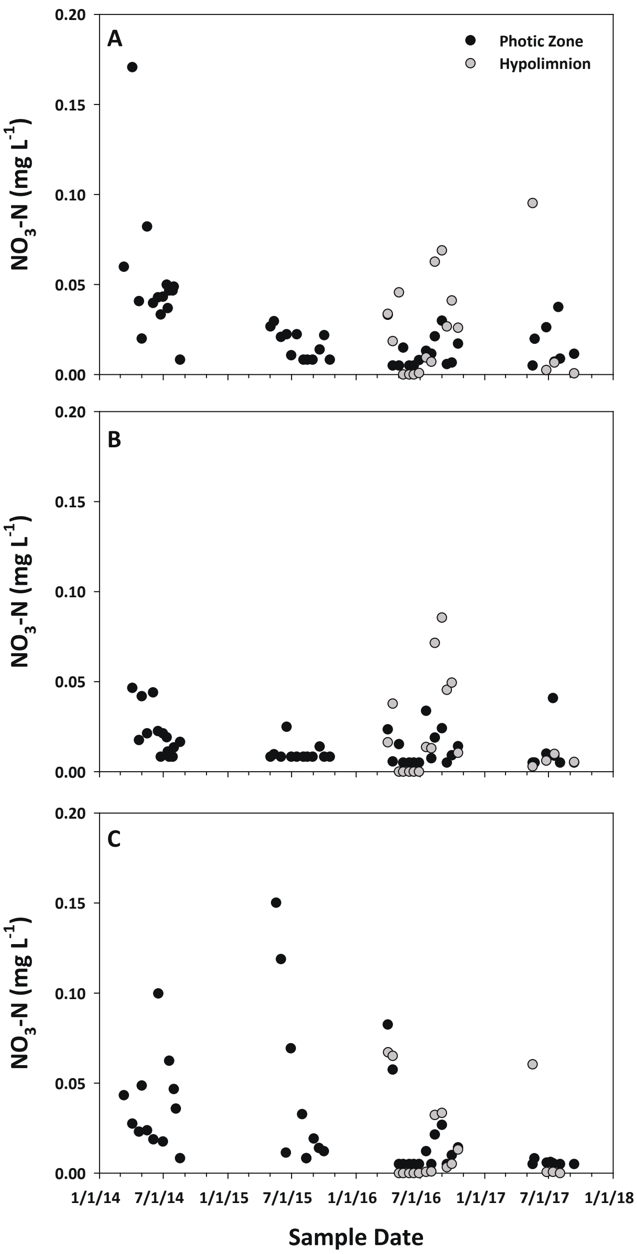

Figure 3. Measured nitrate-N (NO3-N) concentrations for the Forest Service Lakes during the 2014-2017 growing seasons. Black circles represent photic zone samples and gray circles represent hypolimnion samples.

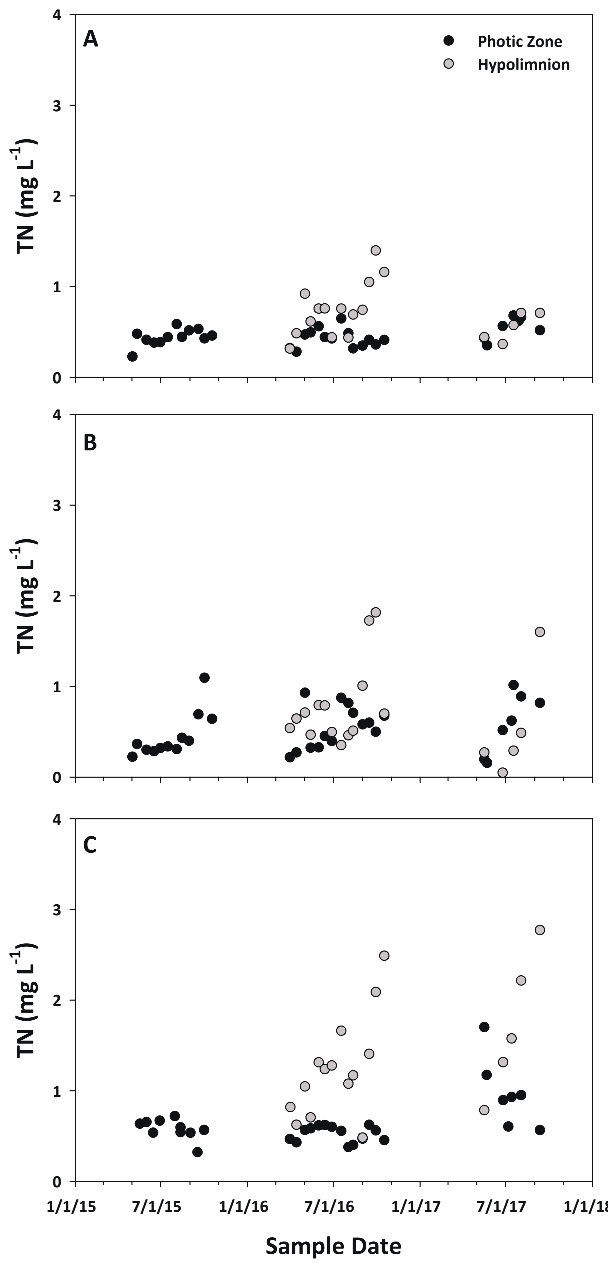

Figure 4. Measured total nitrogen (TN) concentrations for the Forest Service Lakes during the 2015-2017 growing seasons. Black circles represent photic zone samples and gray circles represent hypolimnion samples.

a similar pattern to secchi transparency in Cove Lake, starting at 0.5 m and increasing to 3 m by September (Figure 5).

