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An assessment of the physical, chemical, and biological properties of Christine Lake, NH

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Abstract

As part of a comparative assessment of seven New Hampshire lakes, performed throughout the month of September 2003, students and faculty from the University of New Hampshire's Center for Freshwater Biology sampled Christine Lake in Stark, NH. The goal of the study was to quantify the lake's physical, chemical, and biological properties and compare it to the six other lakes studied, as well as to results from identical sampling of Christine Lake in June, 2003.

Christine Lake is an oligotrophic lake with very little primary production and low densities of zooplankton. Nutrient levels were low, likely due to the forested composition of the lake's watershed and the small number of homes on the lake's shore. The low phosphorus concentration and high N:P ratio (TN:TP = 50) typify a phosphorus-limited system which is likely to be the cause of the minimal algal abundance (1.6 ± 0.1 µg L^{-1} average epilimnetic chlorophyll compared to 39.4 ± 1.0 µg L^{-1} in eutrophic York Pond). Predation by young Brook and Brown Trout most likely favored the increased densities of the smaller zooplankter *Bosmina* (average body length: 0.42 mm ± 0.01), as they are not readily visible to the trout like the larger *Daphnia* (average body length: 1.39 mm ± 0.03). Evidence for increased predation on *Daphnia* can be seen in their location in the water column (8 m and 12 m) which indicates migration to deeper waters to avoid fish predation. The depressed density and size of the zooplankton in the lake are most likely due to a lack of suitable grazing material and predation from the planktivorous fish population. Interactions between zooplankton and higher trophic levels, as well as phytoplankton, are discussed in the context of a model food web.

Introduction

Freshwater lakes serve a wide variety of purposes, making them a precious resource. Lakes provide water for industrial purposes such as cooling, as well as irrigation for agriculture. In addition, humans, indeed all life on Earth, need potable water to maintain life and freshwater lakes are often used to provide this necessity.

Lakes also provide many communities with revenue-generating tourism. Lakes have many additional uses including boating, swimming, recreational diving, fishing, ice fishing, and ice skating to name a few. Often associated with these recreational lakes are restaurants, lodging, and retail sales. If these lakes are not clean and

aesthetically pleasing, the market for these activities, and their associated businesses, may be lost.

Eutrophication is a slow, natural process that involves an increase in nutrients, primary production, and algal biomass (Lampert and Sommer 1997). Anthropogenic nutrient loading from various sources, such as fertilizers and detergents, have caused many lakes to become eutrophic at an accelerated rate. The result is a lake with a host of problems such as oxygen depletion and biotoxins that are not found in oligotrophic lakes. Examination of trophic interactions may further clarify the causes of eutrophication.

Two predominant theories concerning trophic interactions include: the top-down and bottom-up models of control. The top-down model states that community composition and dynamics are controlled from the highest trophic level (Carpenter *et al.* 1985). For example, an abundance of planktivorous fish would depress the zooplankton population, which, in turn, would allow an increase in phytoplankton abundance due to the lack of zooplankton grazing. Conversely, the bottom-up model states that phytoplankton community composition and

dynamics are most affected by nutrient levels (Schindler 1978). Increased levels of phosphorus and nitrogen facilitate an increase in phytoplankton, which further supports a larger zooplankton population. Increased abundance of zooplankton would sustain a larger population of planktivorous fish. Both models could be applied to the problem of eutrophication, as the two are not mutually exclusive. In both scenarios, zooplankton play a vital role; they can control the abundance and composition of phytoplankton and act as primary consumers, transferring energy to higher trophic levels.

Zooplankton, the community of animal organisms suspended in the water, are composed primarily of Rotifera and Crustacea. Crustacean zooplankton are mostly dominated by the Copepoda and Cladocera (Wetzel 1983).

Rotifers are predominantly freshwater organisms. Approximately 100 species (25 % of all known rotifers) are planktonic. Due to their small size, they are not a significant source of food for planktivorous fish (Wetzel 1983). Rotifers are primarily grazers with only a few carnivorous species.

Copepods range in size and can be divided into three groups based on morphology. Calanoida are mostly planktonic and herbivorous grazers. Cyclopoida, however, are carnivorous, eating rotifers and small crustaceans (Lampert and Sommer 1997). The third group, Harpacticoida, is almost exclusively littoral and not a significant element of the pelagic zooplankton community (Wetzel 1983).

Cladocerans generally range in size from 0.2 to 3.0 mm. They are an important element in the aquatic food chain as they graze on phytoplankton and bacteria, transferring energy and nutrients to higher trophic levels. Cladocerans are equipped with two large antennae used for swimming, thereby regulating their position in the water column to avoid predation and maximize growth and reproduction (Wetzel 1983).

In this comparative study, the zooplankton community of Christine Lake, in northern NH, will be compared to six other lakes throughout the state. Zooplankton community composition, densities, body lengths, and position in the water column were examined in order to elucidate relationships between the zooplankton community and the lake's other trophic levels. Interactions between phytoplankton, zooplankton, and planktivorous fish are used to construct a model food web illustrating which zooplankton regulate the phytoplankton community and how they, in turn, are regulated by higher trophic levels in Christine Lake.

Methods

Study Sites- Christine Lake was examined as part of a seven-lake study completed during the fall of 2003 by students in the University of New Hampshire's Field Limnology class. Located at 44° 37.80' N latitude, 71° 24.19' W longitude and 361 m above sea level in the town of Stark, NH, Christine Lake is a relatively remote and pristine lake (Fig. 1). The lake's average depth is 6.9 m and the maximum depth is 19.5 m (Table 1). Surrounded mostly by mountainous forest, there is little residential impact. The few existing homes are located on the western shore and a public boat launch is located at the beach on the eastern shore. The locations and morphometric descriptions of the other six lakes studied are outlined in Table 1.

Field Methods- Many parameters were measured, using a variety of equipment and methods. An integrated tube (IT) sampler, consisting of a 10 m polyethylene tube with a weighted end, was lowered to the bottom of the epilimnion. Triplicate samples were used for measurements of fluorometry, total phosphorus, total nitrogen, total chlorophyll, and total dissolved color. Acid neutralizing capacity (ANC) was determined according to Lind (1985) with 0.002N H_2SO_4 titrant. Water was also collected from up to eight discrete depths with a Haney Chamber (Aquatic Research Instruments, Inc.; 5.27 L sample volume). A multiparameter sonde (YSI model 6600M) connected to a data logger (YSI model 650) was used to measure temperature, dissolved oxygen, pH, chlorophyll *a*, Oxidation-Reduction Potential (ORP), turbidity, specific conductivity and fluorescence. The sensors for the multiparameter probe were calibrated at the lake and lowered to the bottom at a rate of approximately 0.5 m min^{-1}. Data were logged every 3 s or at approximately 2.5 cm intervals. Light was measured with an underwater quantum sensor (Licor LI-1400) at 0.5 m intervals 9 m and corrected against

Fig. 1: Topographic map depicting Christine Lake and its watershed. Sampling site is indicated by the X.

Table 1: Descriptive data for the seven lakes sampled by the Center for Freshwater Biology, University of New Hampshire.

Lake	Abbr.	Town	River	Sampling Site (Lat./Long.)	Date Sampled (2003)	Elevation (m)	HRT (yr)	Lake Area (Ha)	Lake Volume (Ha-m)	Mean Depth (m)	Max. Depth (m)	Area of Wtrshd (Ha)
Barbadoes Pond	BP	Madbury	Coast	43° 11.25'N/70° 56.16'W	Sept. 9	40.2	0.5	5.8	34.9	6.1	14.6	38.8
Cedar Pond	CP	Milan	Connecticut	44° 35.73'N/71° 16.21'W	Sept. 26	349.6	0.4	31.5	261.5	8.3	17.7	1243.2
Christine Lake	CL	Stark	Connecticut	44° 38.80'N/71° 24.19'W	Sept. 26	360.9	0.8	68.8	474.7	6.9	19.5	1165.5
York Pond	YP	Milan	Connecticut	44° 30.48'N/71° 20.26'W	Sept. 25	451.1	2.5	8.5	23.5	2.8	5.2	90.4
Townhouse Pond	TP	Milton	Coast	43° 26.05'N/70° 58.87'W	Sept. 18	126.5	0.0	48.0	158.4	3.3	10.1	760.1
Lower Sawyer Pond	LS	Livermore	Saco	44° 03.04'N/71° 22.07'W	Sept. 11	621.8	1.0	19.0	231.4	12.2	29.6	310.8
Upper Sawyer Pond	US	Livermore	Saco	44° 03.02' N/71° 22.80'W	Sept. 11	621.8	N/A	2.5	12.5	5.0	10.0	23.6

simultaneous light measurements at the surface. Secchi disk (20 cm diameter) depth was measured using a viewscope to eliminate surface reflection.

