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The effects of alewife (*Alosa pseudoharengus*) on zooplankton community structure in Depot Pond NH and a comparison of seven New Hampshire lakes

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Abstract

Physical, chemical and biological features of seven New Hampshire lakes were examined in September and October of 1997. Zooplankton communities exhibited evidence of "top-down" control in Milton Three Ponds (Depot, Norteast, and Townhouse Ponds), showing effects of a planktivorous fish, *Alosa pseudoharengus*: small mean body size, dominance of small grazers such as *Bosmina*, and absence of large grazers such as *Daphnia*. Phosphorus concentrations were positively correlated to fluorescence of all water fractions, chlorophyll *a* and a phytoplankton biotic pollution index (modified from Hillsenhoff, 1978), revealing a level of "bottom-up" control.

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Introduction

Lake ecosystems are complex and are best studied through observation of their physical, chemical, and biological characteristics. The interaction between these three types of characteristics determine the composition and activity of a lake. Physical and chemical features of aquatic ecosystems have a strong impact on the types and abundance of organisms, as well as, the interactions between them.

Carpenter *et al.* (1985) used the term "trophic cascade", for the control of energy flow through. The theory is based on the activity of organisms in one trophic level shaping the composition of other trophic levels. Two main mechanisms of control in aquatic ecosystems are known as, "top-down" and "bottom-up" (Carpenter *et al*., 1985). The top-down concept holds that predatory fish are the controlling force in lake ecosystems; predation of upper trophic level orgranisms decreases abundance of lower trophic levels. The "bottom-up" concept proposes, nutrient levels control lake ecosystems; inceases in nutrient concentrations increase phytoplankton populations; in turn, increasing predator population size. Alewife have an extensive impact on predator-prey interactions through top-down pressure. As these fish prey intensely on large zooplankton, the grazing pressure exerted on the phytoplankton is dramatically decreased.

Many chemical and physical factors can be used to describe lake ecosystems. Both oxygen and carbon dioxide concentrations can give clues to the amount and types of biological activities occurring at different places in a lake. Specific conductivity, oxidation/reduction potential, alkalinity, color and pH provide information about the chemical conditions present and possible effects on organisms. These parameters may be altered by biological activities of the same organisms they affect. Secchi disk depth and light attenuation

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indicate where organisms may be located and how much influence they have on layers below. Chlorophyll *a* concentration and fluorescence provide clues to the amounts and types of phytoplankton present. Phosphorus levels act as an indicator for the potential and/or realized amount of production. Finally, analysis of zooplankton and phytoplankton samples indicate trophic interactions and the general biological response to the conditions of the lake.

We studied the chemical, biological and physical characteristics of seven lake basins in the fall of 1997 as part of a Field Limnology class at the University of New Hampshire. In late summer and fall, lakes are highly stratified, thus clearly illustrating the characteristics of a lake and making it an optimal time for sampling. The lakes we chose represented a range of morphological and biological characteristics, including the Milton Three Ponds (Depot, Townhouse and Northeast Ponds), which contain a landlocked population of alewife (*Alosa pseudoharengus*). Alewife have been found to have a significant impact on the zooplankton populations of freshwater lakes (Brooks and Dodson 1965). An analysis of the differences between lakes with and without alewife was a main focus of this study.

Methods

Vertical profiles of the chemical parameters were taken with a YSI meter multi-parameter probe (model 600XL). The probe was linked to a notebook computer (Gateway 2000 Handbook 486) used to record data. The probe was calibrated, then lowered through the water column at approximately 1 m min^{-1} with readings taken every second, producing vertical profiles of pH, temperature, dissolved oxygen, oxidation/reduction potential (not corrected for pH), and specific conductance (corrected for 25°C) with a vertical resolution of about 2 mm.

Transparency measurements were taken using a Secchi disk and recorded as the mean value between disappearance and reappearance of the disk. Underwater light attenuation was measured with a Li-Cor underwater quantum sensor, (series UWQ 3694) lowered vertically into the water column while a second sensor, located on the boat, recorded fluctuations of incoming solar radiation. Measurements were taken at the surface, 0.1 m, then every 0.5 m until light levels decreased to < 1 µE. Cofficient of attenuation (k_{ext}) was calculated from a regression on a semi-log plot of depth and light intensity.

Triplicate whole lake water (WLW) samples were taken from the epilimnion of each lake using an integrated tube sampler. A clear plastic (Tygon) tube was lowered into the water, weighted end first, until the depth of the bottom of the epilimnion was reached. The top of the tube was pinched and the weighted end was raised by means of an attached string. The water contained in the tube was transferred to a translucent sample bottle for further processing.

WLW samples were analyzed for dissolved oxygen (Winkler method), dissolved carbon dioxide, chlorophyll *a*, and total phosphorus following Lind (1985). Phosphorus values for Northeast Pond were excluded from most analyses due to sample contamination. Alkalinity was determined for WLW by titrating 100 mL of the sample. For every 100 mL, 10 drops of bromcresol green - methyl red alkalinity indicator solution were added. Titrations were performed under constant stirring with 0.002 N H_2SO_4 to both a gray and pink endpoint. To determine water color (or CDOM), WLW samples were passed through a 0.45 µm Millipore filter under vacuum. The filterate samples were analyzed on a spectrophotometer (model Milton Roy 1001 Plus) for absorption at 440, 493, 750 and 880 nm.

For determination of phytoplankton fluorometry, three fractions were taken from the WLW sample and measured on a model 10-AU Turner field fluorometer with an *in vivo* chlorophyll filter set. The values were reported as relative fluorescence units (RFU). The WLW fraction was analyzed without any modifications. The second fraction was produced by passing the WLW through a 30 µm Nitex net. The final fraction was a background water fraction produced by filtering WLW through a 0.45 µm Millipore filter using a vacuum filter.

To collect net phytoplankton, vertical tows were performed with an 80 µm mesh closing phytoplankton net. The tow started 1 m from the lake bottom and continued throughout the entire water column to the surface. Samples were fixed with 4% formalin-sucrose solution. Phytoplankton were idenfitied to genus under a compound microscope. A phytoplanketon biotic index (adapted from Hilsenhoff (1987) by A.L. Baker) was calculated from phytoplankton counts according the pollution tolerance of each class.

Zooplankton samples were collected through vertical tows using an 80 µm mesh net. The 30 cm diameter closing net was used to collect a vertical profile of the zooplankton. A total of 10 or more discrete samples were taken, providing a representative sampling of the entire water column. Samples were fixed with 4% formalin-sucrose solution. Zooplankton were idenfitied to genus under a compound microscope.

Statistical analyses were accomplished with Systat 5.0 for Windows and Systat 5.1 for Macintosh. Variance of the parameters and significanct differences were analyzed by ANOVA. Tukey's test was used to test for significant differences ($p < 0.05$) between lakes for each parameter. Linear regressions were determined with least-squares best-fit, and significance considered at $p < 0.05$ unless otherwise noted.