Phytoplankton Biomass

Chlorophyll-a concentrations ranged from 0.7 to 59.3 µg L^{-1} across all three lakes, but approximately half of the concentrations were below 10 µg L^{-1}. Chlorophyll-a concentrations generally increased throughout the growing season each year in these lakes (Figure 6), although CHL-a concentrations decreased from 25 µg L^{-1} to 2.4 µg L^{-1} by mid-July at Lake Wedington in 2014. Spring Lake typically had the greatest CHL-a concentrations of the three lakes, which often exceeded 40 µg L^{-1} later in the season.

The response of CHL-a concentrations to fertilization was variable across lakes and years. Chlorophyll-a typically increased by ~20 to 100% after fertilization events; in one instance, CHL-a increased by ~1800% (from 3.0 µg L^{-1} to 56 µg L^{-1}) following lake fertilization in Spring Lake in 2017. In contrast, there was no measurable change in CHL-a concentrations following fertilization in Cove Lake in 2017. While CHL-a regularly increased after fertilization, the amount it increased was inconsistent.

Soluble reactive P and CHL-a were also not related ($p>0.05$) in the water samples, because of the low dissolved P supply in all three lakes. Additionally, CHL-a was not related to TP ($p>0.05$) in the water samples, but mean CHL¬-a and TP during the growing seasons were strongly correlated ($R=0.798$, $p=0.010$; Figure 7A) across all three lakes. Positive correlations of CHL-a with TP suggests that while SRP concentrations are generally low in all three lakes, the dissolved P is taken up relatively quickly and incorporated into algal biomass.

Chlorophyll-a was not related to NO_3-N ($p>0.05$) in the water samples, because NO_3-N was really low in all three lakes. Chlorophyll-a showed a significant positive correlation with TN at both Cove and Spring Lakes (Cove: $R= 0.355$, $p=0.042$; Spring: $R=0.467$, $p=0.006$), but this correlation was not significant at Lake Wedington ($R=0.027$, $p=0.885$). Mean CHL¬-a and TN concentrations during the growing season were correlated across all three lakes ($R=0.683$, $p=0.043$; Figure 7B).

Secchi transparency was not related to CHL-a ($p>0.05$) in the water samples collected in the photic zone on individual sampling dates. Additionally, in Cove and Spring Lakes mean CHL-a and secchi transparency during the growing season were not related ($p>0.05$), but they were negatively correlated in Lake Wedington ($R=0.998$, $p=0.041$). The relationship between mean secchi transparency and CHL-a during the growing season and across all three lakes was not significant ($R=0.050$, $p=0.899$; Figure 7C).

Nutrient Limitation Experiments

Cove Lake

In May 2017, the dissolved nutrient supply in Cove Lake was low (NO_3-N and SRP 0.02 mg L^{-1}),

