

## An assessment of plankton populations, toxic cyanobacteria, and potential impact of introduced marine alewife (*Alosa pseudoharengus*) in Pawtuckaway Lake, New Hampshire

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### Abstract

A field study was conducted during the summer, 2005 to evaluate the lake water quality and planktonic communities in Pawtuckaway Lake, NH. Of special concern was the condition of the plankton populations since the lake had been subjected to introductions of adult sea-run alewife.

Overall water quality ranged from mesotrophic to eutrophic based on total phosphorus ( $8\text{--}31\ \mu\text{g L}^{-1}$ ), chlorophyll *a* (max South,  $5.0\ \mu\text{g L}^{-1}$ ) and Secchi disk transparency (max North 5.1 m, min South 2.8 m). Of the three sites sampled, Fundy, North and South, Fundy ( $Z_{\text{max}} < 2\text{ m}$ ) did not stratify and had the highest concentrations of total phosphorus, followed by North and South sites, respectively. North and South sites stratified throughout the summer and developed anoxic hypolimnia, with the most severe oxygen deficit at the North site.

Potentially toxigenic cyanobacteria were detected at all three sites. Throughout the summer, the concentrations of the cyanotoxin microcystin in the lake were well above the average for NH lakes. Lakewater concentrations of microcystins exceeded WHO drinking water standards ( $1000\ \text{ng L}^{-1}$ ) at the North site ( $1204.0\ \text{ng L}^{-1}$ ) on July 21. The two dominant cyanobacteria were *Anabaena* spp. and *Microcystis aeruginosa*. *Oscillatoria* (*Planktothrix*) were also present, but only rarely and therefore were probably not responsible for most of the microcystins present in the lakewater.

Mean zooplankton body lengths were significantly ( $p < 0.05$ ) smaller at Fundy than South and North sites (Fundy  $0.56 \pm 0.052\ \text{mm SE}$ , North  $0.79 \pm 0.031\ \text{mm SE}$ , South  $0.83 \pm 0.043\ \text{mm SE}$ ). Grazing rates of the zooplankton were generally less than  $20\ \%\ \text{day}^{-1}$ . Maximum zooplankton grazing occurred at Fundy in late summer and correlated with a chlorophyll *a* minimum, suggesting zooplankton may at times control the phytoplankton abundance in Pawtuckaway Lake. The small body size of the zooplankton at the Fundy site in July indicates an overabundance of planktivorous fish in this region of the lake. Such excessive predation on the grazing zooplankton can cause a “bottleneck” in the flow of energy through the lake food web resulting in a build up of undesirable phytoplankton, potentially leading to harmful algal blooms.

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### Introduction

The zooplankton community occupies a central

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position in the pelagic food web of lakes. Their abundance and composition reflect the productivity and composition trophic levels above and below (Brooks and Dodson 1965). Zooplankton body size is a useful indicator of the intensity of predation on the zooplankton community by forage fish, since zooplankton body size is inversely correlated with the abundance and growth of planktivorous fish and positively correlated with the abundance of piscivorous game fish (Christoffersen *et al.* 1993; Galbraith 1975; Mills and Schiavone 1982). Body length measurements of zooplankton also provide a basis for predicting the grazing impact of the community on the phytoplankton (Lampert 1988) and its consequent effect on water transparency (Stemberger and Miller 2003).

Alewife (*Alosa pseudoharengus*) are anadro-

mous herring that are extremely efficient zooplanktivores as adults and as immature fish. The presence of alewife in lakes can cause dramatic shifts in the composition of the zooplankton, resulting in a zooplankton community made up of small species (Brooks and Dodson 1965). The absence of large grazers such as *Daphnia* can result in more eutrophic-like conditions, such as higher levels of phytoplankton and lower water transparency (Edmondson 1982). In an effort to increase the marine stocks of *A. pseudoharengus*, the Marine Division of NH Fish & Game began a program of transplanting adult *A. pseudoharengus* in Pawtuckaway Lake. Central to this transplant program was the assumption that each fall the adult and young-of-year alewife would leave Pawtuckaway Lake via the Lamprey River and return to the ocean. Citizens from the Town of Nottingham and the Pawtuckaway Lake Improvement Association raised questions about the possible impact of an introduced population of

alewife on the planktonic food web and water quality in the lake, especially since the lake has had problems with algal blooms. In response to these concerns, this study set out to examine the condition of the lake in regard to its trophic status, the integrity of the food web, including the zooplankton grazing community, and the occurrence of microcystin, a potent toxin produced by cyanobacteria and a serious problem world-wide (Carmichael *et al.* 2001).

### The lake and Sampling Sites

Located in the town of Nottingham, NH, and a headwater of the Lamprey River, Pawtuckaway Lake has the following morphometric features: maximum depth ( $Z_{\max}$ ) = 15.2 m, mean depth ( $Z_{\text{mean}}$ ) = 2.9 m, lake surface area = 364.22 ha, watershed area = 5361.3 ha, watershed:lake = 14.72, flushing rate = 2.3 year<sup>-1</sup>. Because the lake

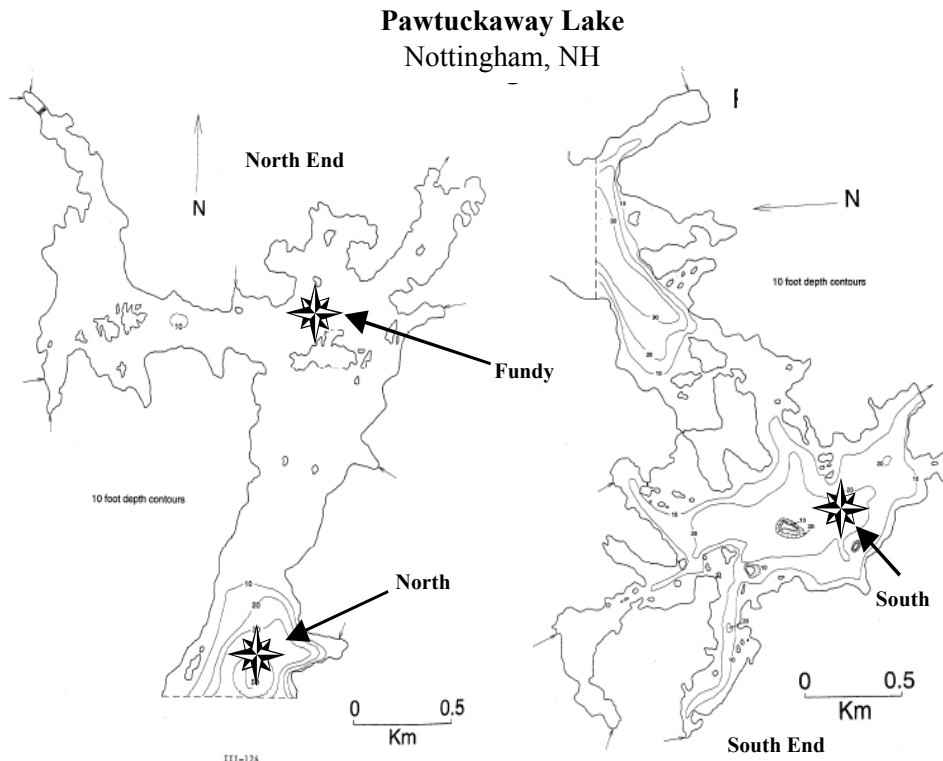


Fig. 1. Depth contour map of Pawtuckaway Lake, NH, showing the three sampling locations, North, South, and Fundy. Map modified from NH DES.

has a complex morphometry, sample sites were located at each of the three distinct basins, i.e. North, South, and Fundy (Fig. 1).

## Methods

*Physical and Chemical Parameters* - A multiparameter Sonde (YSI model 6600M) connected to a data logger (YSI Model 650) was used to measure depth, temperature, dissolved oxygen, pH, chlorophyll *a*, Oxidation-Reduction Potential (ORP), turbidity, specific conductivity and chlorophyll *a* fluorescence. The depth of the epilimnion was determined from these temperature readings. The probe was lowered into the water at  $\sim 0.5$  m  $\text{min}^{-1}$ . Data were logged every 3 s or at approximately 2.5 cm depth intervals.

Transparency of the lake water was determined using a view scope and a 20 cm Secchi disk. The disk was lowered over the side of the boat until it could not be seen and then it was slowly raised, and the depth at which it was again in view was recorded to the nearest 0.1.

The LI-COR Datalogger LI-1000 and the Underwater Quantum Sensor LI-192SA recorded the intensity of light at 0.5 m depth intervals at the deepest part of the lake. An additional light photosensor recorded the surface incident light intensity to correct for changes in light due to cloud cover. The natural log of the light intensity was regressed against depth and the slope of the resulting regression line was used to estimate the coefficient of light attenuation ( $k_{\text{ext}}$ ).