In addition to the physical and chemical characteristics, many biological parameters were measured. Water from each of the IT sampler replicates was size fractionated in the field, using a portable vacuum pump and filtration apparatus, into samples of whole lake water (WLW), <50 μm (50 μm mesh), <2 μm, and <0.2 μm (47 mm Millipore isopore membrane filters). The three size fractions correspond to netplankton (>50 μm), nanoplankton (2 μm – 50 μm), and picoplankton (0.2 μm – 2 μm), with the WLW fraction serving as a composite of all three. Discrete water samples from the Haney Chamber were divided into WLW, <50 μm, and <2 μm size fractions. Fractionated discrete samples, along with the fractionated IT samples, were analyzed in the field with a fluorometer (Turner model 10-AU) with an excitation wavelength of 340-550 nm and an absorption wavelength of 680 nm for chlorophyll *a* to estimate the relative abundance phytoplankton in each size fraction, assuming constant fluorescence per unit of biomass. Water collected from the IT samples was also filtered through a 0.45 μm filter (47 mm Millipore HAWP), frozen, and saved to measure dissolved color, phosphorus and nitrogen. Filters were immediately placed in a dark desiccating box and saved for analysis of extracted chlorophyll *a*.

Plankton was collected via three vertical tows as well as with the Haney Chamber. Vertical tows were made with an 80 μm mesh plankton net from 1 m above the bottom to the surface. Plankton samples collected at each of the discrete depths (0.5, 2, 4, 6, 8, 10, and 12 m) were collected onto a 50 μm mesh. Each plankton sample was preserved with 4 % sucrose formalin.

Laboratory Methods- 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, nitrogen, and dissolved color. Samples frozen lakeside for nitrogen analysis were thawed, preserved with 1 ml of 36N H_2SO_4 per 250 ml of lake water, and frozen again. Spectrophotometry for chlorophyll, phosphorus, and color determination was accomplished using a Milton Roy Spectronic 1001+ spectrophotometer. Chlorophyll was measured according to Lind (1985), substituting an absorption coefficient of 11.9 in place of the 28.9 value as outlined, and Vollenweider (1969) using a 5 cm path length optical glass cuvette, with absorption measured at 663 nm. Average phosphorus was determined according to AHPA (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) using a 5 cm path length quartz cuvette. Nitrogen was calculated through differential spectroscopy according to Bauchmann and Canfield (1996) and Crumpton *et al.* (1992). 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.

Phytoplankton and zooplankton abundance were determined from samples preserved in the field and

allowed to settle. Phytoplankton genera abundance was calculated as a percentage of the total, counting at least 50 individuals in the discrete samples and 100 individuals in the vertical tows using a light microscope and a plain glass microscope slide. Crustacean zooplankton densities (ind. L^{-1}) were calculated in both the vertical tows and the discrete samples. Large numbers of zooplankton in the vertical tow samples necessitated sub-sampling with a Henson-Stemple pipette. Final densities were estimated by relating the sub-sample volume to the total volume of water sampled. Based on previous calibrations, a sampling efficiency of 70 % was assumed in determining the amount of water sampled by the plankton net. Zooplankton were much less prevalent in the discrete samples, necessitating the counting of the entire sample. Zooplankton body lengths were measured using digital analysis (MetaMorph Version 4.01), counting 30 or more individuals in each vertical tow sample.

Post-measurement Processing- *In situ* chlorophyll *a* was corrected based on extracted chlorophyll with the following equation: (Measured Chlorophyll *a* ($\mu g\ L^{-1}$)) * 0.8192 + 0.4587. It was further corrected against epilimnetic averages of extracted chlorophyll obtained from the integrated tube sample. ORP was corrected for a pH of 7 (denoted as E_7 in tables and figures) with the following equation: (7-measured pH) * (-58) + measured ORP (mV). In addition, data points logged when the multiparameter probe had entered the sediments were not used as they are not representative of the entire water column.

Statistical Analysis- Statistical analysis was performed using simple and multiple least squares regression analysis (SigmaPlot 2000) as well as ANOVA using the Systat (Version 7) statistical software package, assuming significance of $p < 0.05$. All average values reported are accompanied by estimates of standard error.

Results

Vertical Profiles- Christine Lake was thermally stratified during the sampling period, with the metalimnion beginning at approximately 8.7 m
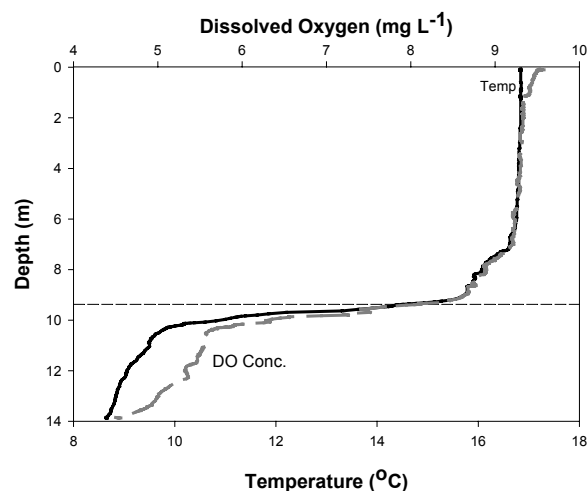

Fig. 2: Vertical profiles of temperature and dissolved oxygen for Lake Christine on September 26, 2003. Thermocline is represented by dashed line.

and extending to approximately 10.3 m. In addition, there was a temporary metalimnion forming at 6.2 m. The thermocline began at a depth of approximately 9.4 m (Fig. 2). Oxygen declined with depth, decreasing sharply at the thermocline, but was still present at the deepest depth sampled with values recorded at 4.5 mg L^{-1} (Fig. 2). Chlorophyll *a* values fluctuated around 2 $\mu g\ L^{-1}$ (epilimnetic average: 1.95 $\mu g\ L^{-1} \pm 0.01$; Table 2) with an increase to about 9 $\mu g\ L^{-1}$ at the surface of the sediment (Fig. 3). The pH was 7.4 at the surface and decreased to approximately 5.9 at the sediment interface, with a slight increase at the thermocline. This slight increase was mirrored by the measurements of ORP (Fig. 3). In general, ORP decreased substantially near the surface from 170.0 to 160.0 mV and then increased until the thermocline. From there, ORP decreased greatly through the metalimnion and then increased slightly to 173 mV at the bottom, never

Table 2: Average multiparameter values (±1 SE) for Christine Lake on September 26, 2003.