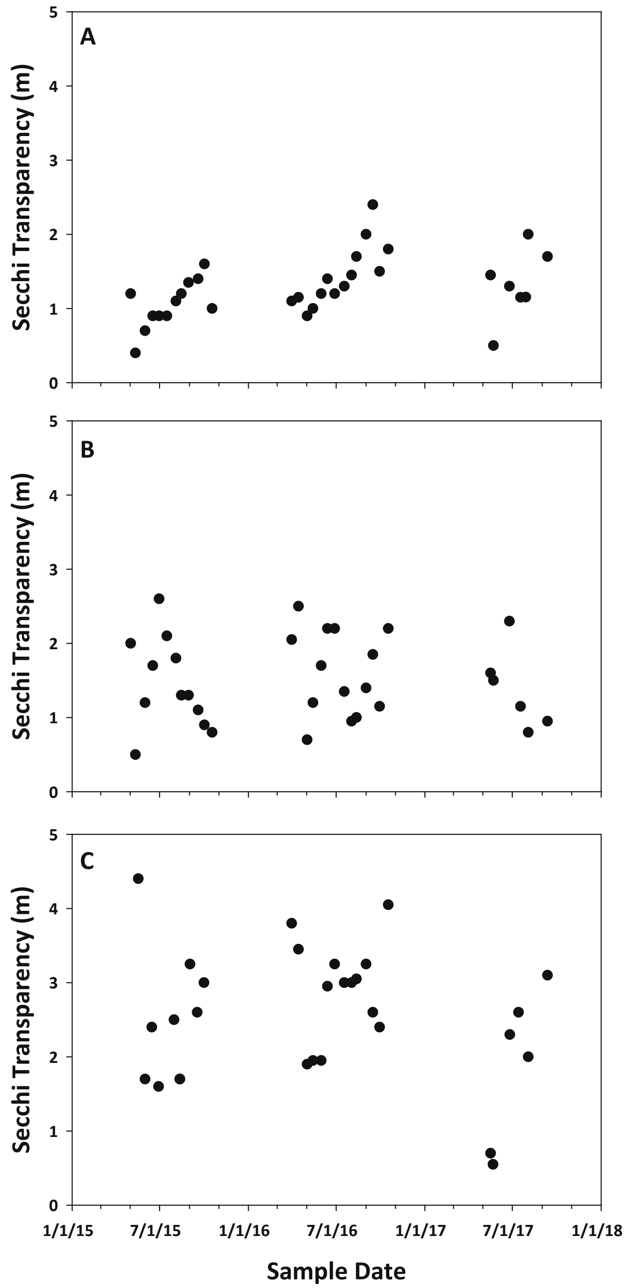

Figure 5. Measured secchi transparency for the Forest Service Lakes during the 2015-2017 growing seasons.

and CHL-a concentrations in the photic zone were 7.0 µg L^{-1} or less. The first nutrient limitation experiment started on the 23rd, and it showed that N and P additions increased algal biomass (CHL-a) twofold relative to the control (0.6 µg L^{-1}). However, the addition of N and P in a balanced ratio (10:1 by mass) increased CHL-a concentration 17 times greater than the control (Figure 8A). The algae at Cove Lake were likely co-limited by N and P early in the growing season, based on this experiment.

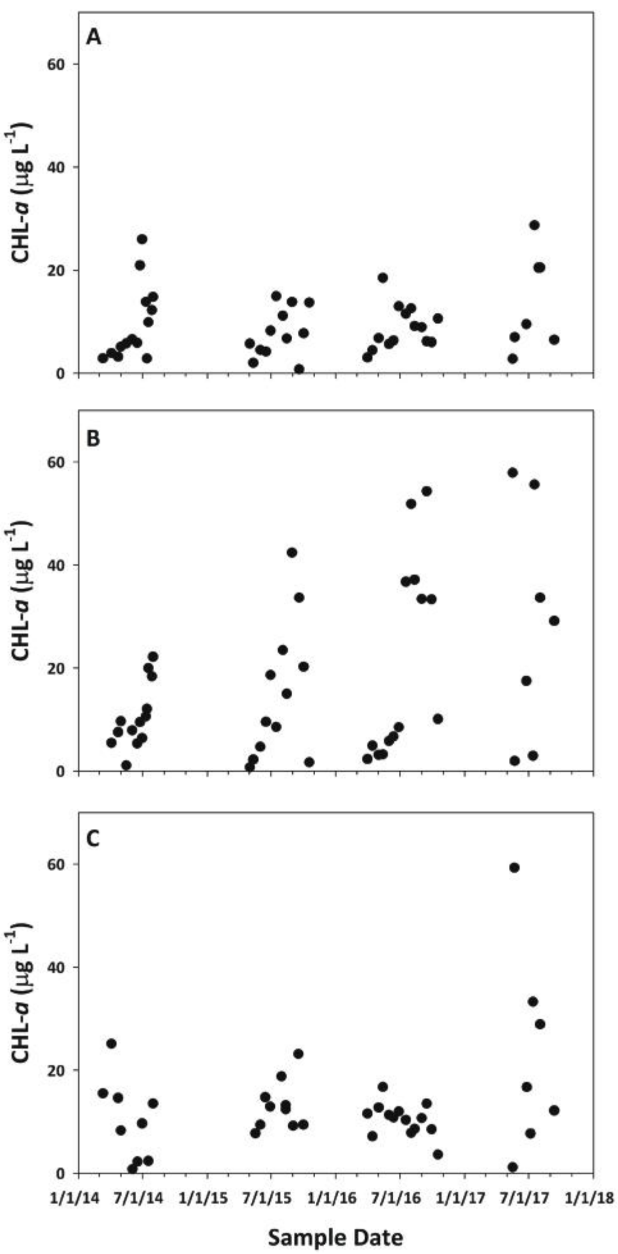

Figure 6. Measured chlorophyll-a (CHL-a) concentrations in the photic zone of the Forest Service Lakes during the 2014-2017 growing seasons. Vertical bars represent when lakes were fertilized. Fertilization dates for Cove and Spring Lakes in 2016 were not available.

In June 2017, the dissolved nutrient concentrations in the photic zone were low (NO_3-N=0.03 mg L^{-1}; SRP<0.004 mg L^{-1}) and CHL-a was slightly greater (9.5 µg L^{-1}) than that observed in May. The second nutrient limitation experiment showed very similar results to the first, where N and P individually increased CHL-a threefold relative to the control (0.8