A sonar survey was conducted at the North site during the October sampling trip using a Lowrance LCX-25 recording sonar with a 200 kHz transducer.

Alkalinity or acid neutralizing capacity (ANC) samples were taken with an integrated tube sampler, lowered to the lower boundary of the epilimnion. Alkalinity titrations followed the method described by Lind (1985), except for the use of 0.002 N sulfuric acid as the titrant and bromocresol green – methyl red as the indicator. The gray and pink endpoints were recorded for each titration indicating approximately pH = 5.1 and 4.6, respectively. The gray endpoint represents ANC while the pink endpoint is useful for

comparison with historic data using the methyl orange indicator technique.

Water samples collected in the field were returned to the Center for Freshwater Biology Analytical Laboratory (University of New Hampshire, Durham, NH) and analyzed for chlorophyll, phosphorus, and dissolved color. Spectrophotometry for chlorophyll, phosphorus, and color determination was accomplished using a Milton Roy Spectronic 1001+ spectrophotometer. Chlorophyll *a* was measured according to Lind (1985), substituting an absorption coefficient of 11.9 for the 28.9 value, and Vollenweider (Vollenweider 1969) using a 5 cm path length optical glass cuvette, with absorption measured at 663 nm. Average phosphorus was determined according to AHPA (Apha 1998) using a 10 cm path length optical glass cuvette, with absorption measured at 880 nm.

Dissolved color was calculated according to Cuthbert and Giorgio (1992) and APHA (1998). Samples were thawed and scanned for absorbance at 190 and 250 nm with a Cary 50 scanning spectrophotometer and a 5 cm path length quartz cuvette. The second derivatives of the curves at 227.5 nm were calculated with Cary 50 software in order to correct for interference by colored nitrogenous material.

*Biological Parameters* - Zooplankton were collected using vertical net tows (25 cm diam) with a 50  $\mu\text{m}$  mesh net. An integrated vertical plankton tow was taken with triplicate samples. The net was lowered to just above the sediments, towed vertically to the surface and rinsed three times. The contents the cod end bucket were poured through a 50  $\mu\text{m}$  ring net. Plankton in the ring net were rinsed into a sample jar and preserved with 4% formalin/sucrose solution according to Haney and Hall (1971). Zooplankton were identified using taxonomic keys of Pennak (1989), and the CFB interactive key, "Zooplankton of the Northeast (USA)" (CFB 2005).

Samples from the integrated plankton tow were analyzed to estimate densities of net phytoplankton and zooplankton. Phytoplankton abundance was calculated as a percentage of the total, count-

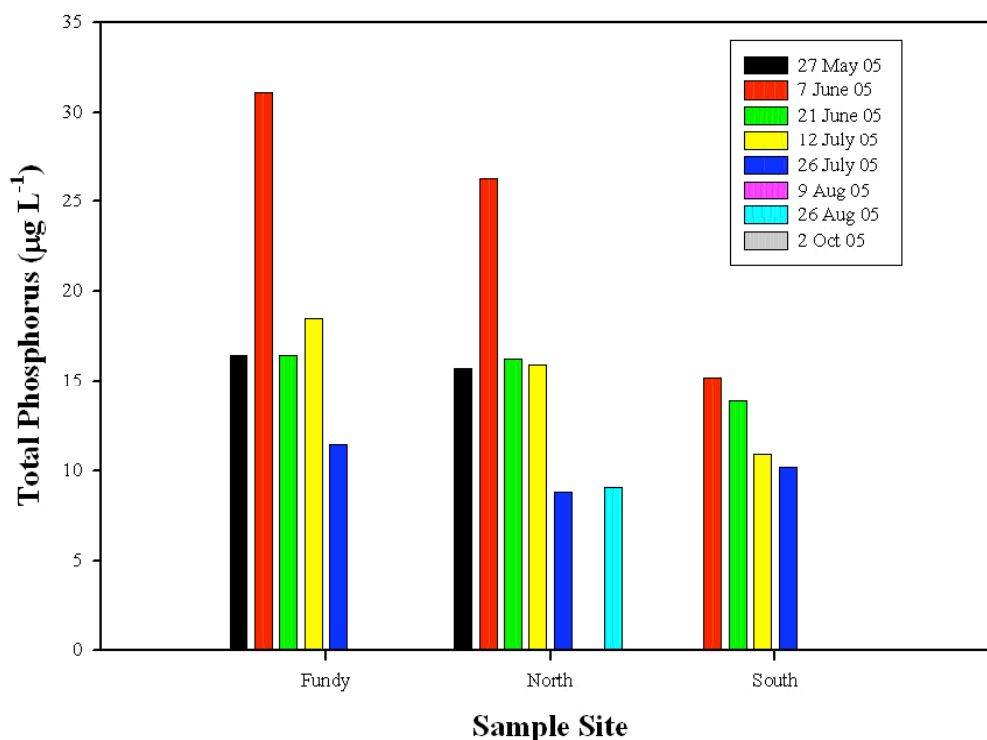


Fig. 2. Total phosphorus measured at Fundy, North, and South stations, Pawtuckaway Lake, summer 2005.

ing number of individuals in subsections of a 1 ml Sedgwick-rafter cell under a compound microscope.

Zooplankton in each sample were counted using a compound microscope and a Sedgwick-Rafter counting cell. The lake density was determined from the number of individuals counted and the volume of the water sampled. To determine the total biomass for each taxon, the average dry weight for each taxon (Dumont *et al.* 1975) was multiplied by the density of the taxon. Zooplankton body lengths were determined from digital images of 20-40 animals using MetaMorph imaging software (MetaMorph Version 4.01). Dry weights of zooplankton species were estimated from body length versus body weight relationships from Dumont *et al.* (1975) and Culver *et al.* (Culver *et al.* 1985). Zooplankton dry weights were converted to estimated zooplankton community grazing rates from the relationship of Lampert (1988), where Community grazing (% day<sup>-1</sup>) = 4.5

+ 231 X Zooplankton biomass (mg dry wt L<sup>-1</sup>).

Water collected from the IT samples was used for total phosphorus analyses and also filtered through a 0.45 µm filter (47 mm Millipore HAWP), frozen, and saved to measure dissolved color. Filters were immediately placed in a dark desiccating box and saved for analysis of extracted chlorophyll *a*.

*Statistical Analyses* - Linear regressions were calculated using SigmaStat (Systat Software Inc.). Significant differences between means were tested using one-way ANOVA; all tests of significance were conducted at  $p \leq 0.05$ , unless otherwise stated.

## Results

*Total Phosphorus* - All three sites ranged between 8 and 31 µg L<sup>-1</sup> total phosphorus (TP)

throughout the summer (Fig. 2). Changes in phosphorus were synchronous at the all sampling locations, each peaking on June 7, with Fundy reaching the highest TP concentration of  $31 \mu\text{g L}^{-1}$ , followed by North at  $26.3 \mu\text{g L}^{-1}$  and South at  $15.2 \mu\text{g L}^{-1}$  (Fig. 2). Throughout the season, Fundy maintained the highest overall TP values, followed by North and South.

*Chlorophyll a* - There was a general increase in chlorophyll levels for all three sites until August 26 at which time the values exhibited a steep decline (Figs. 3). All three sites then dramatically increased on October 2, the last sampling date. Fundy demonstrated the most dramatic decrease from  $3.47 \mu\text{g L}^{-1}$  on July 9, to below detectable limits on July 26. Similarly, South decreased from  $4.71 \mu\text{g L}^{-1}$ , to  $1.87 \mu\text{g L}^{-1}$  and North from  $2.55 \mu\text{g L}^{-1}$ , to  $2.54 \mu\text{g L}^{-1}$ .

*Secchi Disc Depth* - Mean water transparency at North was  $3.82 \text{ m}$  ( $n = 8$ ,  $\text{SE} = 0.63$ ),  $3.85 \text{ m}$  at South ( $n = 8$ ,  $\text{SE} = 0.21$ ), and Fundy was too shal-

low for water transparency measurements (Fig. 4). Visibility declined from May to June (high reached by South  $4.1 \text{ m}$ , low at South  $2.8 \text{ m}$ ) and then gradually increased throughout the rest of the summer (overall high reached by North,  $5.1 \text{ m}$ ). Secchi disk depth decreased again in early fall, coincident with the autumn increase in chlorophyll *a*.