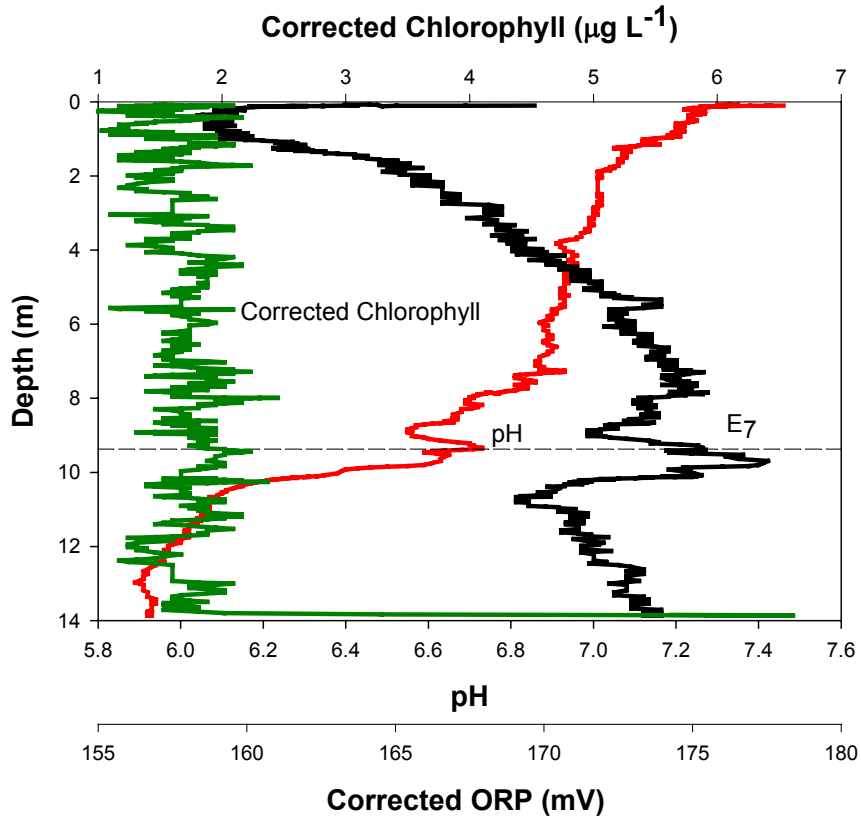| Parameter	Epilimnion	Metalimnion	Hypolimnion
Temperature (^{o}C)	16.61 (0.01)	11.05 (0.22)	9.09 (0.03)
Specific Cond. ($\mu S\ cm^{-1}$)	25.00 (0.00)	26.00 (0.00)	26.04 (0.02)
DO %	94.53 (0.15)	58.44 (1.35)	45.40 (0.31)
DO (mg L^{-1})	9.21 (0.01)	6.40 (0.11)	5.24 (0.03)
E_7 (mV)	168.38 (0.25)	173.06 (0.31)	171.76 (0.13)
Turbidity (NTU)	0.15 (0.02)	0.90 (0.03)	1.15 (0.31)
Corr. Chlorophyll ($\mu g\ L^{-1}$)	1.95 (0.01)	2.10 (0.03)	2.24 (0.12)

Corrected Chlorophyll (μg L^{-1})

Fig. 3: Vertical profiles of corrected chlorophyll, pH, and corrected ORP for Christine Lake on September 26, 2003. Thermocline is represented by the dashed line.

dropping below 158 mV throughout the entire water column. The increases in pH and ORP at the thermocline likely indicates a photosynthesis maximum.

There was little variation in the specific conductivity with consistent readings of 25.0 μS cm^{-1} throughout the epilimnion and 26.0 μS cm^{-1} in the meta- and hypolimnion. At the bottom of the lake, specific conductivity increased from 26.0 to 27.0 μS cm^{-1} (Fig. 4). Turbidity also remained relatively constant, fluctuating around 0.5 NTU with a sharp increase to 2.2 NTU at approximately 4 m (Fig. 4).

Light attenuation was relatively weak with an average K_{ext} coefficient of 0.45 (± 0.02; Fig 5). This was consistent with the secchi disk values (7.35 m ± 0.0; Table 3). Dissolved color for Christine Lake was 16.23 CPU (± 0.27; Table 3). The photosynthetic compensation depth, calculated as 1 % average surface light, was 10.23 m.

Christine Lake had an acid-neutralizing capacity (ANC) of 2.23 mg CaCO$_3$ ml^{-1} (± 0.10; Table 3), indicating a weak buffering ability. Average values of nitrogen and phosphorus were 203 μg L^{-1} (±
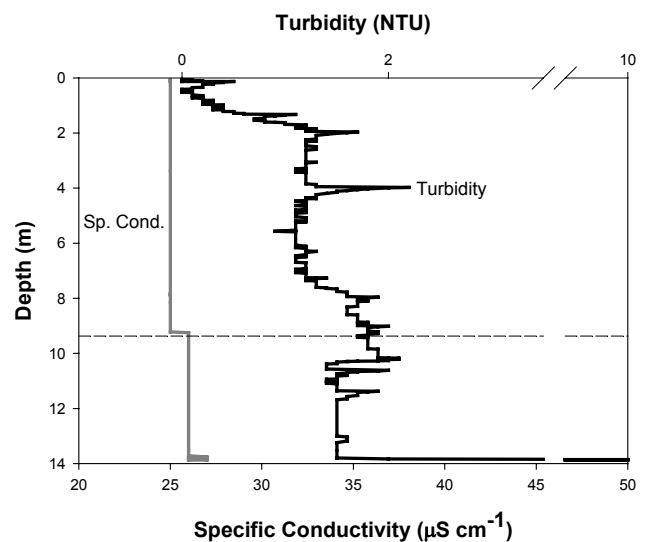

Fig. 4: Vertical profiles of turbidity and specific conductivity for Christine Lake on September 26, 2003. Thermocline is represented by the dashed line.

Table 3: Average epilimnetic values (±1 SE) for Christine Lake on September 26, 2003.

Parameter	Average Value
SDD (m)	7.35 (0.0)
ANC (mg CaCO^3 ml^{-1})	2.23 (0.10)
Dissolved Color (CPU)	16.23 (0.27)
Nitrogen (μg L^{-1})	203.00 (11.02)
Phosphorus (μg L^{-1})	4.07 (0.09)

11.02; Table 3) and 4.07 μg L^{-1} (± 0.09; Table 3) respectively, giving Christine Lake a mass TN:TP ratio of 50:1 and a molar ratio of 111:1.

Phytoplankton- Dinobryon, of the class Chrysophyceae, dominated the community of netplankton with a relative abundance of 70.51 % (Fig. 6). Other genera of phytoplankton found include: *Cryptomonas* (class: Cryptophyceae), *Gymnodinium* (class: Dinophyceae), *Melosira* (class: Bacillariophyceae), and *Aphanocapsa*, a member of the class Cyanophyceae.

Discrete samples revealed similar phytoplankton compositions (Fig. 7). *Dinobryon* dominated at all depths except 13 m, where dominance switched to *Melosira*. In addition, there was a large percentage of *Gleocapsa* (class: Cyanophyceae) found only at 4 m.

Size fraction analysis based on fluorometry revealed a dominance of picoplankton (70.4 %), followed by nanoplankton
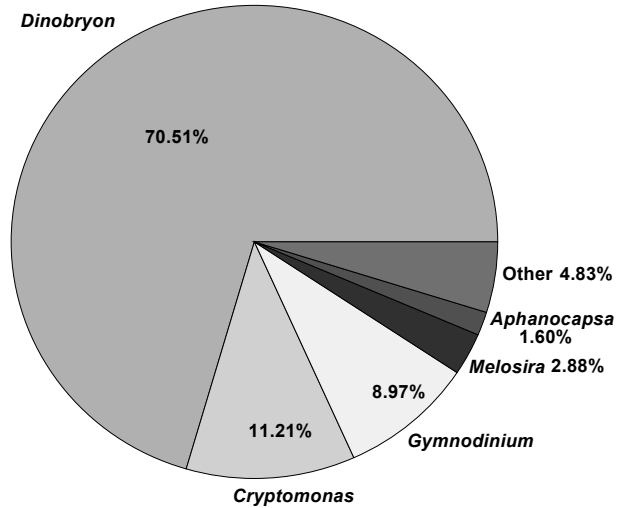

Fig. 6: Relative abundance of netphytoplankton genera in Christine Lake on September 26, 2003.

(22.2 %). Netplankton had the smallest relative abundance at 7.4 % (Fig. 8).

Examination of samples taken at discrete depths had similar results. Picoplankton was the dominant size fraction at all depths with an average relative abundance of 76.3 % (± 0.73). Nanoplankton was the next most abundant size fraction and was also found at all depths sampled. Netplankton, however, was not detected at 4, 6, 8, or 10 m. It was found in small percentages at 0.5 and 2 m, and in slightly larger percentages at 12 and 13 m (Fig. 9).