Study Sites

Seven New Hampshire lakes were sampled during September and October of 1997 (Table 1). Depot Pond, Townhouse Pond and Northeast Pond are all located in Milton and known collectively as the Milton Three Ponds (Fig. 1). Swains Lake is in the town of Barrington and is divided into east and west basins. The smallest lake of the study, Barbadoes Pond is in the town of Madbury and the deepest lake, Russell Pond, is located in the town of Woodstock.

Depot Pond is located at 43°25' N, 70°59' W at 126 m above sea level. Depot Pond has a surface area of 72.8 Ha, a mean depth of 5.5 m and a maximum depth of 16.8 m (Table 1). The watershed area is over 29,500 Ha and the dominant vegetation is a mixed deciduous and pine forest. The lake is surrounded by development and has many shoreline houses and camps. The soil at the shore is mostly sand. Depot Pond is surrounded on all sides by roads, often running within 20 m of the shore. The northwest end of Depot connects with Townhouse Pond and the northeastern end meets the southwestern end of Northeast Pond (Fig. 1). There are several intermittent streams that drain into different parts of the lake, but the main inflow of water comes from the other lakes. The outlet of the Milton Three Ponds system is through the dam at the southern end of Depot Pond.

Table 1. Location, characteristics and sampling dates of New Hampshire study sites (from The New Hampshire Department of Environmental Services lake database).

Lake	Barbadoes	Russell	Swains East	Swains West	Northeast	Depot	Townhouse
Town	Madbury	Woodstock	Barrington	Barrington	Milton	Milton	Milton
County	Strafford	Grafton	Strafford	Strafford	Strafford	Strafford	Strafford
River basin	Coast	Merrimack	Coast	Coast	Coast	Coast	Coast
Elevation (m)	40	499	85	85	126	126	126
Shore length (m)	1000	1600	11400	11400	10600	3400	9800
Lake area (Ha)	5.8	15.8	170.2	170.2	228.5	72.8	48
Lake volume (Ha-m)	34.9	129.6	510.6	469.8	617	400.4	158.4
Lattitude	43ϒ11'N	44ϒ01'N	43ϒ12'N	43ϒ12'N	43ϒ27'N	43ϒ25'N	43ϒ26'N
Longitude	70ϒ05'W	71ϒ39'W	71ϒ03'W	71ϒ03'W	70ϒ58'W	70ϒ59'W	70ϒ59'W
Mean depth (m)	6.1	8.2	3	2.8	2.7	5.5	3.3
Maximum depth (m)	14.6	23.7	8.8	7.9	14.9	16.8	10.1
Watershed area (Ha)	38.8	147.9	1046.2	1113.7	29597.5	29571.6	29525.9
Date sampled	5-Oct-97	18-Oct-97	29-Oct-97	29-Oct-97	22-Oct-97	22-Oct-97	22-Oct-97

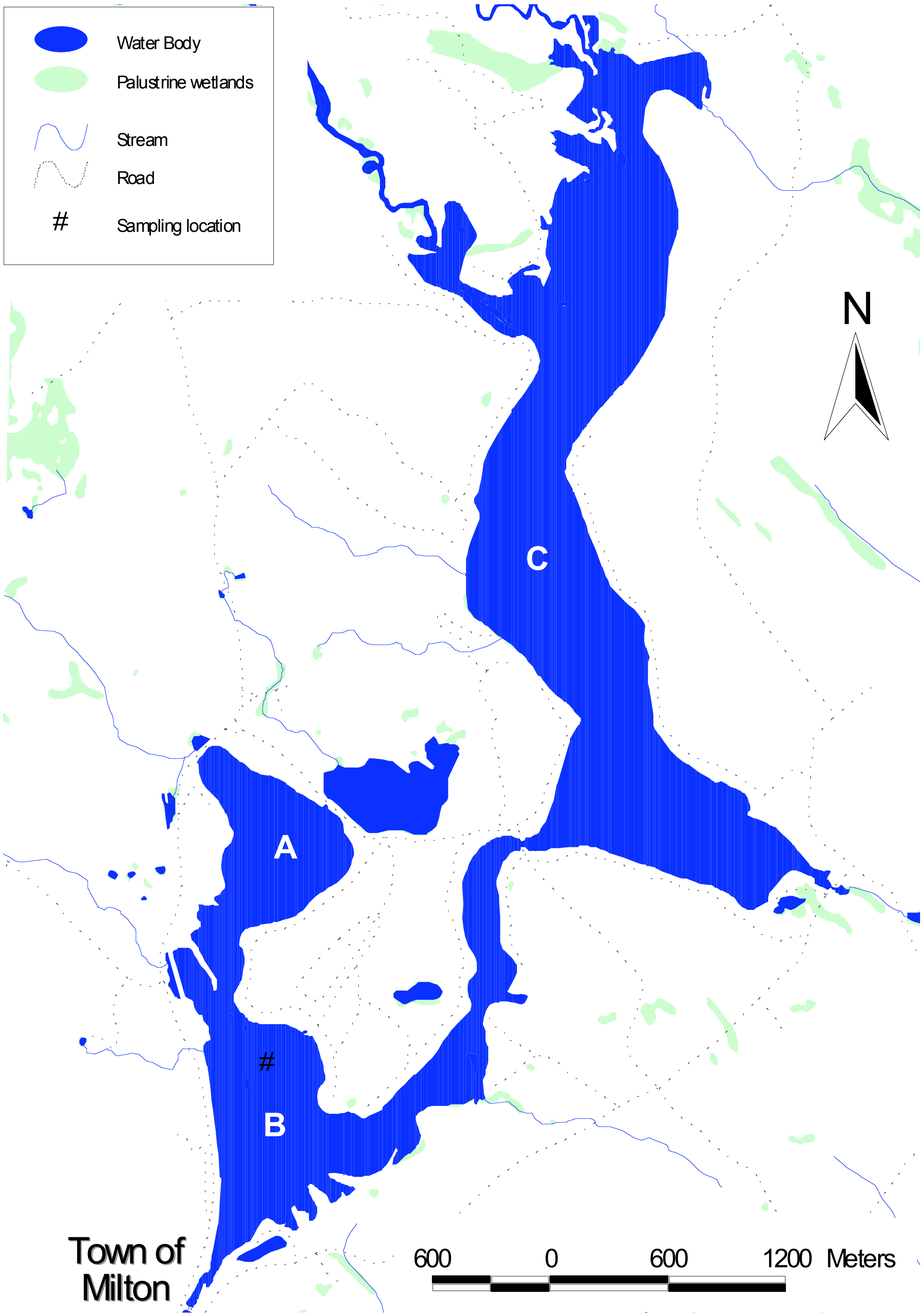

Fig. 1. Map of the Milton Three Ponds: Townhouse Pond (A), Depot Pond (B), and Northeast Pond (C). NWI, hydrological and road data obtained from GRANIT New Hampshire.