*Physical Parameters & Stratification* - While both North and South sites displayed pronounced thermal and chemical stratification, Fundy was considerably shallower and was not stratified on any of the sampling dates (see Appendix A). North, the deepest site, was thermally stratified at the time of the first sampling in May (Fig. 5). Peak stratification of North occurred in late fall (October), with a sharp decrease in dissolved oxygen at  $6 \text{ m}$ . In addition, turbidity levels were highest at  $8$  to  $9 \text{ m}$ . However, and the metalimnetic turbidity maximum did not correspond to high levels of chlorophyll, suggesting the particles causing the turbidity were not non-photosynthetic or at

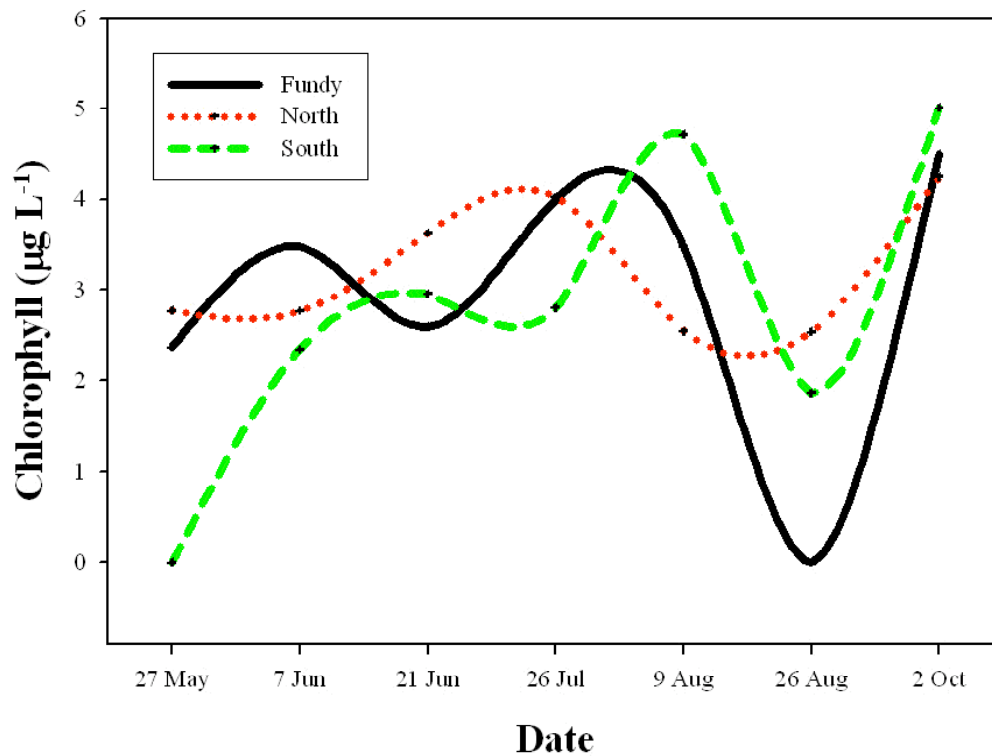


Fig. 3. Chlorophyll *a* measurements at Fundy, North, and South stations, Pawtuckaway Lake, NH, summer 2005.

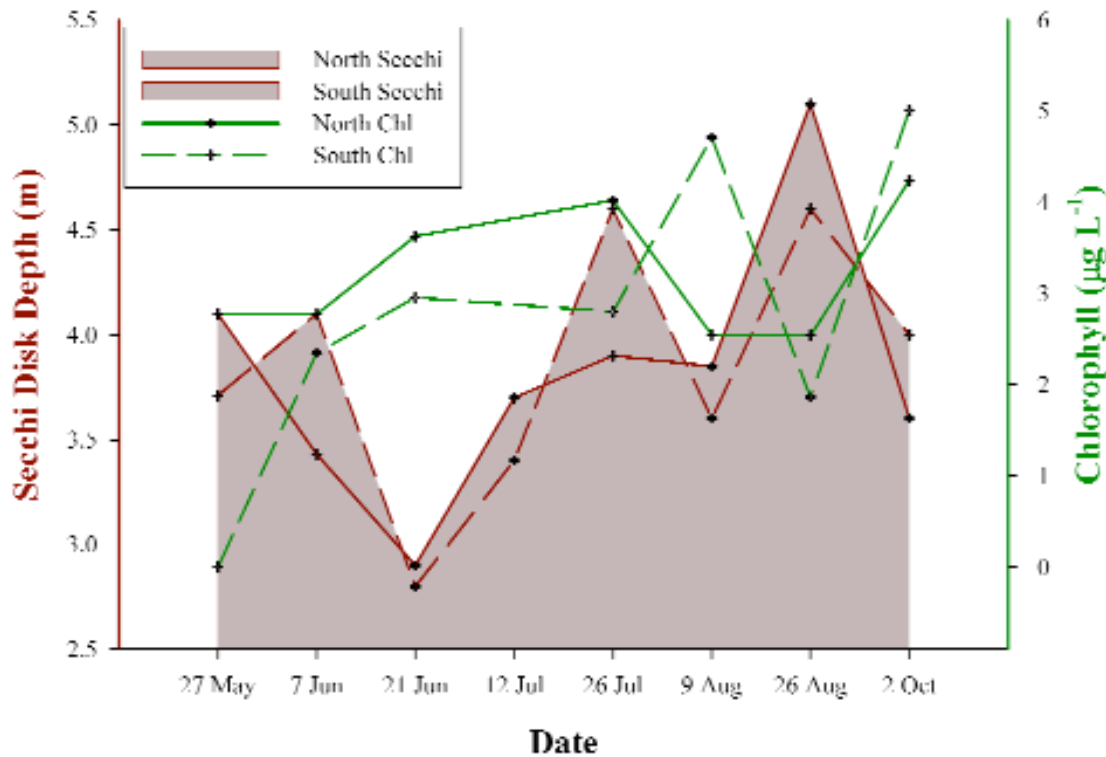


Fig. 4. Secchi Disk visibility and chlorophyll levels at North and South stations, Pawtuckaway Lake, NH, summer 2005.

least not containing the photosynthetic pigment chlorophyll *a*. It is probable that the turbidity was caused by a dense layer of bacteria or fine sediment suspended in the thermocline. At roughly 8 m pH also reached its minimum value of 6, rising thereafter with the deeper water (Fig. 5). The decrease in acidity in the hypolimnion is likely the result of bacterial decomposition and the release of buffering minerals, such as phosphorus, calcium and magnesium. Below 10 m, the redox potential (ORP, or Oxidation Reduction Potential;  $E_7$  in Fig. 6) reached negative values, a strong indication of highly chemically reduced conditions. This, in addition to the anoxic environment at this depth, leads to release of bound phosphorus and its loading into the water column from the sediments.

**Sonar** - The sonar transect at the deepest site (North) revealed a highly reflective layer just above the lake sediments at approximately 13 m depth, in highly reduced, anoxic water (Fig. 6). Based on previous sonar experience this layer is

most likely caused by a population of phantom midge larvae (*Chaoborus*). These 5-8 mm aquatic larvae of the non-biting midges have the unique ability to tolerate periods of anoxia during the day, and at night they migrate to the surface to feed on small zooplankton. Also seen in the sonar are numerous fish in the upper warm layer (epilimnion) and a few isolated fish in the cooler water of the metalimnion. A second deep-water reflective layer corresponds closely to the deep turbidity maximum. Since the turbidity probe is most responsive to small particles, it is unlikely that *Chaoborus* larvae caused these sonar reflections.

**Net Phytoplankton** - The net phytoplankton (>50 µm) were dominated by two genera: *Anabaena* and *Microcystis*. Densities of *Anabaena* were greatest at the South site, reaching approximately 80, whereas the North site had the highest concentrations of *Microcystis*, with roughly 1 L<sup>-1</sup>. Fundy had lower amounts of both of these Cyanobacteria, reaching 6 and 0.2 colonies L<sup>-1</sup> for *Anabaena* and *Microcystis*, respectively.