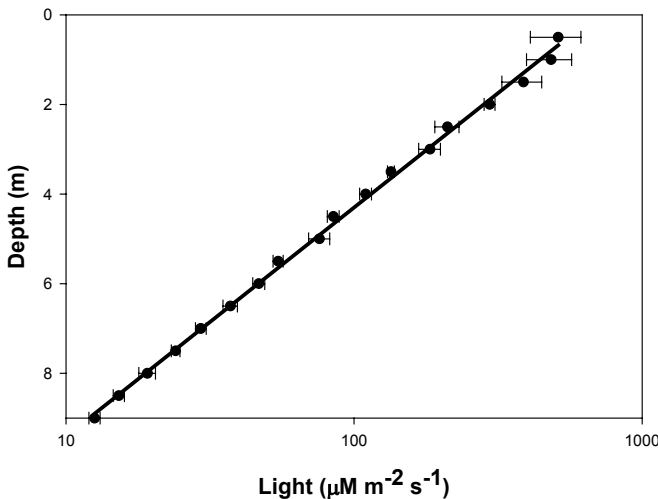*Zooplankton-* Vertical tows with the plankton net

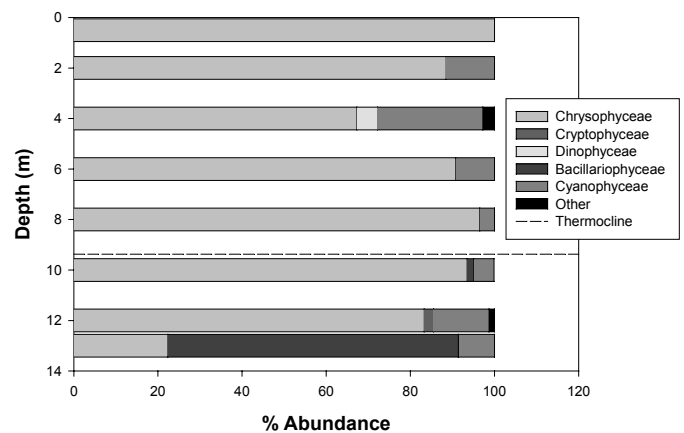Fig. 5: Light profile for Christine Lake on September 26, 2003.

Fig. 7: Relative abundance of phytoplankton genera at discrete depths in Christine Lake on September 26, 2003. Thermocline is represented by the dashed line.
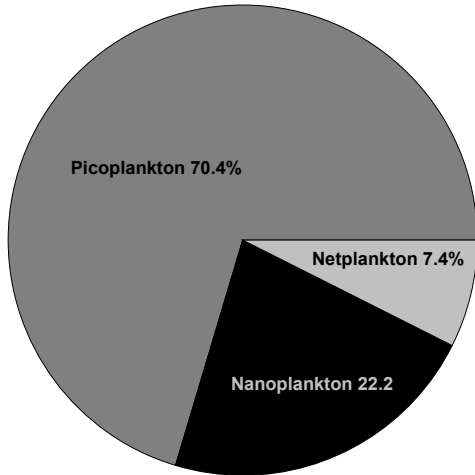
Fig. 8: Relative abundance, based on size fraction fluorescence, of the three phytoplankton size fractions in Christine Lake on September 26, 2003 bases on integrated epilimnetic samples.

revealed a dominance of *Bosmina* with an average density of 2.63 ind. L^{-1} ($\pm$ 0.06; Fig. 10) and an average body length of 0.42 mm ($\pm$ 0.01; Fig. 11). Other genera identified include the Cladocera *Daphnia* and *Holopedium* and calanoid and cyclopoid copepods. *D. dubia*, the only *Daphnia* species found in Christine Lake. This was a large-bodied species with an average body length of 1.39 mm ($\pm$ 0.03; Fig 11). The average body
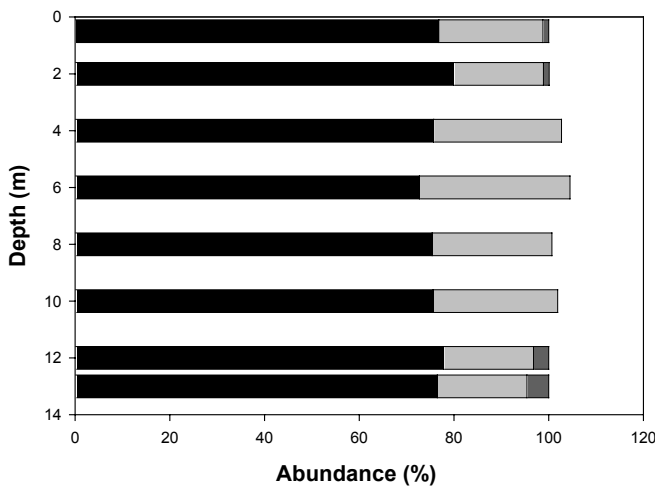

Fig. 9: Percent composition of the picoplankton (black), nanoplankton (light gray) and net plankton (dark gray) in Christine Lake on September 26, 2003 at discrete depths, based on size fraction fluorescence.
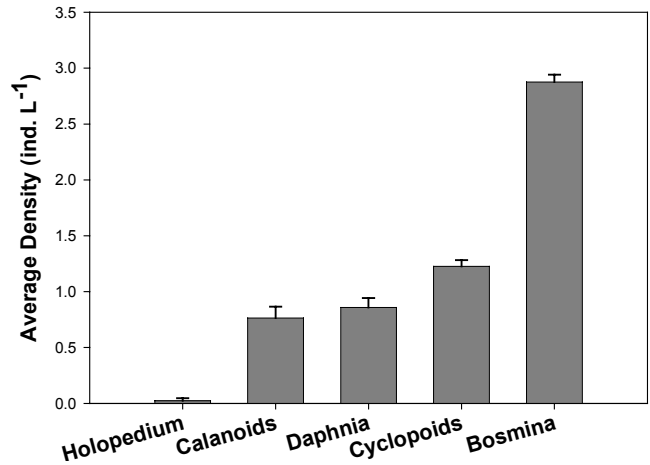

Fig. 10: Average density (± 1 SE) of zooplankton in Christine Lake on September 26, 2003

length of all crustacean zooplankton was 0.75 mm ($\pm$ 0.04).

Discrete samples of zooplankton revealed the varied depth distributions (Fig. 12). *Bosmina*, Calanoida, and Cyclopoida were found at all depths with the greatest density of Calanoida found at 6 m, the greatest density of Cyclopoida found at 13 m and the greatest density of *Bosmina* found at 8 m. *Daphnia* were found only at 8 and 12 m with the greatest density (1.14 ind. L^{-1}) at 8 m. *Polyphemus*, a predatory crustacean, was found in low densities at 0.5 and 2 m.

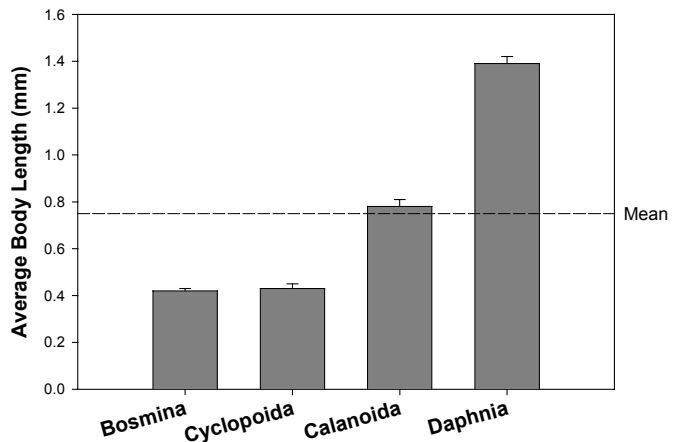**Discussion**

Examination of the physical, chemical, and

Fig. 11: Average body length (± 1 SE) of zooplankton in Christine Lake on September 26, 2003.

biological parameters lead to the conclusion that Christine Lake is an oligotrophic lake, which is phosphorus limited. This is exemplified by the lake's morphometric para-meters, watershed characteristics, TN: TP ratio, various tropic state indices, and the phytoplankton and zooplankton commun-ities.

Christine Lake has a relatively large watershed:lake area ratio of 15.06, suggesting that the lake's watershed plays a crucial role as a source of both water and nutrients for the lake. The catchment area is large compared to the lake and there is a extensive shoreline over which water can enter the lake. The watershed's landscape, which is dominated by remote coniferous and deciduous forest, plays a role in the types of nutrients that reach the lake's shore. Forest ecosystems readily immobilize phosphorus, thus limiting its input to the lake (Downing and McCauley 1992). As the watershed provides the lake with a majority of its water, the forested

composition likely leads to low levels of phosphorus input. The lake's watershed, combined with the lack of residential housing or farms surrounding the lake, probably limits nutrient input, giving Christine Lake a mass TN:TP ratio of 50:1. This value is within the oligotrophic range of 21 to 240 designated by Downing and McCauley (1992).