Depot Pond Results

Samples and profiles were taken at Depot Pond on September 22, 1997. All samples were taken from a location in the center of the basin at a depth of 16.0 m. Results of the YSI meter profiles can be seen in Fig. 2, while results for other parameters measured can be found in Table 2 and on Figures 7-9.

Depth distributions of temperature and dissolved oxygen in both percent saturation and mg L^{-1} followed similar patterns, including relatively stable values from surface to about 7 m followed by a steady decrease to the bottom (Fig. 2a). The lake had thermal stratification at the date of sampling, forming three distinct temperature zones. A strong epilimnion began at the surface and ended at 7 m with a mean temperature of 19.0 °C. The metalimnion began at 7 m, with a total thickness of 3.5 m, and an mean rate of temperature change close to 2.5 °C m^{-1}. The hypolimnion began at 10.5 m with an mean temperature of 8.6 °C and continued to the bottom of the lake.

The shape of the dissolved oxygen profiles followed the temperature curve very closely throughout the entire water column, although the initiation of the oxycline came at a point lower than the thermocline. Just below the surface, levels were 115% saturation and 10 mg L^{-1}. The dissolved oxygen was fairly constant in the first 8 m of the water column, with means of 103.2% saturation and 9.5 mg L^{-1}. These values decreased quickly (15.2 % m^{-1} and 1.6 mg L^{-1} m^{-1}) over the next 5 m until there was no detectable oxygen.

The three other parameters (Fig. 2b) showed very little change in the first 7 m. Means for specific conductivity, oxidation reduction potential, and pH in this section of the profile were 72 μS cm^{-1}, 197.8 mV, and 7.1 mV, respectively. After this point, the specific conductivity and pH decreased until around 12 m, then increased throughout the rest of the column. Specific conductivity displayed a much greater rate of increase. Oxidation reduction potential first increased from 7 to 12 m, then decreased sharply.

A low or reduced oxidation reduction potential, like that present in Depot Pond, implies that there is no oxidized microzone (OMZ). This OMZ would normally be present in the layer of water immediately above the lake bottom. An OMZ is a layer usually no greater than a few millimeters thick that contains oxidized matter such as iron. This zone is effective in sealing toxic and reduced matter into lake bottom sediments. In its absence of an OMZ, reduced matter comes out of the sediments and mixes with the overlaying water.

Zooplankton were counted in 11 depth samples (Fig. 3, Table 3). Come larger bodied species, such as Daphnia and Holopedium were present, but at very low densities (Table 3). *Bosmina* were found equally distributed in the epilimnion, but in low densities in the rest of the column. *Cyclopoids*, the only planktonic predator found widely in the lake, had relatively constant levels except in the hypolimnion, where levels were greatly reduced. *Keratella* was the most abundant zooplankton found and had its highest concentrations in the epilimnion. The highest of these values came between 3 m and 6 m. Nauplii copepods were found in low densities where there were high densities of *Bosmina*, and high densities where *Bosmina* were scarce. The mean size of zooplankton in the lake was 0.33 mm.

Depot Pond Discussion

The temperature profile had a direct relationship with the amount of dissolved oxygen in Depot Pond. The same relationship between the profiles was also present in mid-September of 1996 (Craycraft and Schloss 1996). The relationship was not expected on the basis of physical conditions, since water holds more dissolved gases at cooler temperatures than at warmer ones. Therefore, some other factors must be involved.

The decrease in dissolved oxygen concentration observed as depth increased was due to oxygen sinks being greater than oxygen sources at greater depths. Oxygen can be added to the lake by photosynthesis and entry from the atmosphere. During stratification, atmospheric oxygen is not supplied to the hypolimion and most photosynthesis occurs in the epi- or metalimnion. Oxygen consuming processes in the hypolimnion, such as

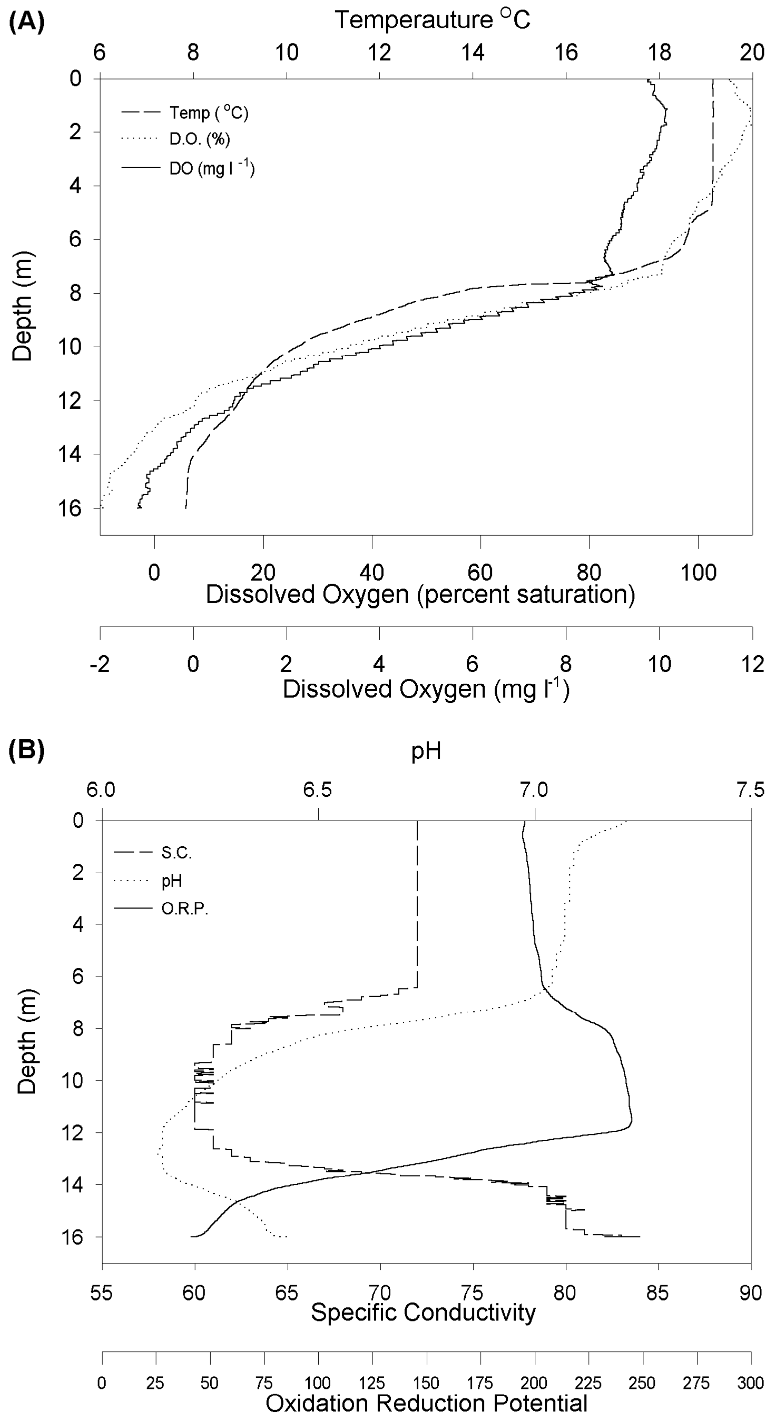

Fig. 2. Vertical profiles of Depot Pond, Sept. 22, 1997. (A) Temperature and dissolved oxygen. (B) pH, specific conductivity, and oxidation reduction potential.

respiration and decomposition, may produce anoxia by depleting all available oxygen.