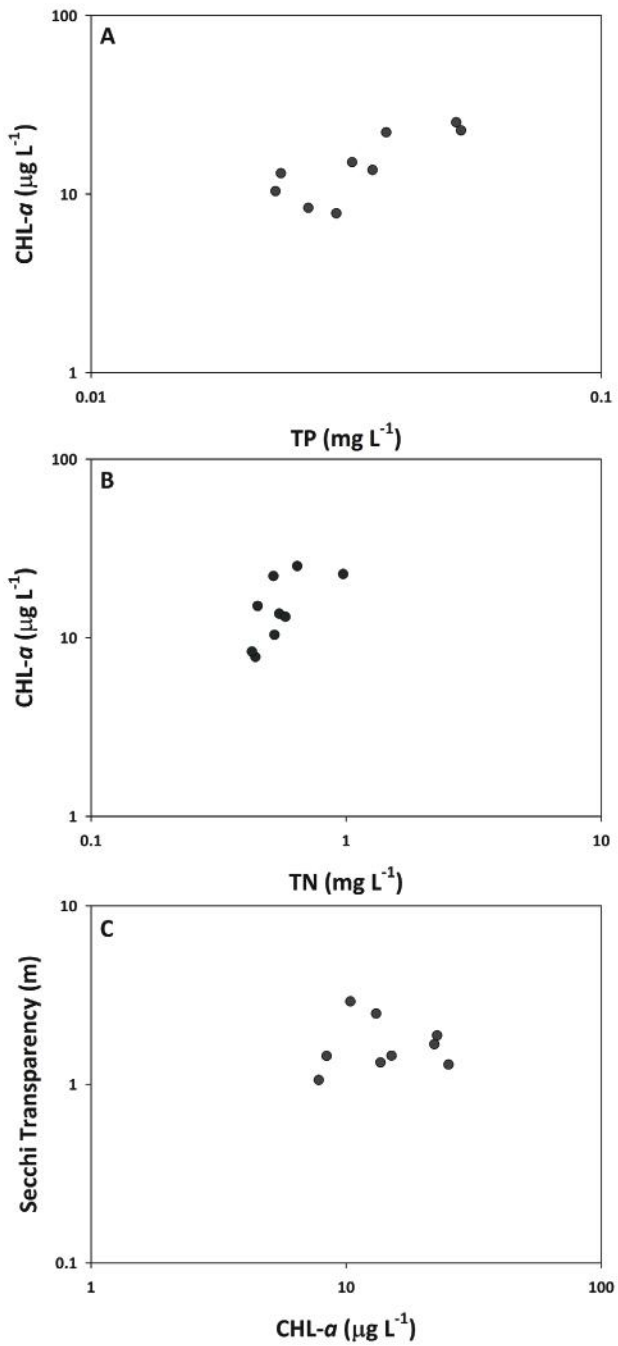

Figure 7. A: Relationship between growing season mean chlorophyll-a (CHL-a) and total phosphorus (TP) in the Forest Service lakes from 2015 through 2017. B: Relationship between growing season mean CHL-a and total nitrogen (TN). C: Relationship between growing season mean CHL-a and secchi transparency.

µg L^{-1}). But, the addition of both nutrients increased algal growth by 15 times relative to the control (Figure 8B). Algal growth was still likely co-limited by N and P as the growing season progressed at Cove Lake.

In mid-July 2017, the dissolved nutrient supply continued to be low (NO_3-N=0.01 mg L^{-1}; SRP<0.004 mg L^{-1}), but the CHL-a concentration was the greatest it had been in the four years of sampling (29 µg L^{-1}) before lake fertilization. Then on July 29th, two days after lake fertilization, the dissolved nutrients remained relatively unchanged, and the CHL-a concentration in the lake had decreased to 21 µg L^{-1}. The third nutrient limitation experiment started on the 29th, and it showed very different results from the first two experiments. At the end of the third experiment, CHL-a was relatively similar across all of the treatments (p=0.202), suggesting that lake fertilization had removed the nutrient limitation of algal growth (Figure 8C). In the lake, one week after fertilization, the dissolved nutrient supply remained low, and the CHL-a concentration remained unchanged (21 µg L^{-1}). At the end of the growing season, the dissolved nutrient supply was still low (NO_3-N=0.01 mg L^{-1}; SRP<0.004 mg L^{-1}), and CHL-a concentration decreased to 6.5 µg L^{-1}.

Spring Lake

In May 2017, the CHL-a concentration in Spring Lake started high (58 µg L^{-1}) and then decreased to 2.0 µg L^{-1}, and the dissolved nutrient supply was low (NO_3-N < 0.01 mg L^{-1}; SRP < 0.004 mg L^{-1}). The nutrient limitation experiment on May 23rd showed that adding either N or P increased CHL-a concentrations by fivefold compared to the control (0.28 µg L^{-1}). But, adding both N and P in a balanced ratio resulted in algal biomass increasing by 50 times relative to the control (Figure 9A). Algal growth in Spring Lake was likely co-limited by N and P at this time, based on the experiment.

In June 2017, the dissolved nutrient supply in Spring Lake was below detection (NO_3-N<0.01 mg L^{-1}; SRP<0.004 mg L^{-1}), and CHL-a had decreased to 1.4 µg L^{-1} by the 25th. The second nutrient limitation experiment showed that adding P did not increase CHL-a relative to the control (0.3 µg L^{-1}). Whereas when N was added, CHL-a increased by fourfold in comparison to the control and P treatment, and CHL-a increased by 24 times when both N and P (10:1 by mass) were added (Figure 9B). The algae in the photic zone at Spring Lake were limited by N but the addition of both nutrients really increased growth at the end of June.