The low levels of nutrients are fundamental to Christine Lake's oligotrophic status. According to Carlson's (1977) Trophic State Index (TSI), Christine Lake ranged from 24.4 to 35 on a scale of 1 to 100 (Table 4), where a value of 1 corresponds to the highest water quality. While Carlson purposely failed to assign any of the previously accepted nomenclature to his index, these values generally

Table 4: Trophic State Index (TSI) values for Christine Lake on September 26, 2003 (Carlson 1977).

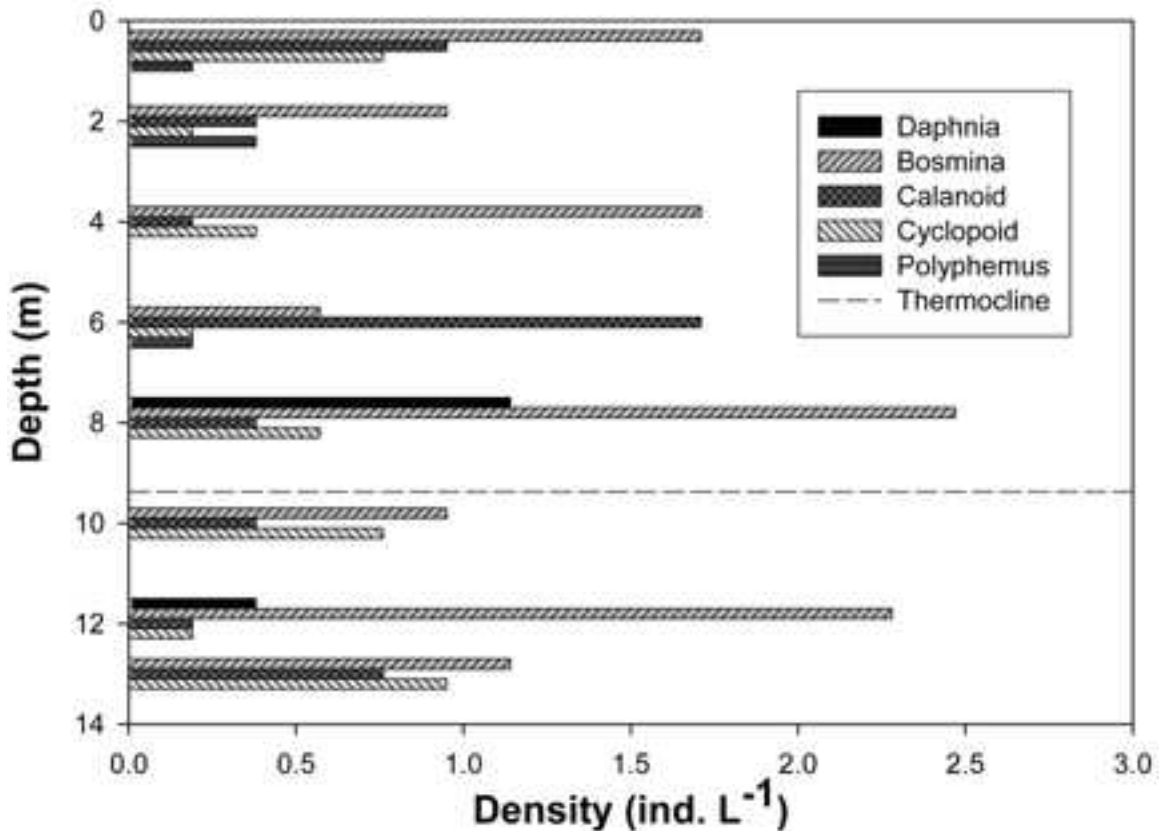| Measured Parameter	TSI
Phosphorus	24.40
SDD	31.22
Chlorophyll	34.99

Fig. 12. Zooplankton density at discrete depths in Christine Lake on September 26, 2003.

Table 5: Trophic state based upon total N, total P, Chlorophyll, and SDD with values for Christine Lake (adapted from Forsberg and Ryding 1980).

Trophic State	Total N ($\mu g\ L^{-1}$)	Total P ($\mu g\ L^{-1}$)	Chlorophyll ($\mu g\ L^{-1}$)	SDD (m)
Oligotrophic	<400	<15	<3	>4.0
Mesotrophic	400-600	15-25	7-Mar	2.5-4.0
Eutrophic	600-1500	25-100	Jul-40	1.0-2.5
Hypereutrophic	>1500	>100	>40	<1.0
Christine Lake	203	4.07	1.57	7.35

correspond to oligotrophic lakes. In fact, other indices such as the Forsberg-Ryding index of trophic status, which uses the traditional nomenclature, classifies this lake as oligotrophic based on all parameters (Table 5; Forsberg and Ryding 1980).

The scarcity of nutrients is the most likely cause for the low levels of primary production in Christine Lake. Of all of the lakes in this study, only Lower Sawyer Pond had less chlorophyll *a* (Fig. 13). Evidence for low production is also seen in Christine Lake's oxygen profile, which does not go below 4.5 mg L^{-1} (Fig. 2). The absence of an anoxic zone is due to the low amounts of decomposition, which normally consumes the oxygen in the hypolimnion. This oxidized zone in Christine Lake also contributes to the lake's phosphorus limitation through the

binding of phosphorus to oxidized iron (Fe^{3+}) in the sediments and hypolimnion. Evidence for the decreased amount of production and decomposition can also be seen in the vertical profile for ORP (Fig. 3). During decomposition, cells are broken down and electrons released, driving ORP down (Wetzel, 1983). The shift to negative ORP values is most often seen at the bottom of lakes, where detritus settles and decomposes. A shift towards electronegativity at the bottom was seen in each lake in our study, except Christine Lake (Fig. 14). This also indicates that there was weak decomposition at the bottom of Christine Lake, most likely due to limited detritus and settling phytoplankton. Negative ORP values are also seen in anoxic waters where elements such as iron and sulfur are being reduced. Chemical reduction, though, only occurs in an anoxic hypolimnion, which was not present in Christine Lake (Wetzel 1983).

Secchi disk measurements for Christine Lake were the third deepest in this seven-lake study (7.35 ± 0.0 m), with only Upper and Lower Sawyer Ponds recording greater values (Fig. 13). Christine Lake had low levels of dissolved color (16.23 CPU), which probably had little effect on water transparency. The amount of dissolved color in Christine Lake was significantly different from only highly colored Cedar Pond and hypereutrophic York Pond (Fig. 13; ANOVA; $p < 0.001$). In addition, Christine Lake's TSI values were very similar when calculated using Secchi disk depth and epilimnetic chlorophyll (Table 4). If dissolved
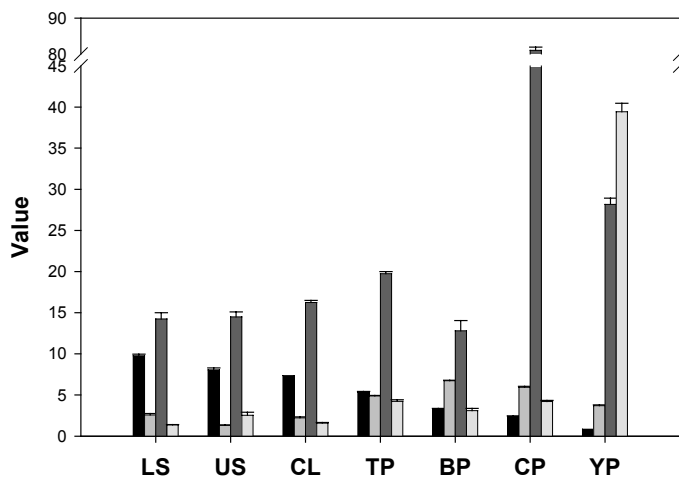