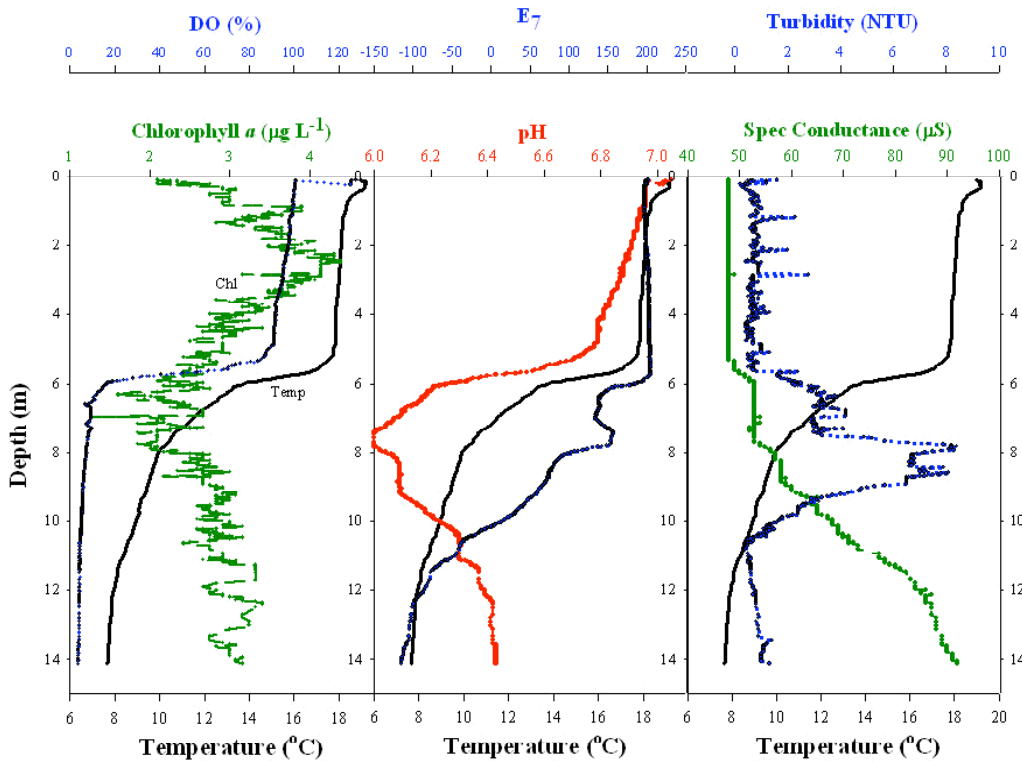


Fig. 5. Multiparameter data showing stratification, chlorophyll, pH, and Spec Conductance of lake at North site on October 2, Pawtuckaway Lake, summer 2005.

#### *Crustacean Community composition*

From May to late June, sites North and South had relatively even composition of the five major taxa, including both cladocerans (*Daphnia*, *Bosmina*, and *Holopedium*) and copepods (Calanoids and Cyclopoids). *Daphnia* dominated North and South in early July, and then co-dominated with an increasing abundance of Cyclopoids by late July (Fig. 7). Fundy again differed from the other locations, beginning with a very high dominance of *Holopedium* in May (after which *Holopedium* remained the lowest represented taxon in all three sites, rarely appearing by August). Unlike North and South, Fundy was rarely dominated by *Daphnia*, but instead often showed high densities of *Bosmina*. However, by early August copepods dominated all three sites by between 60 to 80%, and remained the dominant crustaceans through October (Fig. 7). Overall, the diversity of zooplankton was higher in early summer (May to late

June) with each site generally having representatives of all major taxa of organisms. Diversity continually decreased through late summer and fall (late August to October) with each site having representation by only three of those same taxa.

*Zooplankton body size* - Mean zooplankton in Fundy (Fundy  $0.56 \pm 0.052$  mm SE) were significantly smaller than the zooplankton at both North (North  $0.79 \pm 0.031$  mm SE,  $p = 0.003$ ) and South sampling locations (South  $0.83 \pm 0.043$  mm SE,  $p < 0.001$ ) (Fig. 8). However, mean body lengths between North and South sites did not differ significantly ( $p = 0.79$ ). Mean body length ranged from 0.72 - 0.97 mm and 0.66 - 0.98 mm at North and South sites, respectively. In contrast, crustacean zooplankton at Fundy ranged from 0.33-0.77 mm, barely overlapping with the size of the zooplankton at the other two sites. Overall, zooplankton body sizes gradually increased at North and South sites as summer progressed from May



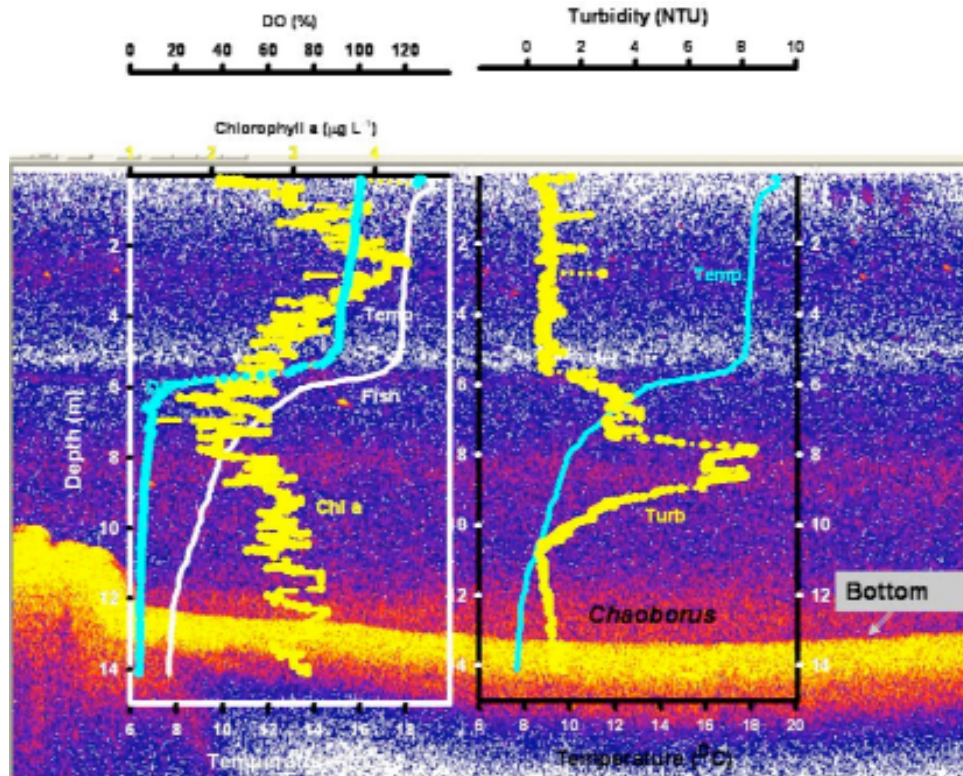


Fig. 6. Sonar transect taken at North site on October 2, 2005, Pawtuckaway Lake. The scattering layer just above the lake bottom represents chaoborus larvae. Fish are represented by distinct light signals, as indicated on the graph. Multiparameter profiles shown were taken on the same day.

into late July. Strikingly, the seasonal changes in body size had the opposite trend at Fundy, with the smallest body size in mid July, the time that North and South reached their largest sizes (0.97 and 0.98 mm respectively). The three regions of the lake had maximum body sizes at different times, with North peaking first in early summer, followed by South in mid-summer, and finally Fundy in late August (Fig. 8). The rapid shift to small body size in Fundy and the contrast with the other sites can be seen in the images of plankton from the three locations (Fig. 9).

**Zooplankton Biomass and Grazing** - Zooplankton biomass averaged for the three sites varied within the range of 10-18 µg dry weight L<sup>-1</sup> from May until August (Fig. 10). Biomass then sharply increased, reaching a maximum of 83.4 µg dw L<sup>-1</sup> by late August, with the greatest biomass at Fundy (226.7 µg dw L<sup>-1</sup>) (Fig. 11). Biomass of

the zooplankton then gradually declined back to 20 µg dw L<sup>-1</sup> by early fall (Figs. 10 & 11). Biomass was also used to calculate zooplankton grazing intensity, according to Lampert (1988). Estimated grazing rates at all three sites remained between 5.1 to 10.6 % d<sup>-1</sup> from early to mid-summer (Fig. 12). During late summer, North and South remained in this range, whereas Fundy experienced a dramatic increase in grazing during late summer, reaching a maximum of 56.9% d<sup>-1</sup>. By early fall, grazing all sites was again within the range of 5.1 to 10.6% d<sup>-1</sup>. Thus, it is likely that phytoplankton were kept under greatest control by zooplankton at the Fundy region during August when more than one-half of the edible phytoplankton was grazed each day (56.9% d<sup>-1</sup>). The inverse relationship between grazing and chlorophyll *a* is apparent again in October, when chlorophyll *a* increases while grazing pressure declines (Fig. 12). Additionally, if phytoplankton are under the



control of high grazing, there should also be an increase in water clarity due to low algal biomass. This is illustrated in Fundy Secchi disk visibility, which also reached its greatest depth (5.1 m) during the high-grazing/low chlorophyll period of late August (Fig. 5).

*Predator:Panfish ratios* - As a measure of

intensity of feeding by zooplanktivorous fish (zooplankton-feeding fish), Predator:Panfish ratios were estimated using mean crustacean zooplankton body length according to Mills & Green (1987). While North and South generally fluctuated between predator:panfish ratios of 0.25 to 0.5, the ratio at Fundy reached remained below 0.2 (Fig. 13).