The abundance of grazing zooplankton, especially *Keratella*, were much higher from 3-7 m. The abundance from 3-5 m is probably due to the number of photosythetic organisms in this "prime" light intensity region. The numbers found from 5-7 m are most likely due to the grazing of sinking phytoplankton or the grazing of heterotrophic organisms utilizing the high oxygen levels found in this layer.

The contribution of phytoplankton photosynthesis to oxygen levels in the epilimnion is suggested indirectly by the vertical zooplankton distribution data (Fig. 3). It is not until the oxygen concentration decreased to below 7 m that the number of grazing zooplankton organisms diminished. Since the epilimnion mixes freely due to a virtual lack of temperature gradient, the increased oxygen produced by photosynthesis would be present throughout the layer. Although oxygen may be found throughout the entire layer, a greater abundance of grazers would be expected in the areas where the most food was present.

Contrary to traditionally accepted theories that nutrient loading is the main factor affecting phytoplankton growth; some studies have suggested zooplankton grazing enhances phytoplankton productivity and chlorophyll *a* concentrations (Porter 1976, Lehman 1980, Shapiro 1980, De Melo *et al*. 1992). Thus, high phytoplankton levels would attract grazers, and in turn, the grazers would stimulate phytoplankton growth. In this case, the removal of phytoplankton by grazers subsequentially leads to the prevention of the build up of a large algal population.

The phytoplankton community was dominated by Chrysophyceae (golden algae) and contained a moderate population of Bacillariophyceae (diatoms). The two most dominant chrysophytes were *Chrysospherella* and *Dinobryon*, followed by a smaller population of *Synura*. *Melosira* and *Asterionella* were the two represent Bacillariophytes. Phytoplankton such as *Dinobryon* and *Synura* form large colonies and are often found in water with low phosphorus levels (Wetzel 1983). These colonial phytoplankton are too large to be consumed by the zooplankton grazers. Creating an energetic "bottleneck", i.e. energy produced by algal production is unable to pass to the higher trophic levels, and is lost as the phytoplankton sinks out of the water column into the sediments.

The phosphorus concentrations for Depot Pond falls within the range of oligotrophic lakes (Forsberg and Ryder 1980). This can cause the phytoplankton community to shift toward larger organisms, more able to take advantage of low levels. The biotic index also indicates very low levels of nutrients. Depot Pond had a 1.05 on the phytoplankton biotic index scale, indicating "possible slight nutrient pollution" (Table 4).

The mean zooplankton length of Depot Pond was relatively small (0.33 mm). A short mean zooplankton body length is typical of lake ecosystems dominated by a visual predator. Brooks and Dodson (1965), Vanni (1986), Vanni *et al.* (1990) and Carpenter *et al.* (1995) discuss the tendency of smaller mean zooplankton lengths in lakes with abundant planktivorous fish. Fish are visually ori-

Table 3. Less abundant zooplankton of Depot Pond. Data are the number of organisms L^{-1}.

Depth (m)	Calanoid	*Daphnia*	*Holopedium*	*Polyarthra*	*Asplanchna*	*Kellicottia*
0-1	-	-	0.014	0.057	-	-
1-2	-	0.028	-	0.057	-	-
2-3	0.057	-	-	-	-	-
3-4	-	-	-	0.952	0.048	0.952
4-5	-	0.058	-	0.233	-	0.233
5-6	0.028	-	0.028	-	0.080	-
6-7	-	-	-	-	0.190	-
7-9	-	-	-	-	-	-
9-11	-	0.046	-	-	0.023	-
11-13	-	0.028	-	-	-	-
13-15	-	-	-	-	-	-