Two days after the first fertilization event on July 14th, dissolved nutrients in the photic zone continued to be low (NO_3-N=0.04 mg L^{-1}; SRP<0.004 mg L^{-1}), and the CHL-a concentration was only 3 µg L^{-1}. The nutrient limitation experiment that began on July

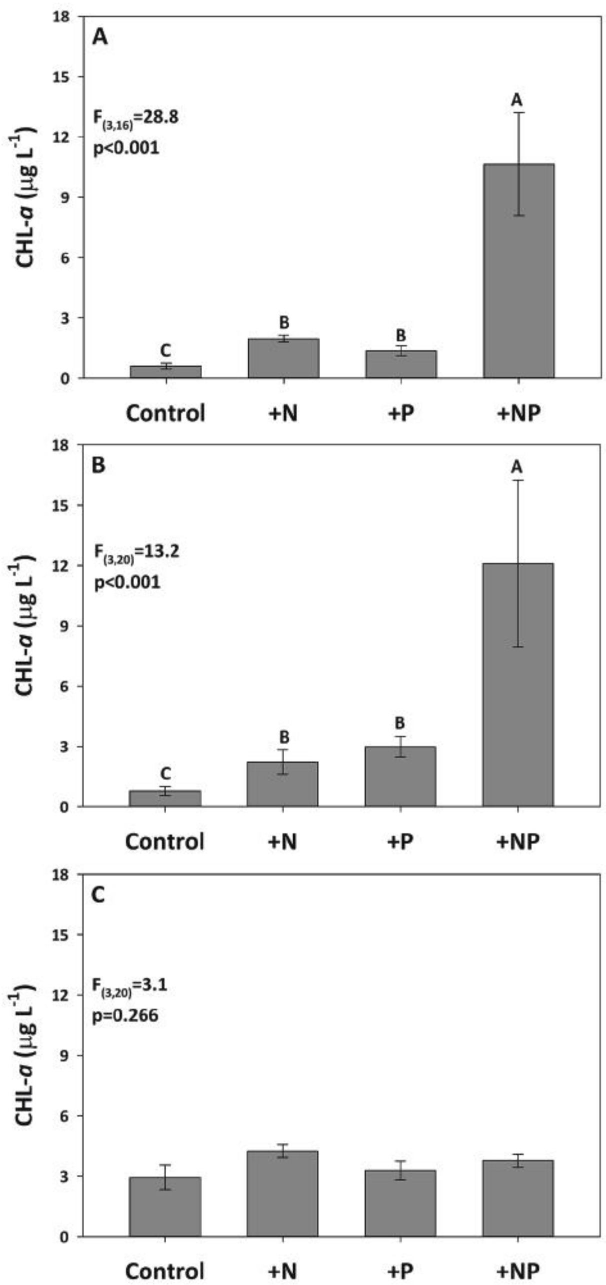

Figure 8. Mean (error bars=± 1 standard error) chlorophyll-a (CHL-a) concentrations across nutrient treatments, including: control, plus nitrogen (+N), plus phosphorus (+P), and plus nitrogen and phosphorus (+NP), for Cove Lake in 2017. Letters above error bars identify homogeneous groups. A: Pre-lake fertilization on May 23 2017. B: Pre-lake fertilization on June 25. C: Post-lake fertilization on July 27.

14th showed similar results to the June experiment, in that adding P did not increase the CHL-a concentration relative to the control (7 µg L^{-1}). Additionally, adding just N had the same effect as adding both N and P, both of which resulted in a twofold increase of CHL-a compared to the control (Figure 9C). Following lake fertilization, algal growth in Spring Lake was likely N limited. One week after the first fertilization event, dissolved nutrients were both below detection in photic zone (NO_3-N <0.01 mg L^{-1}; SRP<0.004 mg L^{-1}), whereas the CHL-a concentration (55 µg L^{-1}) was similar to that measured in mid-May. Spring Lake was fertilized a second time at the end of July, and while dissolved nutrients remained low, CHL-a concentrations were slow to decrease, remaining above 20 µg L^{-1} through the end of the growing season.

Lake Wedington

In May 2017, the dissolved nutrient supply in the photic zone of Lake Wedington was low (NO_3-N<0.01 mg L^{-1}; SRP=0.006 mg L^{-1}), and CHL-a started at 1.2 µg L^{-1} and increased to 59 µg L^{-1} by the 22nd. The first nutrient limitation experiment showed that the addition of N or P alone did not increase CHL-a relative to the control (6.0 µg L^{-1}), but adding both N and P to the lake water resulted in roughly four times more CHL¬-a than in the control treatment (Figure 10A). Similar to the other lakes, algal growth in Lake Wedington was likely co-limited early in the growing season.

By the end of June the dissolved nutrients were below detection (NO_3-N<0.01 mg L^{-1}; SRP<0.004 mg L^{-1}), and CHL¬-a in the photic zone had decreased to 17 µg L^{-1} from May. Similar to the first nutrient limitation experiment, the second experiment showed that adding only N or P did not promote increased CHL-a relative to the control (0.8 µg L^{-1}). However, adding both N and P resulted in a CHL-a concentration that was 16 times greater than the control treatment (Figure 10B). The algae in the photic zone remained co-limited by N and P through June, based on these experiments.