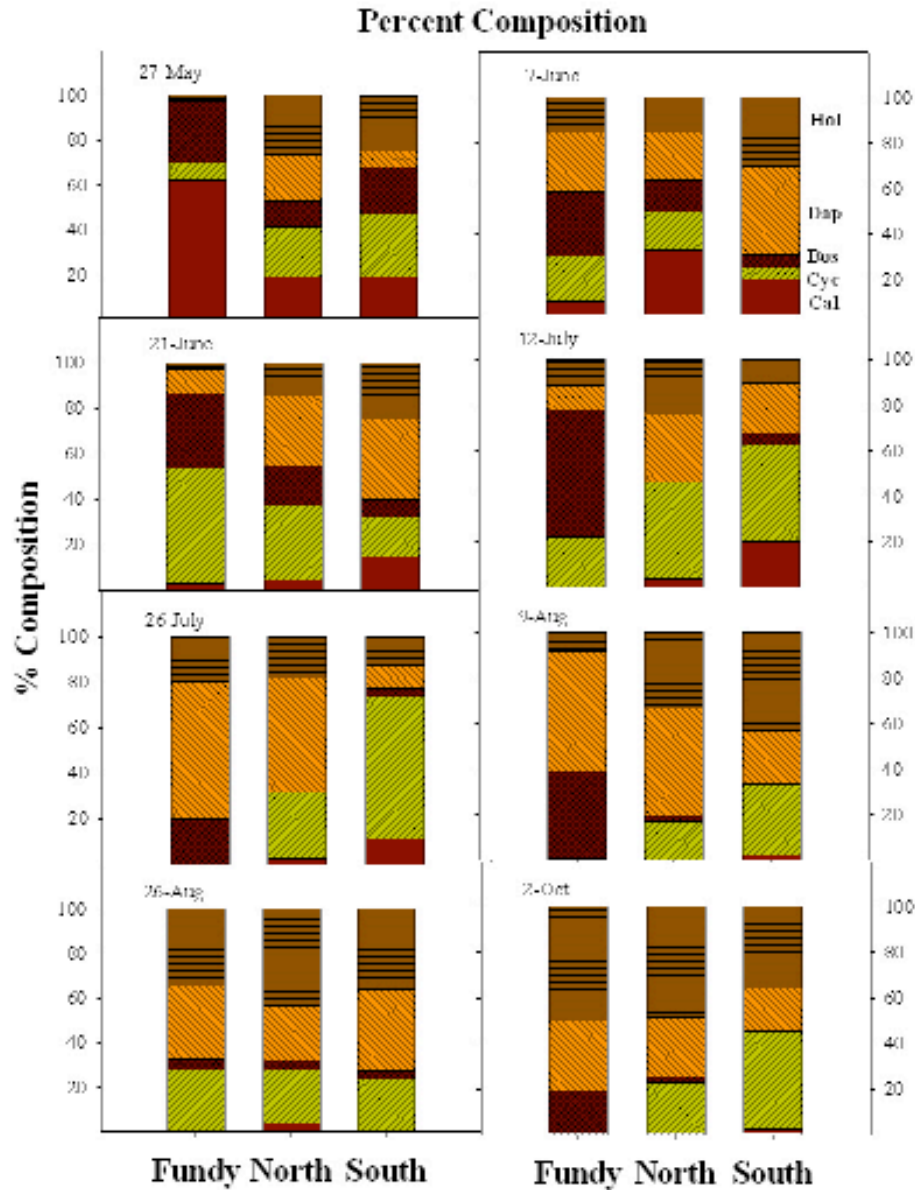


Fig. 7. Zooplankton species composition in Fundy, North and South stations in Pawtuckaway Lake, NH, 2005. Abbreviations used: CAL=calanoids, CYC=cyclopoids, DAP=Daphnia, HOL=Holopedium, BOS=Bosmina.

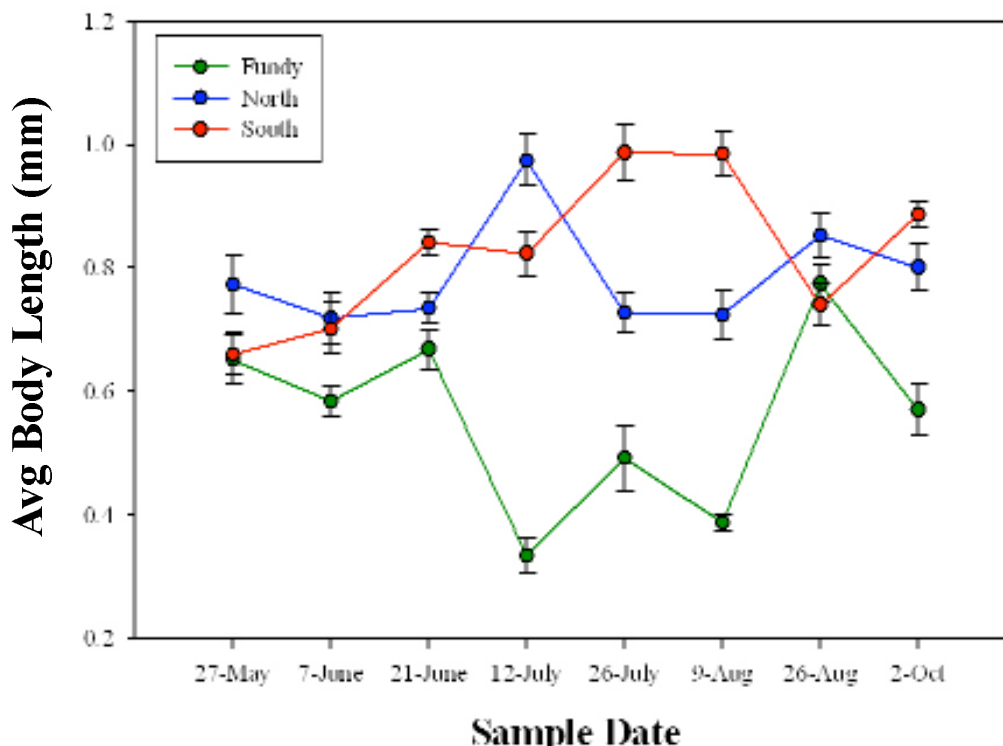


Fig. 8. Average zooplankton body lengths at Fundy, North, and South stations, Pawtuckaway Lake, NH, 2005.

**MC Concentrations** - Microcystins were detected in all samples of lake water. Whole lake water microcystin concentrations varied between the three sites (Fig. 14). Mean MC concentration for the lake (average for the three sites) was  $391.1 \text{ ng L}^{-1}$  ( $n=34$ ,  $SE=56.5$ ), and similarly, the median was  $390.6 \text{ ng L}^{-1}$ . The maximum concentration of MC occurred at the North site in mid July and was dramatically higher than the mean, reaching  $1204.0 \text{ ng MC L}^{-1}$ . In general, MC concentrations peaked in mid-summer at all three sites (Fig. 4).

Microcystin concentrations extracted from plankton were generally within the range of MC values for the plankton in other NH lakes (Fig. 15). The mean MC concentration in plankton was  $91.25 \text{ ng g}^{-1} \text{ dw}$  ( $n=40$ ,  $SE=108.1$ ) and the median  $44.12 \text{ ng g}^{-1} \text{ dw}$ . The highest plankton MC concentrations were at Fundy and South in early summer (both sites reached about  $130.0 \text{ ng g}^{-1} \text{ dw}$ , Fig. 15).

## Discussion

Physical, chemical, and biological parameters in the three lake sites clearly demonstrate that Pawtuckaway Lake consists of three distinctly different basins, i.e., North, South, and Fundy (Fig. 1). North, the deepest of the three sites, was strongly stratified and became anoxic below 6 m. Fish and zooplankton cannot survive in the absence of oxygen and would thus be unable to inhabit the anoxic hypolimnion of the North site. The absence of phytoplankton grazers can lead to an increase in algal growth and further the anoxic conditions. A deficiency in dissolved oxygen also creates ideal conditions for internal nutrient loading through the recycling of sediment nutrients into the water. The internal loading of nutrients such as phosphorus can, in turn, intensify eutrophication of the lake. The South site is shallower than the North and exhibited less severe anoxia, but had developed an oxygen deficit by late summer. The shallowest location sampled was Fundy, which differed most distinctly in all parameters and remained unstratified throughout the study.