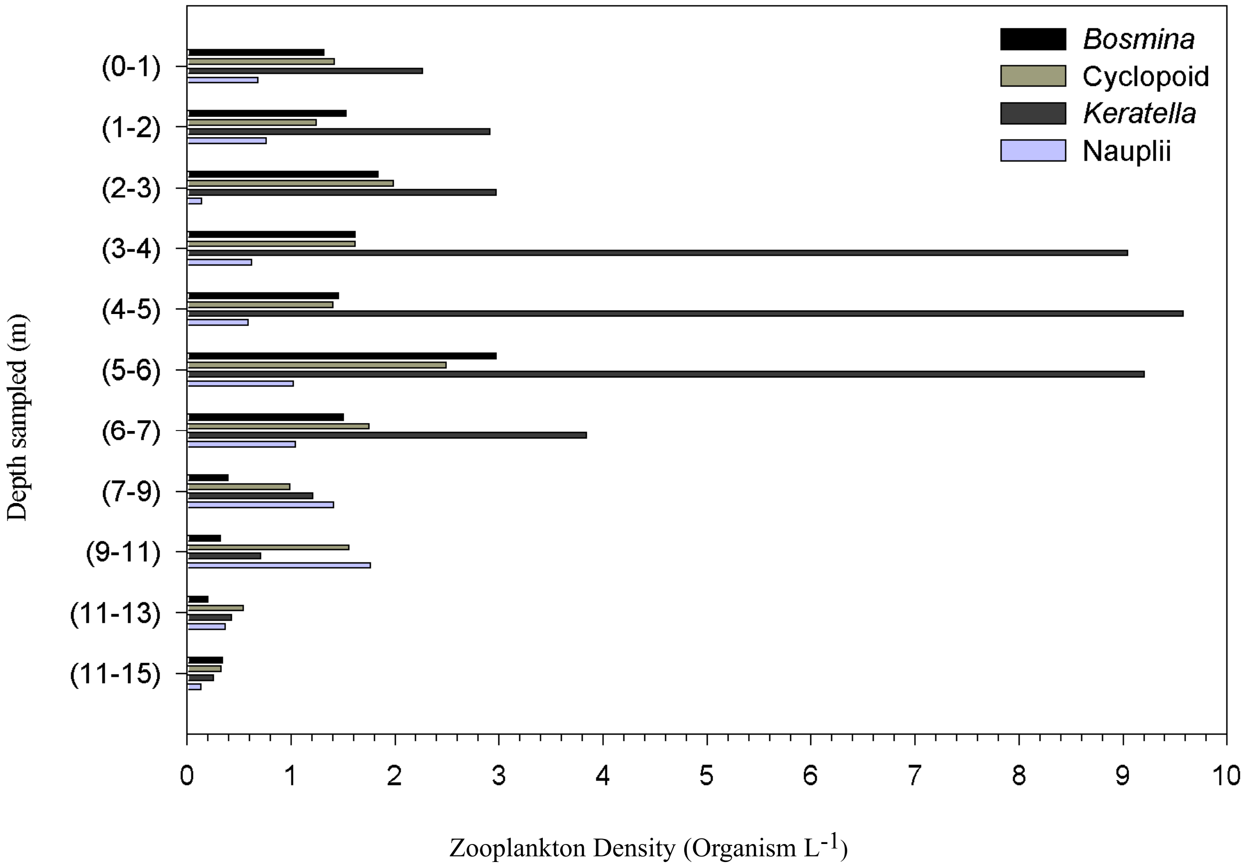

Fig. 3. Vertical distribution of the four most abundant zooplankton in Depot Pond.

ented predators and often have far reaching effects on the food web composition (Lampert and Sommer 1997). A marine species, *Alosa pseudo - harangus*, commonly known as the "alewife", was shown by Brooks and Dodson to have a tremendous impact on the zooplankton community of Crystal Lake (Stafford Springs, Connecticut). The modal zooplankton length decreased from 0.8 mm to 0.3 mm after the introduction of Alewife.

Alewife were originally introduced by Maine Fish and Game into Great East Pond and later migrated 20 km downstream in the Salmon Falls River into Milton Three Ponds. The overall mean length of 0.33 mm and the almost complete lack of larger Cladocerans such as *Daphnia* indicate the tremendous impact of this zooplanktivore. The lake was instead dominated by smaller grazers such as *Bosmina*, copepod nauplii and *Keratella*. Brown (1996) described similar conditions in Northeast and Townhouse Pond from 1994 to 1995.

When planktivore pressure is absent, the larger zooplankton grazer can out-compete the smaller ones due to superior grazing ability (Vanni 1986, Vanni *et al.* 1990). The survival of species in the presence of visual predators is largely dependent upon the size of the smallest instar of egg-producing females (Brooks and Dodson 1965). They also observed that the presence of alewife eliminates the smallest mature females of *Daphnia* and *Leptodora*, allowing smaller grazer such as *Bosmina* and *Asplanchna* to flourish.

Phytoplankton populations reduce a lake system's water clarity by absorbing and defracting the light. In lakes lacking Alewife, generally there are enough large zooplankton grazers to reduce the phytoplankton population, and thus increase water clarity. It is likely the Alewife in Depot Pond reduce its water clarity by removing the zooplankton that would normally graze down the algal phytoplankton. Conversely, if Alewife were not present in Depot Pond, one might expect that its water clarity would be greater.

Comparative Lake Study Results

All of the lakes sampled, except for Swains Lake East, exibited thermal stratification. All thermoclines were found between 7 and 10 m, except for that of Barbadoes Pond (Fig. 5a). Barbadoes Pond had the lowest surface temperature of any lake by 2°C and had a metalimnion between 4 and 7 m. Surface water temperatures ranged from 19 to 15°C and no lake reached a temperature of lower than 6°C.

Trends in the dissolved oxygen concentration in mg L^{-1} profiles varied widely (Fig. 5b). In three lakes, Townhouse, Northeast and Depot, the oxygen curve was similar to the temperature profiles. Russell Pond had a variable dissolved oxygen profile; it was steady through the epilimnion, increased in the metalimnion and then decreased in the hypolimnion. Barbadoes exhibited an initial increase with depth, then a sharp decline to an anoxic state at 5 m. All three of the Milton Ponds also contained anoxic layers. Swains Lake East had already undergone mixis and had a constant increase of dissolved oxygen through the water column. No dissolved oxygen data were obtained in mg L^{-1} for Townhouse Pond. The discrete samples for dissolved oxygen correlated well with the values obtained using the probe, except the value for the hypolimnion in Barbadoes pond.

Two lakes, Russell Pond and Swains Lake East, showed no change in specific conductivity throughout the water column (Fig. 6a). Townhouse, Northeast, Depot, and Barbadoes Ponds all had almost constant values through the entire epilimnion and a different curve in the thermocline. Townhouse Pond showed a constant increase with depth, Northeast Pond decreased first, then increased and Depot Pond exhibited a constant decrease. All of the Milton Three Ponds showed an increase of specific conductivity with depth in the hypolimnion. Townhouse Pond had the greatest rate of increase and Northeast displayed the slowest.

Oxidation reduction potential (ORP) curves were highly variable (Fig. 6b). Russell Pond exhibited almost no change throughout the entire profile while Barbadoes Pond exhibited a constant reading in the epilimnion followed by a sharp decrease in ORP at 5 m. Swains Lake East showed virtually no change throughout the entire water column. Townhouse and Northeast Ponds had constant ORP values until the thermocline, and then decreased through the rest of the water column. Depot Pond values were constant in upper waters, increased through the thermocline, and after 3 m of no change, decreased in the rest of the water column.

Russell Pond had a significantly lower ($p<0.016$) light extinction then all the other lakes (k_{ext}) (Fig. 7a). Russell Pond also had a significantly greater ($p<0.001$) Secchi disk depth, with over twice the depth of Depot Pond (Fig. 7b). The depths ranged from 2.1 to 11.0 m (mean depth = 5.1±1.1 m SE). All other lakes did not differ significantly from eachother in SDD and k_{ext}.

Pink end alkalinities (Fig. 7c) ranged from 0.3 to 6.6 (mean = 3.7±1.3 SE) and gray end alkalinities (Fig. 7d) ranged from 0.3 to 8.4 (mean = 4.8±1.2 SE).

The pink end and gray end measurement of

Table 4. Phytoplankton biotic index adapted by Baker from Hillsenhoff (1978) biotic index. Used to assess water quality using the biotic index values of sample phytoplankton taxa.

Biotic Index	Water quality	Degree of organic pollution
0.00 - 1.75	excellent	No organic pollution
1.76 - 2.25	very good	Possible slight organic pollution
2.26 - 2.75	good	Some organic pollution
2.76 - 3.50	fair	Significant organic pollution
3.51 - 4.25	poor	Very significant organic pollution
4.26 - 5.00	very poor	Severe organic pollution

alkalinity were found to be statistically similar (r^2=0.97) among all sites. Measurements were not taken at all locations for each alkalinity endpoint, but some patterns emerged (Fig. 7c, 7d). Russell Pond and Swains Lake East had significantly lower ($p<0.001$) lower pink alkalinity than all other lakes in which it was measured. The same pattern was observed for Russel Pond in gray alkalinity, but Barbados Pond exibited a significantly higher value. The Milton Three Ponds all had similar alkalinities, although some significant differences could be observed.