Two days after lake fertilization in July, SRP in the photic zone increased but NO_3-N remained below detection (NO_3-N<0.01 mg L^{-1}; SRP=0.025 mg L^{-1}), and CHL-a continued to decrease (7.7 µg L^{-1}). The nutrient limitation experiment conducted at this time showed that adding N or P only did not promote increased CHL-a relative to the control (3.1 µg L^{-1}), but adding a balanced ratio of N and P (10:1 by mass) resulted in a twofold increase of CHL-a compared to the control (Figure 10C). Despite lake fertilization, algal growth in Lake Wedington continued to be co-limited by N and P. A week after Lake Wedington was fertilized, SRP decreased and NO_3-N remained low (NO_3-N<0.01 mg L^{-1}; SRP=0.005 mg L^{-1}); however, CHL-a¬ increased fourfold (33 µg L^{-1}) in the photic zone. Throughout

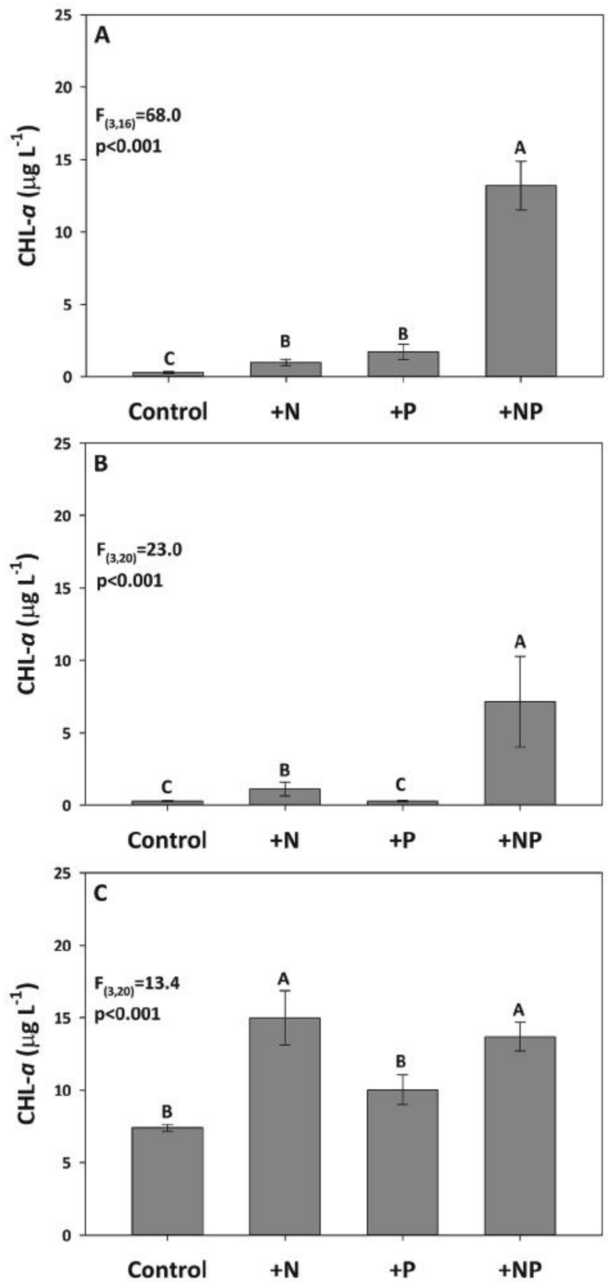

Figure 9. Mean (error bars=± 1 standard error) chlorophyll-a (CHL-a) concentrations across nutrient treatments, including: control, plus nitrogen (+N), plus phosphorus (+P), and plus nitrogen and phosphorus (+NP), for Spring Lake in 2017. Letters above error bars identify homogeneous groups. A: Pre-lake fertilization on May 23 2017. B: Pre-lake fertilization on June 25. C: Post-lake fertilization on July 14.

the remainder of the growing season, dissolved nutrients continued to be low, and CHL-a slowly decreased to 12 µg L^{-1}.

Lake Fertilization Calculator

The fertilization calculator determines how much P (and N based on an N:P ratio of 10:1 by mass) should be added to a lake to achieve a desired increase in algal biomass. This calculator was developed outside of the USFS lakes monitored and studied; so we need to validate the underlying equations used against data collected in these lakes

The first equation in the calculator predicts CHL-a concentration from secchi transparency. The mean CHL-a and secchi transparency in each growing season for these lakes were relatively close to the line predicted by the equation (Figure 11A), where mean CHL-a concentrations deviated from model predicted concentrations by 7 to 32%. This suggests that the model for estimating CHL-a concentration from secchi transparency in Northwest Arkansas lakes is relatively robust, and it can likely be used to predict CHL-a in our study lakes.

The second equation estimates TP concentration from CHL¬-a. In these lakes, the mean CHL-a and TP concentrations were strongly correlated (R=0.764, p=0.004) during the growing season. This relationship fit the modeled line from the calculator extremely well (Figure 11B), with mean TP concentrations differing from predicted concentrations by only 1 to 10%. Again, this suggests that the equation used in the calculator can be broadly applied, especially for these lakes.