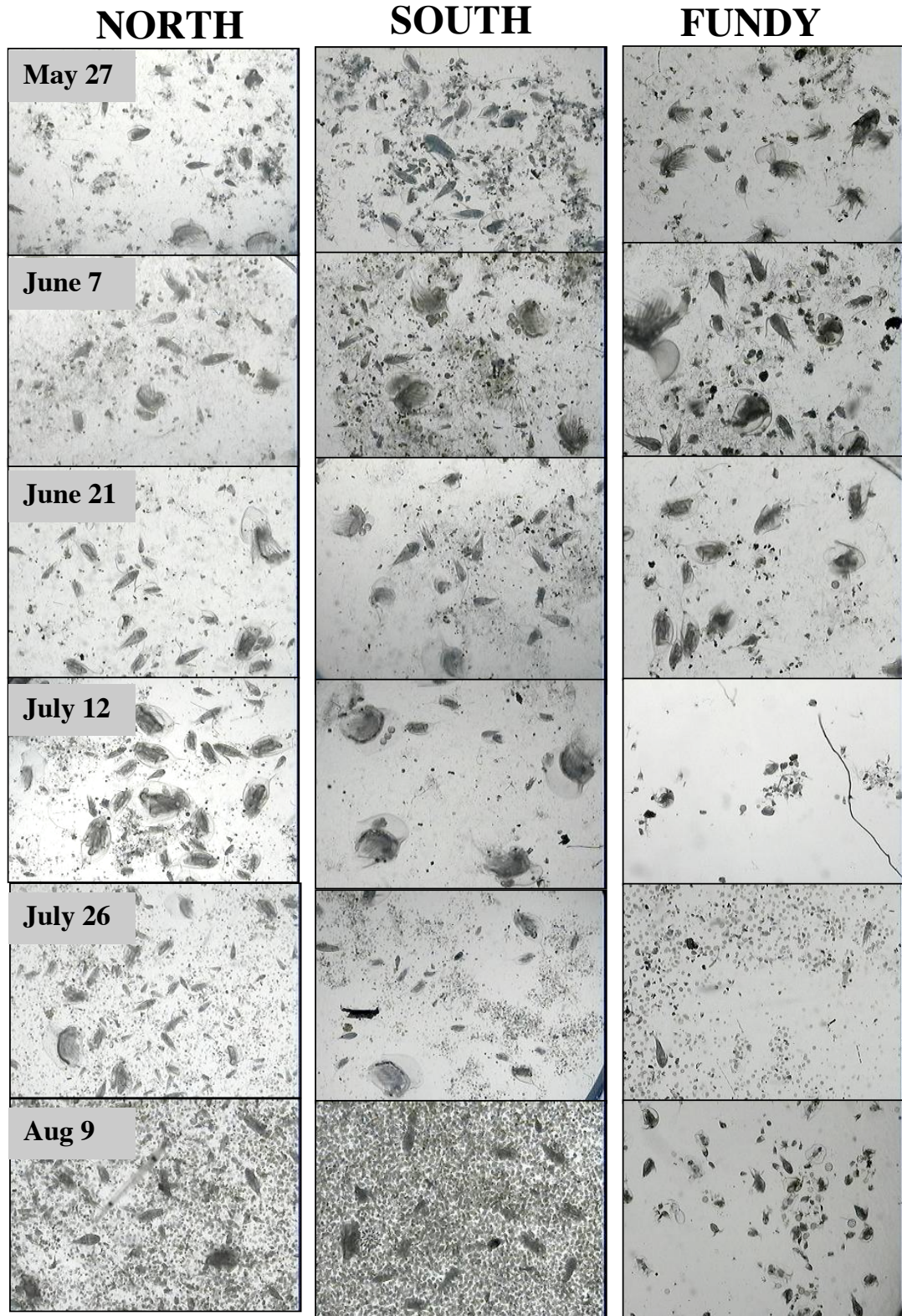


Fig. 9. Digital images showing changes in zooplankton composition for North, South, and Fundy sites, Pawtuckaway Lake, 2005.



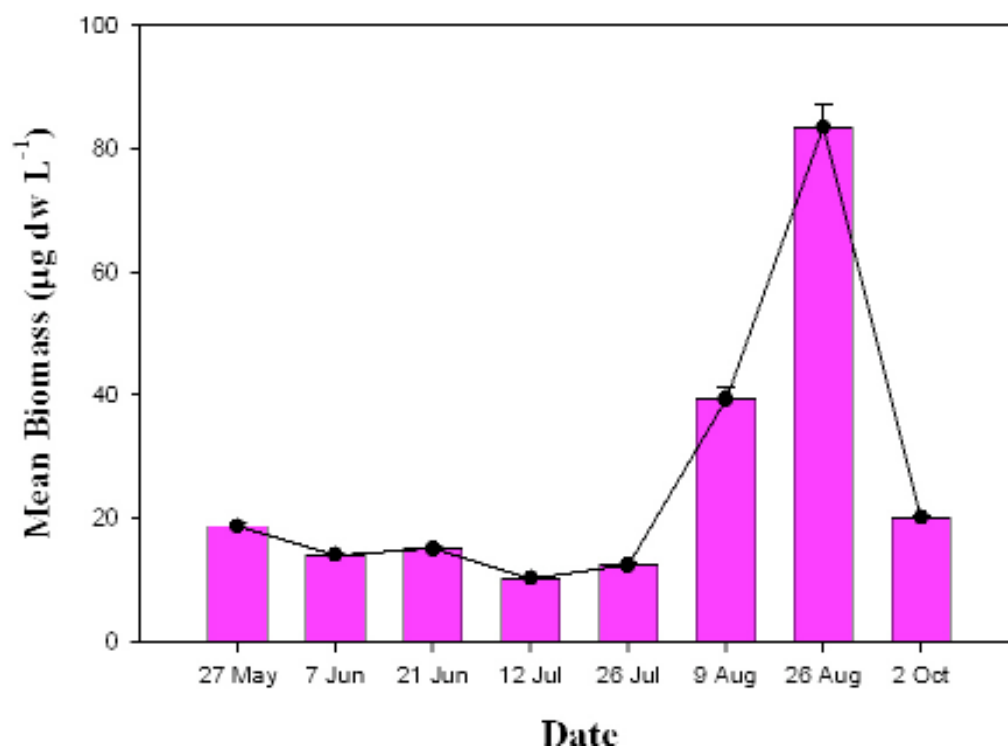


Fig. 10. Estimate of mean zooplankton biomass in Pawtuckaway Lake, NH, summer 2005.

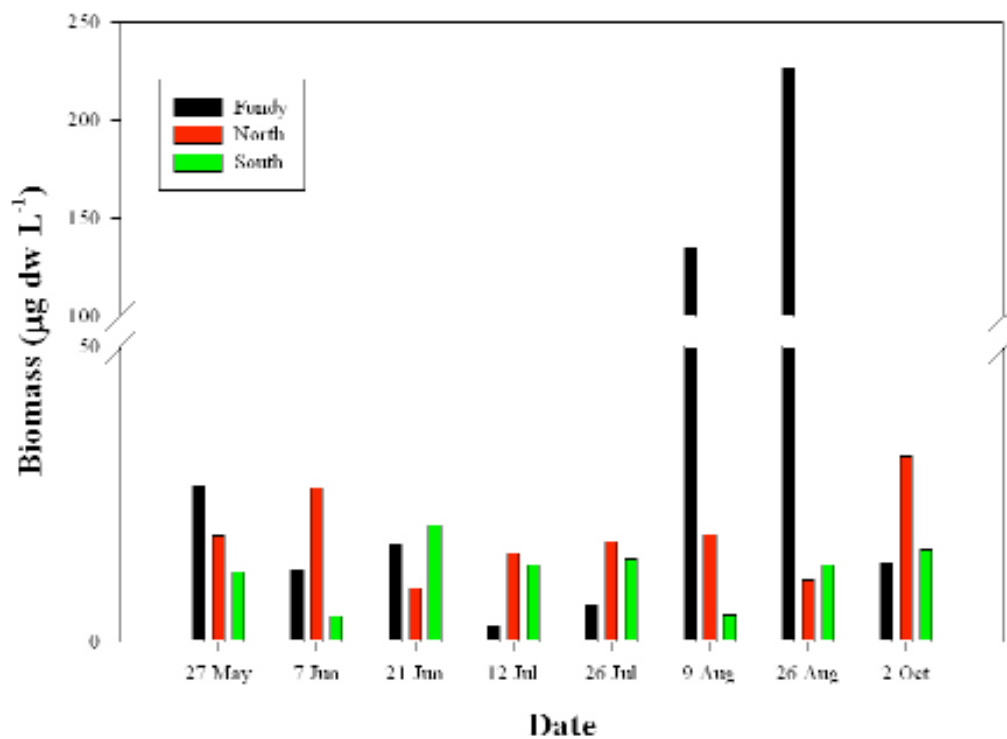


Fig. 11. Zooplankton biomass at Fundy, North, and South stations, Pawtuckaway Lake, summer 2005.