Chloropyll *a* concentrations ranged from Russell Pond at 0.86 µg L^{-1} to Barbadoes Pond at 6.14 µg L^{-1} (mean = 3.6±0.6 µg L^{-1} SE) (Fig. 8a). All other lakes were clustered around the 3 to 4 mg L^{-1} range. Barbadoes Pond and Russell Pond were significantly different from all the other lakes ($p<0.001$).

Phosphorus ranged from Russell Pond at 4.7 µg L^{-1} to Barbadoes Pond at 17.9 µg L^{-1} (mean = 12.2±2.0 µg L^{-1} SE) (Fig. 8b). The data were analyzed by ANOVA, but Northeast Pond was excluded due to sample contamination. Barbadoes Pond (p=0.001 to 0.02) and Russell Pond (p=0.002 to 0.047) were found to be significantly different from the other lakes.

Lake water fraction fluorescence values (Fig. 8c-d) ranged from 0.7 to 5.3 RFU (mean = 3.6±0.6 RFU SE) for WLW, 0.1 to 4.73 RFU (mean = 2.7±0.4 RFU SE) for the greater than 30 µm fraction, and 1.0 to -0.2 - 2.6 RFU (mean = 0.9±0.3 RFU SE) for the less than 30 µm fraction. In the WLW measurement, three significant groups could be seen (Low WLW RFU= RP; Medium WLW RFU= NP, DP, SE, SW; High WLW RFU= TP, BP). In the less than 30 µm measurements, Townhouse and Barbadoes ponds were statistically different from the rest of the lakes ($p<0.001$). In the greater than 30 µm data, only Russell Pond differed significantly ($p<0.05$) from the rest of the lakes and was also the only negative value.

Dissolved carbon dioxide samples showed differences between lake layers, but yielded few significant differences between lakes (Fig. 9a). This may be due to the lack of data available for analysis. Out of the metalimnetic data, Barbadoes was found to be statistically significant in dissolved carbon dioxide from Depot Pond, Russell Pond and Swains Lake West ($p<0.001$). In the hypolimnetic samples, Barbadoes Pond was significantly different from all lakes except Northeast Pond and Townhouse Pond ($p<0.05$) and Depot Pond differed from Russell Pond (p=0.025), Swains Lake East (p=0.005) and West (p=0.018). The dissolved oxygen discrete samples from the epilimnion were different between Barbadoes Pond and all lakes, and between Depot Pond, Russell Pond and Swains Lake East sites.

All of the lakes studied had similar values for water color. The only significant difference in water color was Russell Pond, which had significantly less color than all of the other lakes ($p<0.07$) (Fig. 9b).

Mean zooplankton length also separated the lakes into two distinct groups (Fig. 9c). The first of these groups included The Milton Three Ponds and had an mean body length of 0.32 mm. The other group, including Russell Pond and Barbadoes Pond, had a mean length of 0.65 mm.

Net phytoplankton biotic indexes (NPBI) were calculated from the relative abundance of different taxa of net phytoplankton. Each taxon was given an index value pertaining to its tolerance to pollutants in water. The NPBI value for a lake system provides a rough assessment of water quality. NPBI values for the study lakes ranged from 1.6 to 4.2 (mean = 2.8 ± 0.5 SE) (Fig. 9d).

The NPBI for the lakes could be separated into two groups. One group, including Russell Pond and the Milton Three Ponds, had values (1 to 2.7) indicative of excellent to good water quality. The other group, composed of the Swains Lakes and Barbadoes Pond (values near 4) can be considered to have poor water quality.

Each lake was assigned a trophic level (oligotrophic, mesotrophic and eutrophic) based on ranges of total phosphorus concentration, chlorophyll *a* concentration and Secchi disk transparency, according to Forsberg and Ryding (1980) (Table 5). Oligotrophic lakes are generally deep, clear lakes with large areas of open water areas and little production due to low nutrient levels (Lamper and Sommer, 1997). Eutrophic lakes are