From these two equations, a simple measure of secchi transparency can be used to estimate the CHL¬-a concentration in the lake according to the first equation in Figure 11A. The estimated CHL-a concentration can then be used in the second equation (Figure 11B) to estimate the current TP concentration in the lake. When a target secchi transparency is entered into the calculator, the calculator estimates both the current TP and the target TP concentration needed to reach the target secchi transparency. The difference in the current and target TP concentrations is the increase in concentration needed to achieve the target secchi transparency (Scott 2016), which means how much P (and N) do we need to add.

The third component of the calculator is used to determine how much P (and N based on an N:P ratio of 10:1 by mass) is needed to achieve the target TP concentration. The calculator uses secchi transparency to estimate a photic depth, based on the relationship between secchi transparency and photic depth in the lakes in Bella Vista. Secchi transparency was strongly correlated with the photic depth across individual sampling dates and lakes (R=0.901, p<0.001;

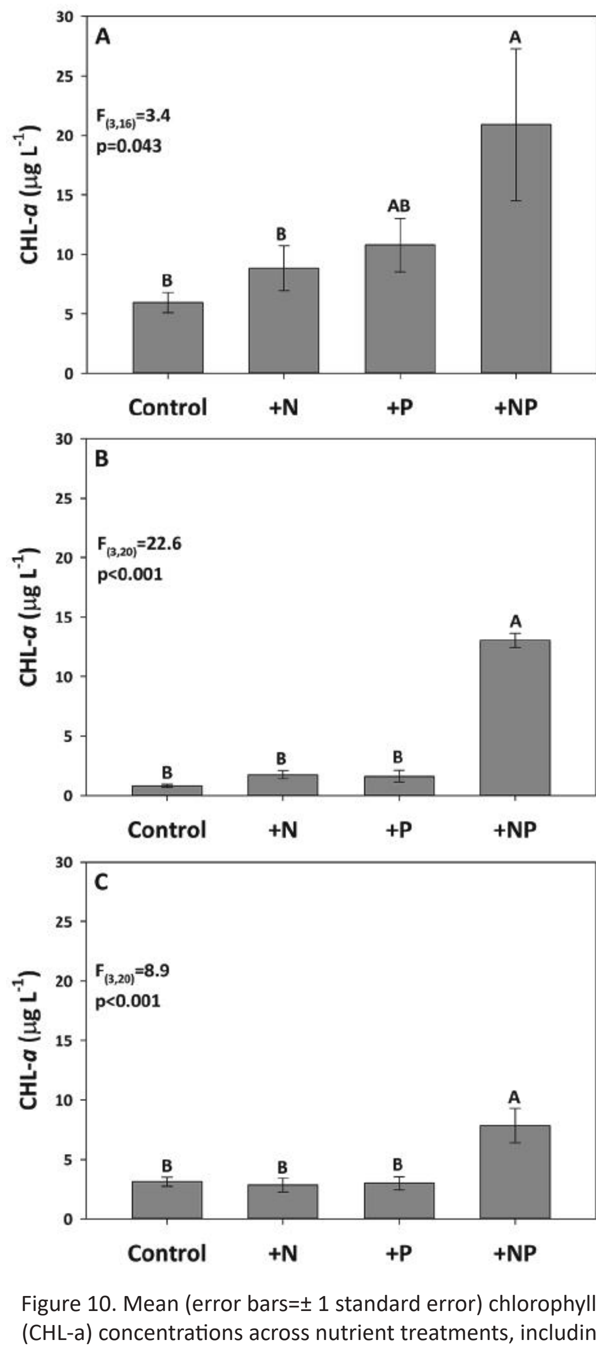

Figure 10. Mean (error bars=± 1 standard error) chlorophyll-a (CHL-a) concentrations across nutrient treatments, including: control, plus nitrogen (+N), plus phosphorus (+P), and plus nitrogen and phosphorus (+NP), for Lake Wedington in 2017. Letters above error bars identify homogeneous groups. A: Pre-lake fertilization on May 22 2017. B: Pre-lake fertilization on June 26. C: Post-lake fertilization on July 7.

Figure 11C). This relationship closely aligned with the modeled line for secchi transparency and photic depth used in the calculator (Figure 11C), and measured photic depth differed from predicted by only 8% on average (range 1 to 45%). This suggests that the model for estimating photic depth from secchi transparency already built into the calculator is acceptable to use for these lakes. At this time, the only aspect of the calculator that needs to be updated is lake surface area. The photic depth and surface area of the lake are then used to compute a photic volume or the volume of the lake where algae are growing.

RECOMMENDATIONS

Algal biomass increased in all three lakes following fertilization efforts; however, the CHL-a response was variable. The following recommendation when fertilizing lakes should help produce optimal algal growth, supporting a healthier aquatic community and sport fish population. The lakes should be fertilized with N and P in a balanced application rate (10:1 by mass) to maximize algal growth.

Overall, the dissolved nutrient supply was low in all three lakes throughout the growing season. Algal growth was co-limited by N and P in May and June 2017 or at least addition of N and P resulted in the greatest CHL-a concentration, in the nutrient limitation assays. This suggests that no matter when you are fertilizing these lakes, a balanced application of N and P would be best to maximize algal growth.