Nutrient regeneration may be particularly important here, as the shallow lake water is easily susceptible to sediment-water mixing. In addition, Fundy also exhibited the most severe food-web problems, consistently having the smallest zooplankton of all three locations and very low predator:panfish ratios. Originally, the design of this study included three sampling sites to provide lake replicate sampling and a statistical average for conditions in the lake. Future investigations as well as management plans should consider more thorough studies of each of the basins, with replicate sampling within each site, so that statistical comparisons could be made between the regions of the lake.

Estimated ratios of predator-to-panfish are used as an index of the ability of larger predatory fish to control the population of planktivorous fish, such as alewife (Mills and Green 1987). When predatory fish are relatively abundant (high predator:panfish ratio), they limit abundance of smaller zooplankton-feeding fish. In contrast, low predatory fish abundance (low predator:panfish ratio) allow

planktivorous fish to predominate, and feed intensely on zooplankton. As larger zooplankton provide more energy than smaller ones, visually feeding planktivores tend to selectively prey upon the largest zooplankton, allowing the smaller-sized zooplankton to become dominant. According to the Size-Efficiency Hypothesis, the body size of the zooplankton is strongly correlated with its efficiency at algal feeding (Brooks and Dodson 1965). That is, larger zooplankton are more effective grazers on planktonic algae and will typically dominate over smaller zooplankton as the large zooplankton are competitively superior. In mid-summer at Fundy, the small average body sizes (Figs. 8 & 9) incited very low predator-to-panfish ratios (Fig. 13). Fundy was dominated by small zooplankton that are less efficient grazers on phytoplankton, suggesting that algal abundance should be higher in this area during this period. The data support this prediction as chlorophyll levels were considerably higher at Fundy from late June to early August (Fig. 12). Thus, the predator:panfish ratio may also be useful as an index of

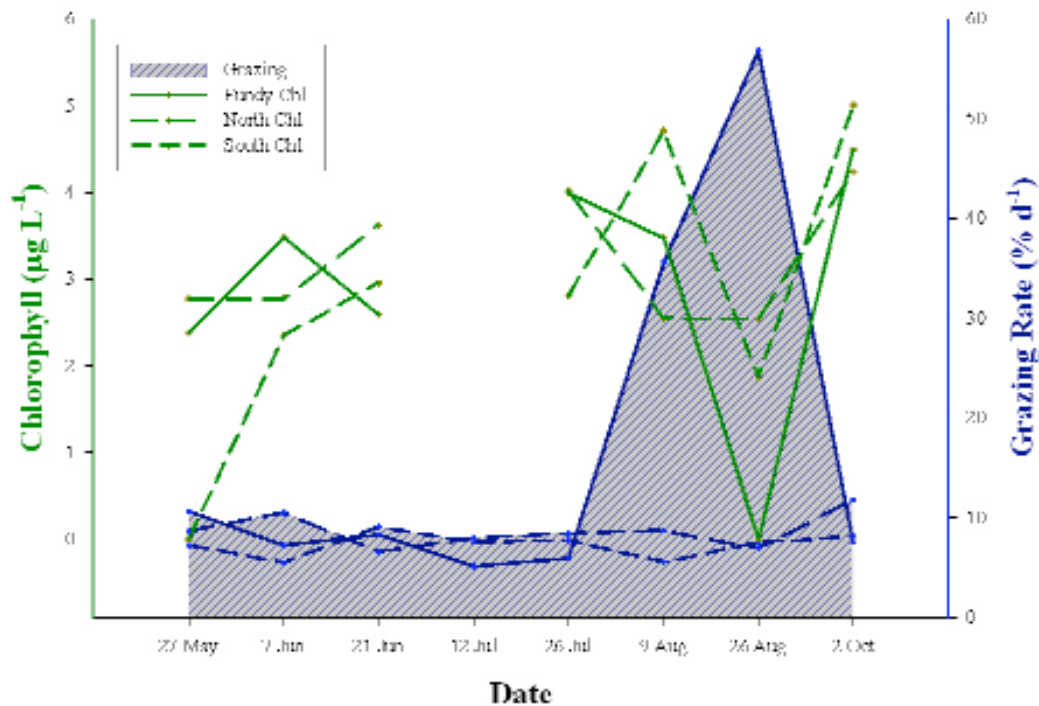


Fig. 12. Chlorophyll levels and estimated grazing rates at Fundy, North, and South stations, Pawtuckaway Lake, NH, summer 2005.

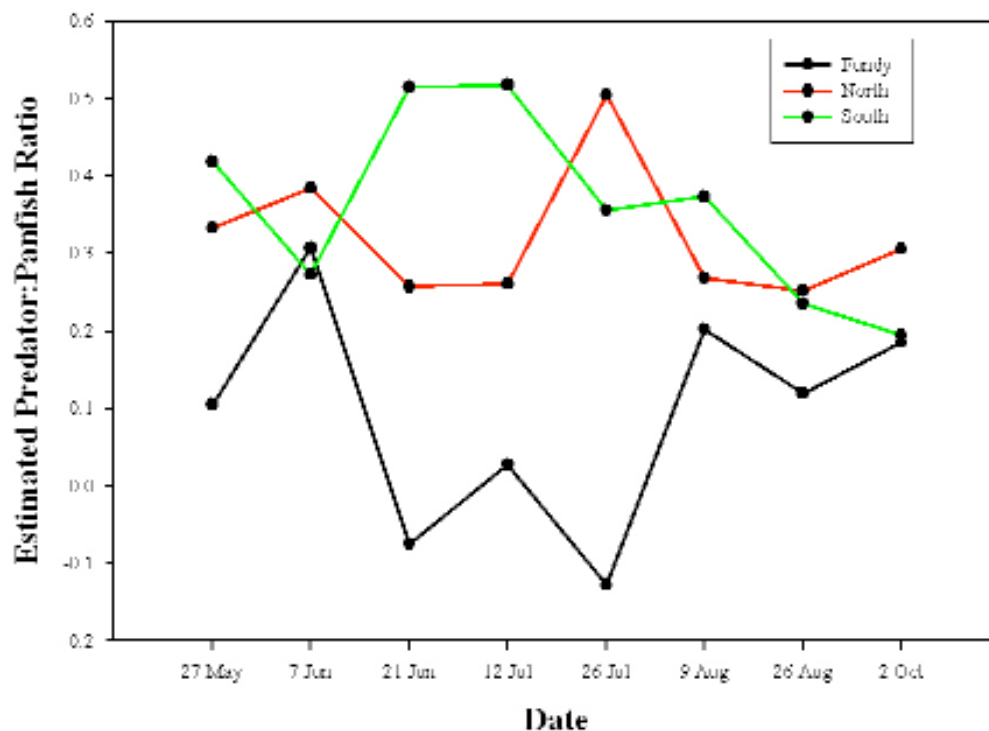


Fig. 13. Estimated Predator to Panfish ratio at Fundy, North, and South stations, Pawtuckaway, NH, summer 2005.

algal abundance.

In addition, greater water clarity during this late summer to early fall may also be linked to more effective grazing control by zooplankton. (Figs. 4 & 12). In early summer, grazing control was weaker and less effective, generally with less than 10 % of the phytoplankton being removed per day. Thus, low grazing control probably accounts for much of the higher chlorophyll seen throughout the early summer months (Fig. 12)..

Concentrations of whole lakewater microcystin (WLW MC) were maximum around mid July at each site (Fig. 10). North reached the highest MC level at 1204.0 ng L<sup>-1</sup>, exceeding the maximum limit for drinking water (1000 ng L<sup>-1</sup>) set by the World Health Organization . It is also interesting to note that all MC levels were all far above the median MC levels of all the lakes tested in the 30 New Hampshire lakes study (Fig. 4) (Sasner *et al.* 2002).

It is important to note that the plankton MC in

this study was extracted from all of the net plankton collected on a 50 mm mesh net and thus represents the microcystin concentration in the combined net phytoplankton and zooplankton. In an earlier survey of microcystins in 30 NH lakes, Sasner *et al.* (2001) measured MC in separated phytoplankton and zooplankton fractions. Comparing the two studies, planktonic MC concentrations in North and South exceeded the median MC concentration of zooplankton found in the 30 NH lakes study through most of the entire season (Fig. 15). At North site, all of the plankton concentrations were higher than the median zooplankton MC concentration (17.3 ng g<sup>-1</sup> dw) recorded by the 30 NH lakes study (Fig. 15), and at South they were higher on all but one sampling date (exception date on July 26, MC=11.16 ng g<sup>-1</sup> dw). Additionally, the peak levels reached in early summer by South and Fundy (both sites reached ~130.0 ng g<sup>-1</sup> dw) far exceeded the median phytoplankton MC concentration (88.2 ng L<sup>-1</sup>) recorded



by the 30 NH lakes study (Fig. 15). These results indicate the highly toxigenic nature of the phytoplankton in Pawtuckaway Lake in comparison to other NH waters.