Figure 13: Average values (±1 SE) for Secchi disk depth (m; black bar), average alkalinity (mg $CO_3\ L^{-1}$; gray bar), average dissolved color (CPU; dark gray bar) and average chlorophyll ($\mu g\ L^{-1}$; light gray bar) for all lakes studied (September, 2003). Lake abbreviations as in Table 1.
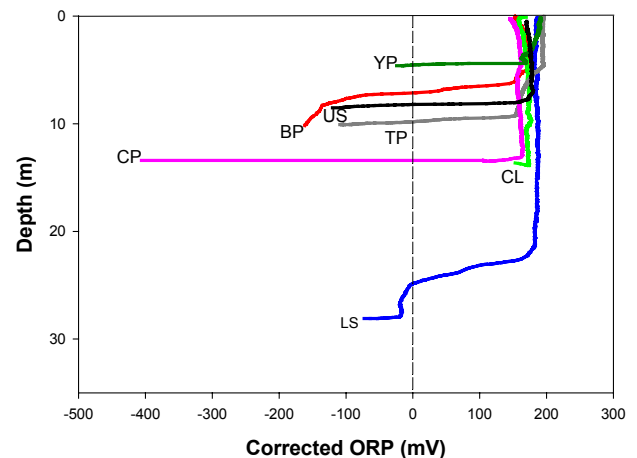

Fig. 14: Vertical profiles of corrected ORP (E_7) in all lakes sampled (September, 2003). Lake abbreviations as in Table 1.
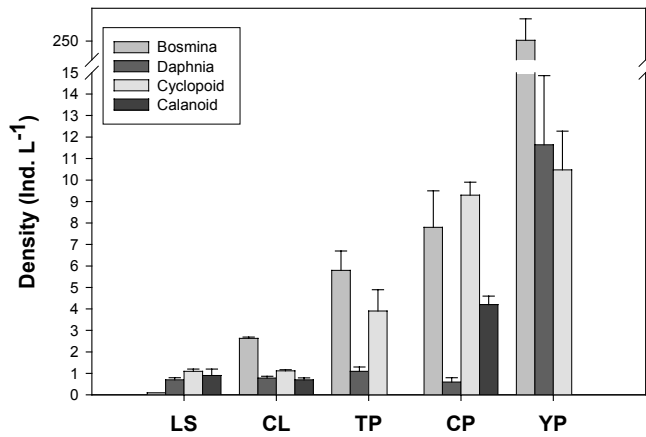
Fig. 15: Zooplankton densities (±1 SE) in five of the lakes studied (September, 2003). Lake abbreviations as in Table 1.

Fig. 16: Average body length (±1 SE) of zooplankton in five of the lakes studied (September, 2003). Lake abbreviations as in Table 1.

color had noticeably affected the Secchi disk depth, the TSI values based upon the Secchi disk depth would be much larger than those calculated from the epilimnetic chlorophyll (Carlson 1977). The similarity between the TSI values based upon Secchi disk depth and epilimnetic chlorophyll values indicate that Secchi disk depth is a reliable indicator of primary production in Christine Lake.

In general, the composition of the phytoplankton community was also indicative of oligotrophy as the dominant alga, *Dinobryon,* is most often found in lakes considered to be oligotrophic (Lepistö and Rosenström 1998; Leitão and Léglize 2000). Although there were low densities of cyanobacteria (*Aphanocapsa* and *Gleocapsa*) present, this does not necessarily indicate nitrogen limitation. These particular genera do not possess heterocysts and are not known to fix nitrogen.

The deviation from *Dinobryon* dominance at 13 m (Fig. 7) may be explained by sedimentation. Dominance shifted from *Dinobryon* to the diatom *Melosira*, which typically settles out of the water column more readily than most phytoplankton and collects at or near the sediment. The low abundance of *Melosira* at other depths is not surprising since the silica necessary for frustule development is absent in most lakes during the fall, having been exhausted by diatoms earlier in the season (Lampert and Sommer 1997). There was also a decreased abundance of *Dinobryon* at 4 m with an increase in *Gleocapsa* (Fig. 7) and an
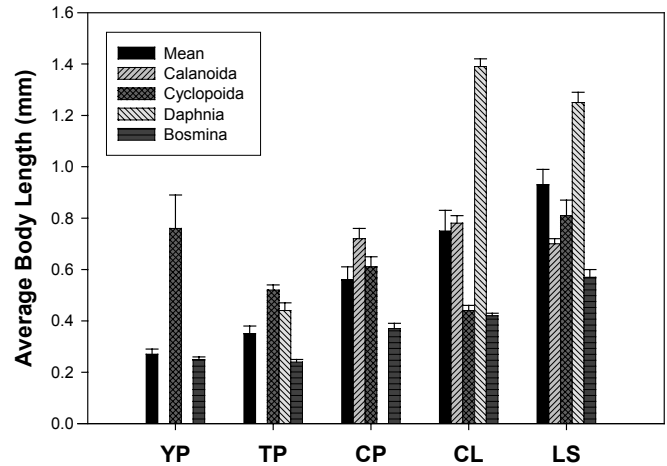
increase in the measurements of turbidity (Fig. 4). *Gleocapsa* a small, spherical, colonial alga, could account for the increase in turbidity at 4 m. The concentration of *Gleocapsa* at 4 m can be explained by the densities of zooplankton at 4 m. At this depth, the dominant zooplankton was *Bosmina* (Fig. 12), which would not likely have a high impact on *Gleocaspa* due to its grazing inefficiency (Haney 1973).

Small-bodied *Bosmina* dominated the zooplankton community (Fig. 10), with an average body length of 0.42 mm. The largest zooplankter, *Daphnia*, was not as abundant, suggesting a high level of zooplanktivory by fish. According to Brooks and Dodson (1965), the largest zooplankton have a

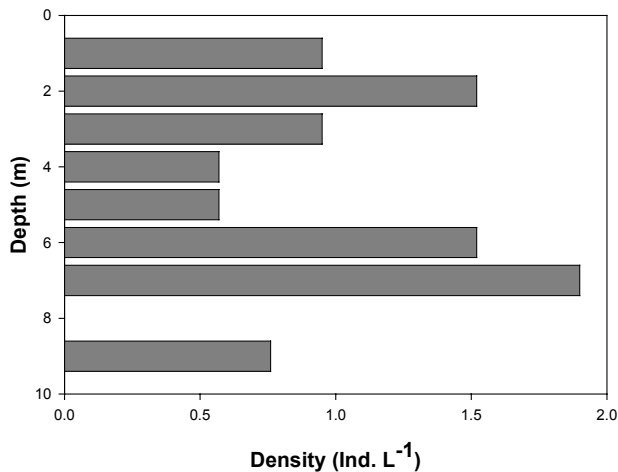Fig. 17: *Daphnia dubia* found in Christine Lake on September 26, 2003.

Fig 18: Depth distribution of Cyclopoida in Townhouse Pond on September 18, 2003.

competitive advantage over smaller-bodied varieties as they have the ability to ingest the larger food particles that are unavailable to the smaller zooplankton. However, the larger zooplankton are exposed to higher levels of predation, as they are more readily visible to visually-orienting predators such as fish. Zooplanktivorous fish may then limit *Daphnia* density. This can clearly be seen when examining the average body length of zooplankton found in Townhouse Pond. This lake, unlike Christine Lake, has a population of Alewife (*Alosa* spp.), which is a very efficient predator of zooplankton (Brooks and Dodson 1965). *Bosmina* dominated the zooplankton population of Townhouse Pond (Fig. 15; average body length: 0.24 mm ± 0.01), which greatly contributed to the relatively small average body size of the overall zooplankton community (0.35 mm ± 0.03; Fig. 16). Furthermore, the *Daphnia* present were smaller with an average body length of only 0.44 mm (± 0.03). Townhouse Pond was dominated by the smaller-bodied varieties of zooplankton and the typically large-bodied zooplankters, such as *Daphnia*, were much smaller, most likely due to the intense predation.