The lake fertilization calculator can be a useful tool for maintaining a desired concentration of CHL-a, based on secchi measurements alone. But, for this calculator to be effective, it is important to have a management plan which sets targets for secchi transparency. For example, the goal for the lakes that this calculator was originally developed for was to maintain a secchi transparency of 1.5 to 2.0 m, wherein lakes are only fertilized when the secchi transparency increases above 2.0 m and, they are never fertilized to achieve a transparency of less than 1.5 m. In this way, setting a maximum secchi transparency (or minimum CHL-a concentration) will determine when lakes should be fertilized and setting a minimum secchi transparency (or maximum CHL-a concentration) will determine how much N and P should be added. The Lake fertilization calculator determines the N and P application rate needed specifically for each lake.

The lakes in this study were relatively small with short hydraulic residence times, so lake and weather conditions should be taken into account before fertilization. The USFS intentionally avoid lake fertilization at times when water is flowing over the spillway at these lakes; the thought is not to apply nutrients when there is a chance you will lose the nutrients

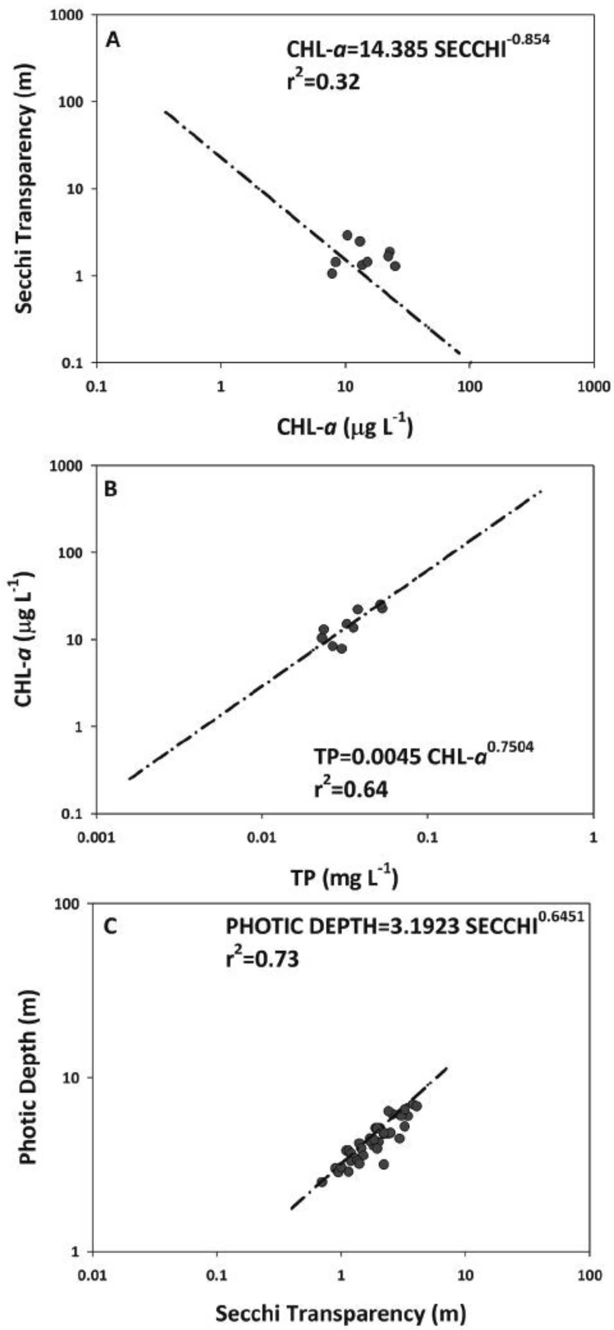

Figure 11. Growing season mean secchi transparency, chlorophyll-a (CHL-a), and total phosphorus (TP), as they relate to the modeled lines (dashed line) derived from the equations (shown on each panel) in the lake fertilization calculator. A: Relationship between CHL-a and secchi transparency. B: Relationship between CHL-a and TP. C: Relationship between secchi transparency and photic depth across all sample periods.

downstream. However, the water residence time should be estimated or the nutrients could be applied furthest away from the spillway to allow for the longest residence time.

While these are forested watersheds, large storms could bring in N, primarily as NO_3, and P into the lakes. In these watersheds, rainwater can be a significant source of NO_3 (GALLOWAY et al. 1984) because rainwater generally has a NO_3-N concentration of 1.0 mg L^{-1} (NADP 2011). The greater biomass early in the 2017 growing season suggests these external sources of nutrients (rain and watershed) were sufficient to increase algal growth. If NO_3¬ is readily available, then you might need to evaluate whether the algae are co-limited or not and adjust your fertilization to focus on the nutrients needed.

These lakes did not show much variation in algal nutrient limitation in 2017, but the dissolved nutrients supply was low through the monitoring period or growing season. However, many small reservoirs shift from co-limitation to N limitation in late summer, whereas forested lakes are often consistently N limited (Hayes et al. 2015). The lakes in this study were mostly forested, but algal growth in the photic zone was co-limited by N and P. It can be useful to actually measure nutrient limitation using assays like what was used in this study to help guide what nutrients to add to lakes during fertilization.

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