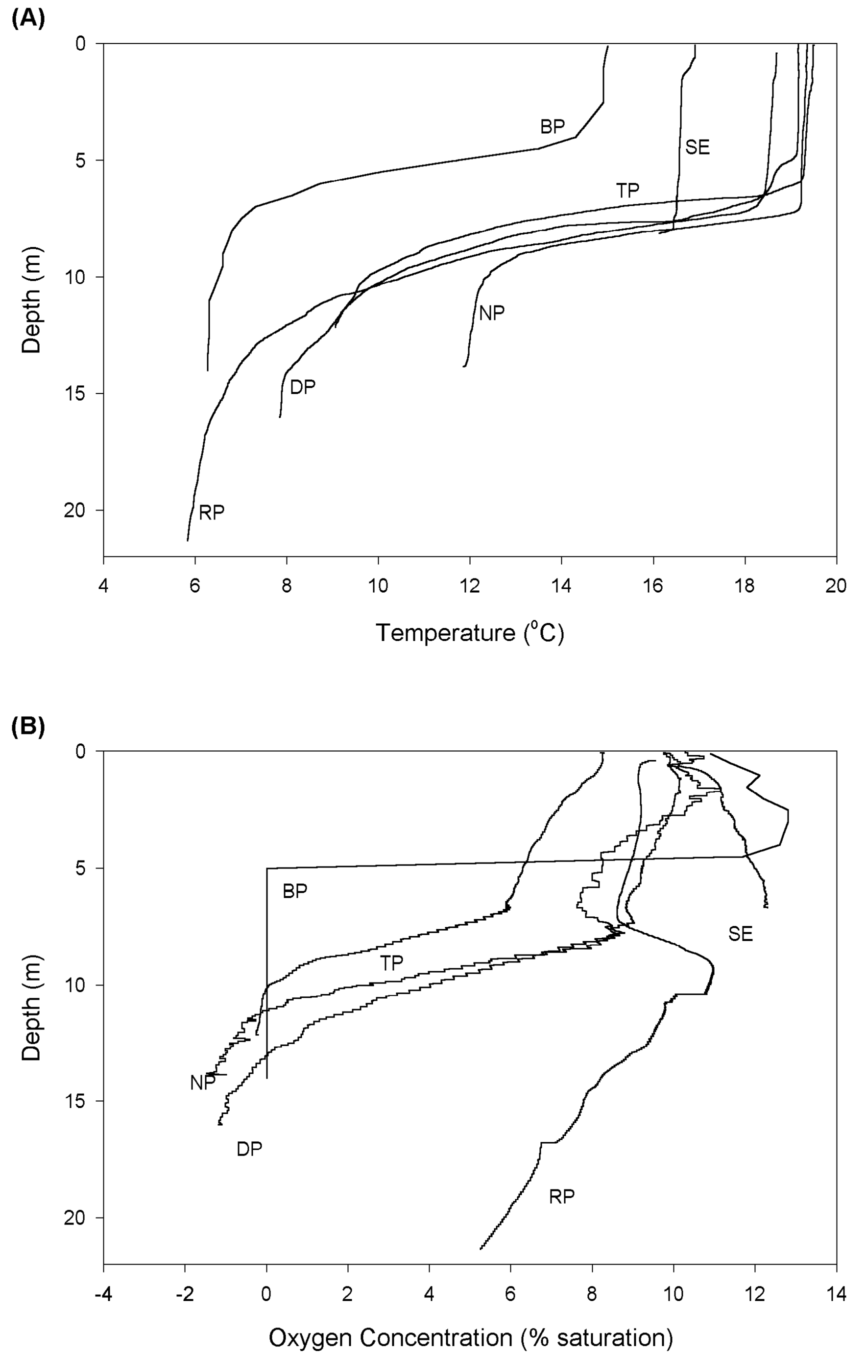

Fig. 5. Vertical profiles of six study lakes for temperature (A) and oxygen concentration (B). Lakes are represented as follows: TP - Townhouse Pond, NP- Northeast Pond, DP - Depot Pond, RP - Russell Pond, SE - Swains lake East, and BP - Barbados Pond.

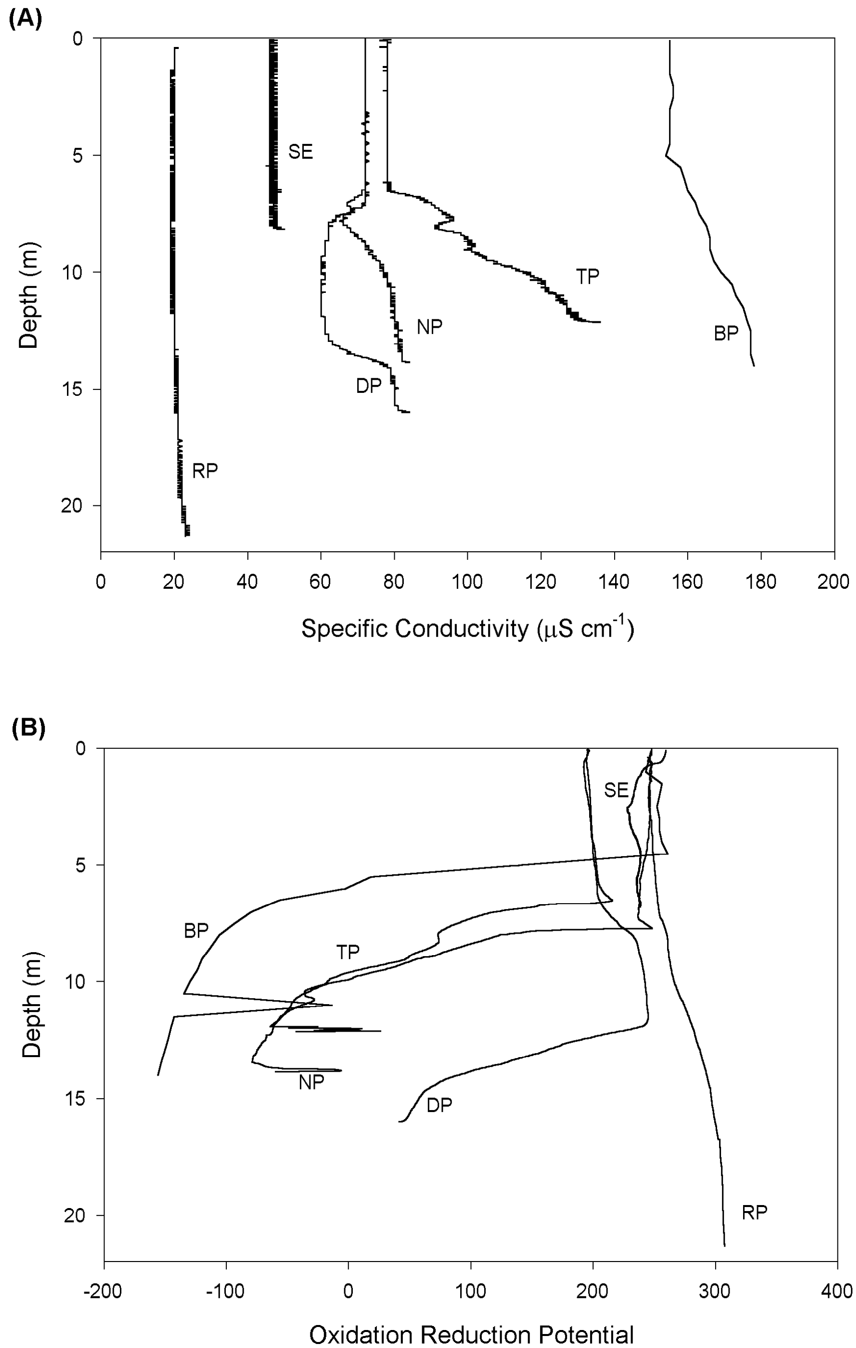

Fig. 6. Vertical profiles of six study lakes for a specific conductance (A) and oxidation reduction potential (B). Lakes are represented as follows: TP - Townhouse Pond, NP- Northeast Pond, DP - Depot Pond, RP - Russell Pond, SE - Swains lake East, and BP - Barbados Pond.

Table 5. Trophic determination of study lakes using method from Forsberg and Ryding (1980) and comparison with New Hampshire Department of Environmental Services trophic levels. Starndard error in parentheses. Italicized trophic levels indicated differences between the studies. (*Sample was contaminated)

Lake	Total-P μg L^{-1}	Trophic level	Chlorophyll a μg L^{-1}	Trophic level	Transparency (m)	Trophic level	This study (Overall)	NHDES (Overall)
Russell	4.7 (0.8)	Oligo	0.9 (0.1)	Oligo	11.0 (0.2)	Oligo	Oligo	Oligo
Townhouse	-	Oligo	4.2 (0.3)	Meso	3.8 (0.0)	Meso	*Meso*	*Oligo*
Northeast	-	Meso	3.1 (0.2)	Meso	3.5 (0.1)	Meso	Meso	Meso
Depot	11.2 (2.3)	Oligo	3.4 (0.2)	Meso	4.6 (0.1)	Oligo	*Oligo*	*Meso*
Swains East	9.8 (0.5)	Oligo	3.1 (0.4)	Meso	3.7 (0.1)	Meso	Meso	Meso
Swains West	12.2 (0.3)	Oligo	4.2 (0.1)	Meso	4.0 (0.0)	Meso	Meso	Meso
Barbadoes	17.9 (0.9)	Meso	6.1 (0.2)	Meso	2.1 (0.0)	Eutro	Meso	Meso

generally shallow, turbid bodies of water with high nutrient levels that allow high production. Mesotrophic lakes are along the gradient in between the two other types of lakes, having a moderate levels of both production and nutrients.