Body morphology and depth in the water column of the *Daphnia* found in Christine Lake provides further evidence for high levels of zooplanktivory. All *Daphnia* possessed elongated tail spines (which were not included in body

length measurements) and a slightly pointed "helmet" (Fig. 17). As each of these structures is made of transparent chitin, they allow the *Daphnia* to appear smaller than they actually are, reducing predation by visual predators without the disadvantage of a reduction in body size. Smaller *Daphnia* would be vulnerable to invertebrate predation, perhaps by the carnivorous cyclopoid copepods. *Daphnia* may also avoid visual predators by positioning themselves at deeper depths during the day. The greatest density of *Daphnia* was at 8 m (Fig. 12). While lower light intensity at this depth provides some refuge from visually orienting predators, the *Daphnia* are exposed to the colder temperatures of the meta- and hypolimnion (Dawidowicz and Loose 1992, Loose and Dawidowicz 1994). This can also be seen in the Cyclopoida population of Townhouse Pond. The average body length of the Cyclopoida in Townhouse pond was larger than those of Christine Lake (0.52 mm ± 0.02 and 0.44 mm ± 0.02, respectively; ANOVA p = 0.006) even though the average body length of all zooplankton was smaller in Townhouse Pond. Many of the large-bodied Cyclopoida were probably able to avoid predation by residing deeper in the water column (Fig 18).

Some *Daphnia* in Christine Lake, however, were exposed to the colder temperatures of the hypolimnion at 12 m. Size differences could explain the presence of *Daphnia* at different depths. Perhaps *Daphnia* at 12 m are larger than those at 8 m, driving them to deeper depths to avoid predation. Unfortunately, actual numbers of *Daphnia* within each discrete sample are too small to provide
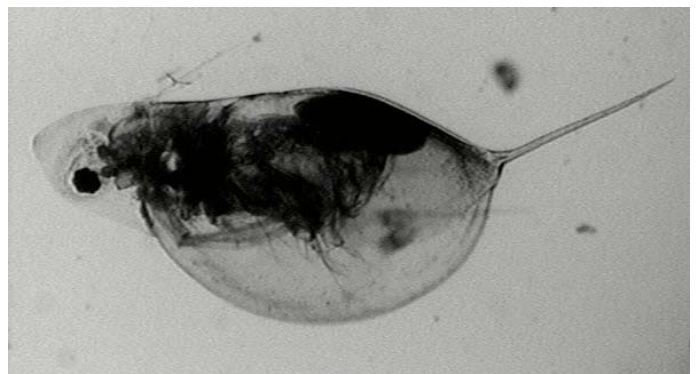

Fig. 19: *Daphnia* dubia from Lower Sawyer Pond on September 11, 2003.

accurate averages of body length.

The pattern of *Daphina* distribution is in direct contrast to the pattern seen in Lower Sawyer Pond, which is similar to Christine Lake in watershed and trophic status. The water in Lower Sawyer Pond, however, is clearer with an average SDD of 9.78 m (± 0.19; Fig. 13) and an average K_{ext} coefficient of 0.39 (± 0.01) and deeper (Z_{max} = 29.6 m). The *Daphnia dubia* are similar in size (average length: 1.25 mm ± 0.04) and morphology as both exhibit slight helmets (Fig. 19). Although the water was clearer and the *Daphnia* were relatively large, they were still located close to the surface in Lower Sawyer Pond (Fig. 20), suggesting that predation pressure from fish is not as substantial in Lower Sawyer Pond as in Christine Lake. The *Daphnia* were able to reside higher in the water column, in the warmer water of the epilimnion, without experiencing population loss due to predation.

Seasonal Comparisons- The average body length of Christine Lake zooplankton in the fall is in sharp contrast to the larger body length of zooplankton measured there in the spring (average body length: 0.91 mm ± 0.03; Fig. 21). During this time of year, the zooplankton community was dominated by Calanoida, a large-bodied copepod
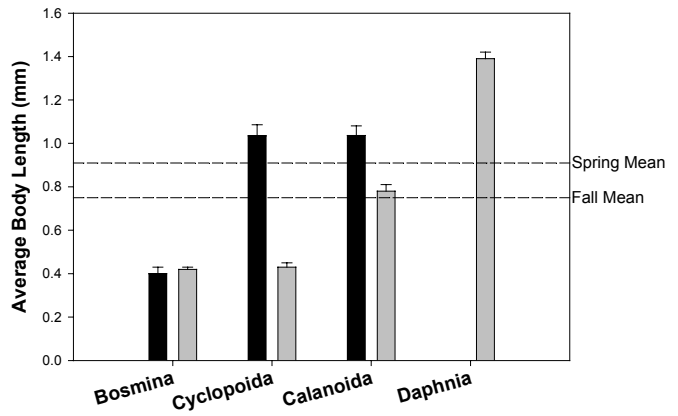

Fig. 21: Average body length (±1 SE) of zooplankton in Christine Lake in the spring (June 5, 2003; black bar) and fall (September 26, 2003; gray bar).

and, unlike the fall, the density of *Bosmina* were greatly reduced (Fig. 22). This would indicate a scenario opposite that of the fall. In the spring, the main source of predation may have been invertebrate. In this case, large-bodied zooplankton have a further advantage, as they are too large to be ingested by most invertebrate predators. This advantage would allow rapid increases in population densities. The change in abundance from Calanoida to *Bosmina* probably stemmed from the hatching of young fish, which has been known to have
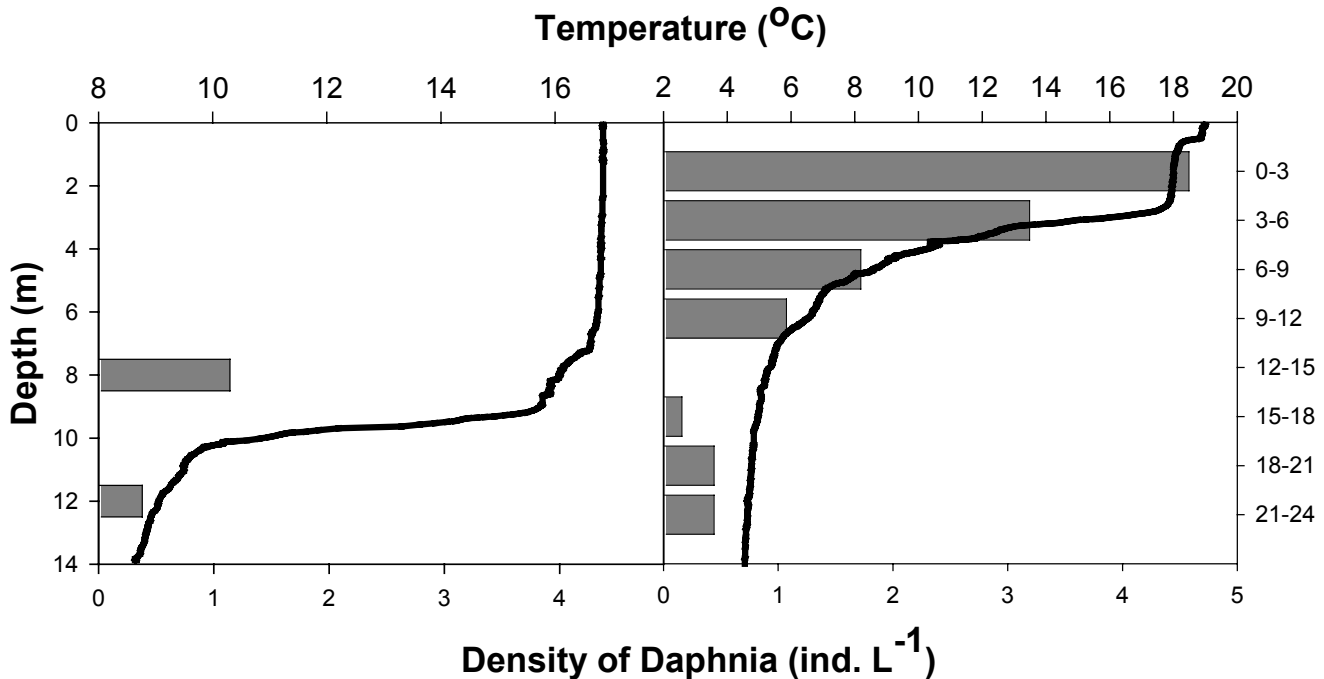

Fig. 20: Vertical distribution of *Daphnia* in Christine Lake (left; September 26, 2003) and Lower Sawyer Pond (right; September 11, 2003) accompanied by the temperature profile for each lake.

devastating effects on the densities of large zooplankton (Mills *et al.* 1987).