The two dominant cyanobacteria were *Anabaena* sp. and *Microcystis aeruginosa*. Although *Oscillatoria* (aka. *Planktothrix*) was also present, it was always at low densities and probably was a minor contributor to the MC levels found. However, the low abundance of *Oscillatoria* in this study was somewhat surprising as it has been reported to form noticeable blooms here in previous years (NH DES and Haney, pers. comm.). Thus, it is likely that *Anabaena* and *Microcystis* were dominant cyanobacteria responsible for the hepatotoxins levels present in Pawtuckaway Lake during the summer, 2005.

This study was initiated in part to investigate whether the stocking of alewife in Lake Pawtuckaway might contribute to problems in water quality. The results presented indicate the lake is highly susceptible to problems associated

with excessive nutrients and phytoplankton growth, because of its overall shallow depth and its anoxic deep basins. Pawtuckaway Lake had periods in the summer with a relatively high abundance of cyanobacteria and cyanotoxins. There is, however, no direct evidence that these problems were caused or exacerbated by the presence of alewife, since the abundance of fish was not a part of this investigation. It is noteworthy, however, that the zooplankton community at the shallow station exhibit small body lengths characteristic of over exploitation by planktivorous fish. The exceptionally small crustacean zooplankton body lengths of 0.35 mm in Fundy in July are approximately the same as body lengths of 0.33 and 0.32 mm, respectively reported for Crystal Lake, Connecticut (Brooks and Dodson 1965), and Milton Three Ponds, New Hampshire (Bradt and Chungu 1999), respectively, lakes with landlocked alewife populations. However, high levels of feeding on the zooplankton can also be caused by an overabundance of young-of-year fish or stunt-

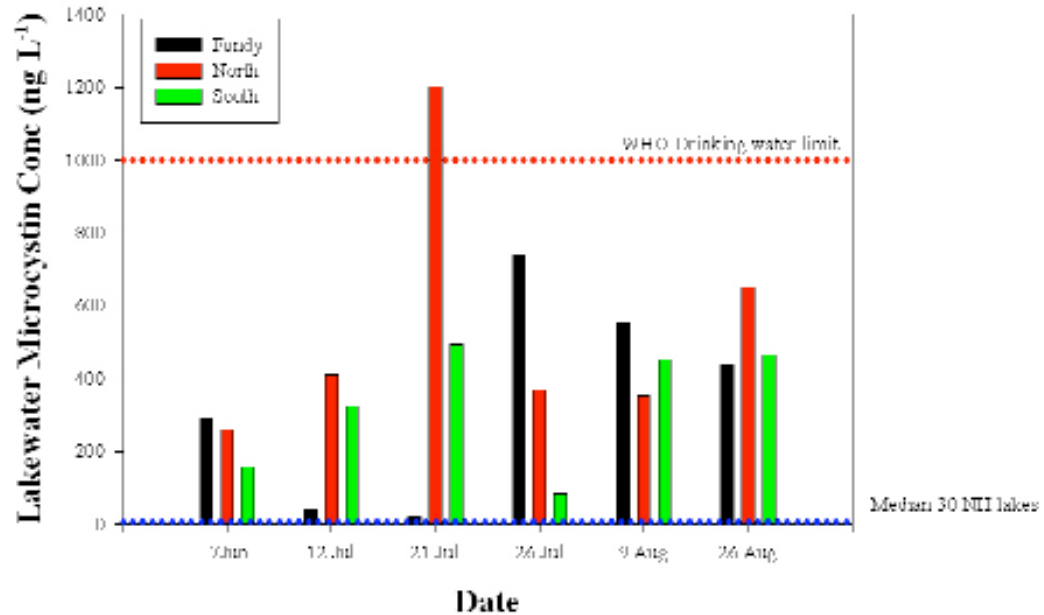


Fig. 14. Microcystin concentrations in lake water at North, South, and Fundy sites, Pawtuckaway Lake, summer 2005. Shown for reference are World Health Organization limit for safe drinking water and median WLW MC concentration calculated by a study of 30 NH lakes in 1999-2000.

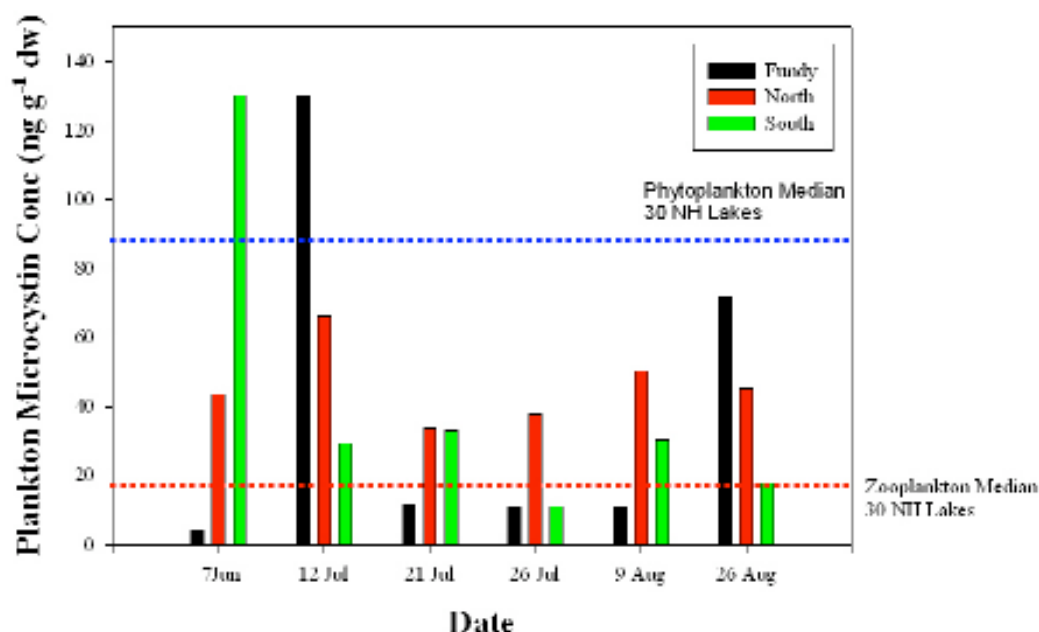


Fig. 15. Microcystin concentrations in the net plankton (zooplankton and phytoplankton) at North, South, and Fundy sites, Pawtuckaway Lake, summer 2005. Shown for reference are phytoplankton and zooplankton medians calculated from a study of 30 NH lakes.

ed populations of fish species in the lake other than alewife or a combination of alewife and other species. In any case, a severe “bottleneck” in the phytoplankton-zooplankton coupling of the food web was observed only at the shallow Fundy location and not at the two deeper sites, suggesting fish populations in these sections of the lake are more in balance with the plankton base.

Since it was reported that relatively few adult alewife were introduced into the lake in the spring of 2005 (T. Thompson, pers. comm.), it might be assumed that the 2005 summer season represents the conditions with low abundance of adult and young-of-year alewife. The addition of greater numbers of adult alewife might be expected to exacerbate the water quality problems in the lake, but the extent of this effect would depend on other factors, such as the rainfall, temperature and the amount of sunlight, which can vary from year to year.

*Summary* - Three sites (South, North and Fundy) were sampled in Lake Pawtuckaway in

order to evaluate the overall condition of the lake as well as determine whether there were differences in water quality issues at the three regions of the lake.

Pawtuckaway Lake is sensitive to nutrient perturbations, such as an increase in runoff because of its extensive shallow areas, overall small mean depth and summer oxygen deficiencies at the two deep sites (South and North). The impact of additions of nutrients, especially phosphorus and nitrogen, are amplified through their recycling from the lake sediments. During this study, a surface bloom of toxic cyanobacteria (*Anabaena circinalis*) appeared at the Fundy site in late May, indicating that problems of Cyanobacteria blooms are transient and not limited to the summer and fall. Other toxigenic species of cyanobacteria including *Microcystis aeruginosa* and *Oscillatoria* were also abundant at times in the plankton. It is noteworthy that toxic cyanobacteria were detected at all three sites, with levels of the liver toxin, microcystin, exceeding drinking water standards recommended by the World Health Organization

at the North site on July 21. Throughout the summer, microcystin levels in the lake were well above the average found in a survey of cyanobacteria toxins in NH lakes.

The small body size of the zooplankton, especially at the Fundy site in July, suggests that there is an overabundance of small, planktivorous fish in the lake. The heavy predation of these fish on the zooplankton that feed on the algae and cyanobacteria can cause a “bottleneck” in the flow of energy through the lake food web and this, in turn, can result in a build up of undesirable phytoplankton, causing potentially harmful blooms of toxic cyanobacteria.

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