Another interesting trend is the similarity in average size for Calanoida and Cyclopoida in the spring. Both groups had an average body length of 1.03 mm (± 0.04 and 0.05, respectively; Fig. 21). Even though both of these groups are of the same size, the density of Calanoida was far greater than Cyclopoida (2.45 ind. L^{-1} ± 0.75 and 0.02 ind. L^{-1} ± 0.02, respectively; Fig. 22). The difference in abundance may stem from competition or natural succession. Through their natural life cycles, it is possible that more of the Calanoida's diapausing embryos hatched first. Copepods are also able to survive under the ice if there is an adequate supply of food. If the difference is caused by another competitive advantage, it does not stem from body size. This competitive edge may be food. Calanoida are grazers and Cyclopoida are carnivores. While Calanoida had an abundance of food (average spring chlorophyll: 2.7 µg L^{-1} ± 0.1; average fall chlorophyll: 1.57 µg L^{-1} ± 0.09, Cyclopoida did not. Spring densities of all other zooplankton, except Calanoida (Fig. 22), were reduced, thus limiting the number of suitably sized prey items available to the Cyclopoida. However, as the smaller *Bosmina* became more abundant, prey would have become more readily available to the Cyclopoida, allowing their densities to increase.

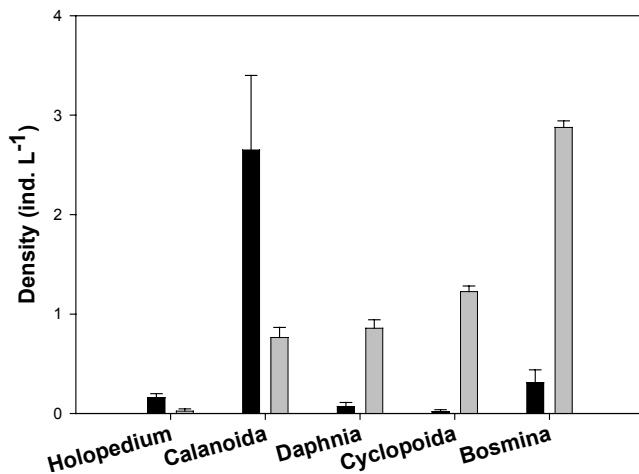The fall phytoplankton community was

Fig. 22: Average density (±1 SE) of zooplankton in Christine Lake in the spring (June 5, 2003; black bar) and fall (September 26, 2003; gray bar).

dominated by the smallest size fraction, picoplankton, with nano- and netplankton following in dominance respectively (Fig. 8). In the spring of 2003, size fractions were similar, with a dominance of picoplankton, yet there was a greater abundance of nanoplankton and no measurable netplankton. Such a size distribution is expected, as the netplankton had not yet had enough time to move into this size category through processes of succession (Sommer *et al.* 1986).

Food Web Model - The food web model constructed for Christine Lake depicts known elements of the lake's phytoplankton and zooplankton communities as well as planktivorous and piscivorous fish (Fig. 23). Netplankton, which includes all phytoplankton over 50 µm in length, is probably too large to be eaten by any member of the zooplankton community. Nanoplankton, ranging from 2 µm to 50 µm, is the most highly grazed element of the phytoplankton community. This is largely due to the size of the filtering apparatus for all of the zooplankton, which allows feeding on this particular size fraction. However, *Daphnia*, and to some extent *Holopeduim*, are the only zooplankton able to efficiently graze on picoplankton (<2 µm). The filtering apparatus of *Bosmina* and Calanoida are too coarse to permit grazing on this size fraction (Lampert and Sommer, 1997).

The carnivorous Cyclopoida probably prey primarily on *Bosmina*. They are not able to eat *Daphnia* or Calanoida as they are limited by their gape size. *Bosmina*, Cyclopoida, and Calanoida are all likely preyed upon in low levels by young Brook Trout (*Salvelinus fontinalis*) and Brown Trout (*Salmo trutta*). The largest source of food for the young trout is most likely the *Daphnia*, as they are probably the most readily visible to the fish. Larger trout and the lake's Small Mouth Bass (*Micropterus dolomieui*) may, in turn, consume the younger fish. Anglers can take all fish in the lake during the designated seasons.

Summary

It appears that the zooplankton community of oligotrophic Christine Lake is controlled by both bottom-up and top-down mechanisms. Nutrient inputs for Christine Lake are probably low, thus limiting phytoplankton abundance and primary
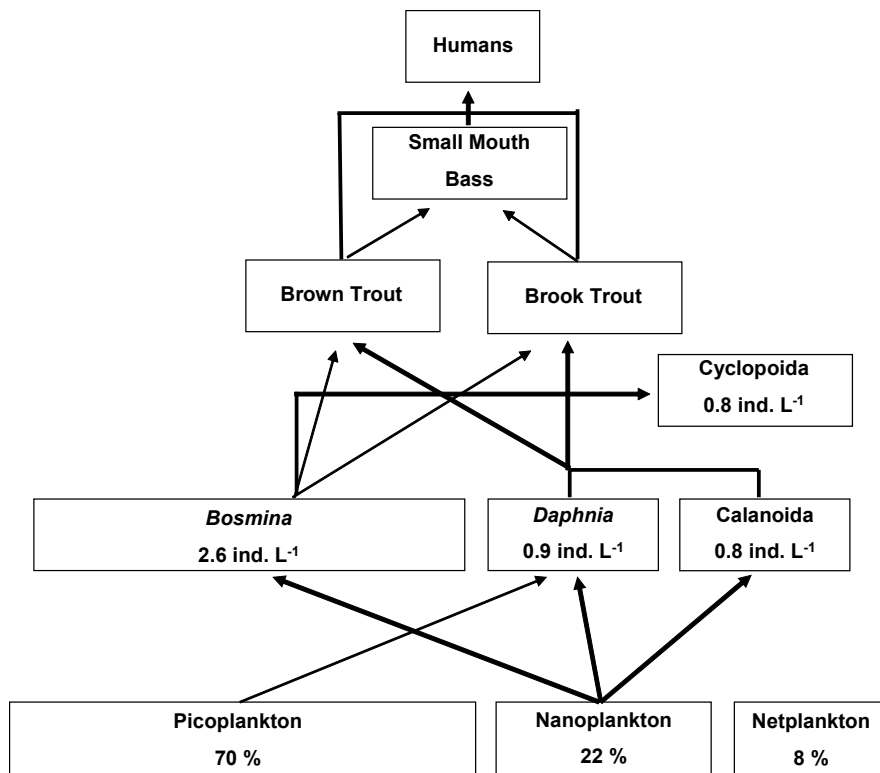
Fig. 23: Food web for Christine Lake based on sampled collected on September 26, 2003. Bold lines represent stronger influences of predation or grazing.

production. The low primary production which limits zooplankton densities by lowering the carrying capacity of the lake. Zooplankton size, however, appears to be limited by the nature of zooplanktivory. Average body lengths were larger in the spring before the summer fish predation. By September 26, 2003, though, following the summer fish predation, the average zooplankton body length was significantly lower. Probably due to both the natural fish population (Brook Trout and Smallmouth bass; Robert Fawcett, New Hampshire Dept. of Fish and Game (NHDFG)*, pers. comm.*) and from increased stocking of Brown Trout. In 2002 the NHDFG stocked 2000 1+ year old fishes into Christine Lake (Robert Fawcett, NHDFG*, pers. comm.*). The morphology of *Daphnia* helmets and their location in the water column may be effects of this predation pressure.

An increase in phosphorus, though, could rapidly change the trophic status of Christine Lake. Increased nutrients could alter the nature of the entire phytoplankton community, resulting in increased algal abundance (Fig. 24). This, in turn,

would decrease water clarity as well as affect the zooplankton and fish communities.

Fortunately, Christine Lake is not strongly affected by cultural eutrophication at this time. Extensive forests in the watershed help to alleviate anthropogenic nutrient input. Most of the land surrounding the lake is protected by conservation efforts, leaving little room for residential homes or farming, typical sources of nutrient loading. The result is a very clear lake with a shoreline dominated by cedars, not cottages, providing an idyllic setting for water-related recreation. The lake's natural fishery, however, is insufficient to draw large amounts of anglers to Coos County, NH. This is rectified by the DFG's artificial stocking efforts. The final product is a lake that can be used for all manner of recreational activities.

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