The classifications determined in this study differed from those reported in the Lake Lay Monitoring Program (LLMP) for the Milton Three Ponds. The LLMP's previous classifications listed Depot Pond as mesotrophic and Townhouse Pond as oligotrophic. Our results indicated otherwise. Barbadoes Pond also had many characteristics indicating a eutrophic body of water, but over all had a mesotrophic classification.

Comparative Lake Study Discussion

Out of all of the profiles taken, only the temperature profile seemed to be consistent throughout all of the lakes. All of the lakes had a thermocline between 7 and 10 m, except for Barbadoes, which had a thermocline between 3 and 5 m. The other profiles were widely varied. Only two of the lakes, Russell Pond and Swains Lake East, did not have anoxic zones.

Phosphorus was found to be connected to WLW flourometry, the under 30 μm fraction, the over 30 μm fraction, chlorophyll *a* concentration, and finally, the phytoplankton biotic index (Table 6). Although these data points agree well with Dillon and Rigler (1974), several factors must be kept in mind when looking at the results. All of the lakes in the study had low phosphorus levels, thus falling low in the range of phosphorus found in lakes. The analyses indicated a linear trend of the worldwide effects of phosphorus levels on chlrorophyll *a* concentrations, while the Dillon and Rigler (1974) noted an exponential trend. This pattern might have been stronger if lakes with higher phosphorus levels had been included in the study. Also, the data were collected on only one day and from one area of each lake. Thus, the data do not represent the entire lake over any period of time. In spite of this, tight correlations emerged and suggested relationships between some of the parameters measure.

The effect of alewife was seen in all of the Milton Ponds. The intense top-down pressure from the planktivores dramatically lowered the mean size of zooplankton in affected lake Northeast, Depot and Townhouse Ponds, all containing populations of these planktivorous fish, had an mean zooplankton length of 0.32±0.01 mm, while the lakes without alewife populations, Russell and Barbadoes Ponds, had an mean size of 0.65±0.02 mm. Data for the Swains Lake Basins were seen in the number of grazers L^{-1}. In the three mesotrophic lakes without alewife, *Daphnia* was much more abundant than *Bosmina*, while the exact opposite occurred in the Milton Three Ponds.

At first glance, the trophic classifications assigned to the lakes in our study seems to indicate changes in the lake trophic levels since the New Hampshire Depot of Environmental Service's determination 17 years ago; however, it is possible that there has been no dramatic change in the lakes. If the data from previous classifications were reevaluated with the Forsberg and Ryding (1980) system, the trophic level classification for

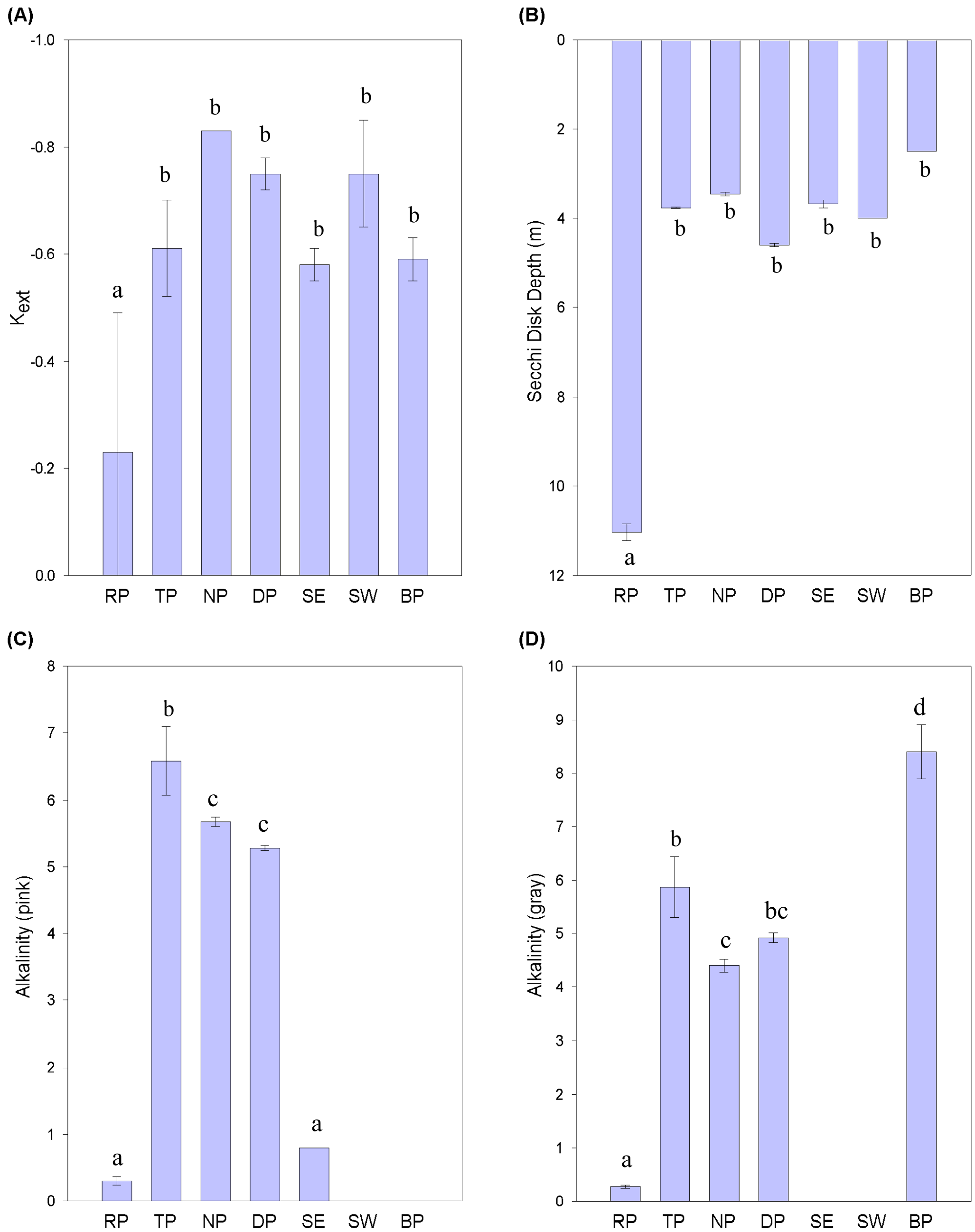

Fig. 7. Comparison of coefficient of light extinction (A), Secchi disk depth (B), pink end alkalinity (C) and gray end alkalinity(D) in six study lakes. Lakes are represented as follows: TP - Townhouse Pond, NP- Northeast Pond, DP - Depot Pond, RP - Russell Pond, SE - Swains lake East, and BP - Barbados Pond. Bars represent standard error.

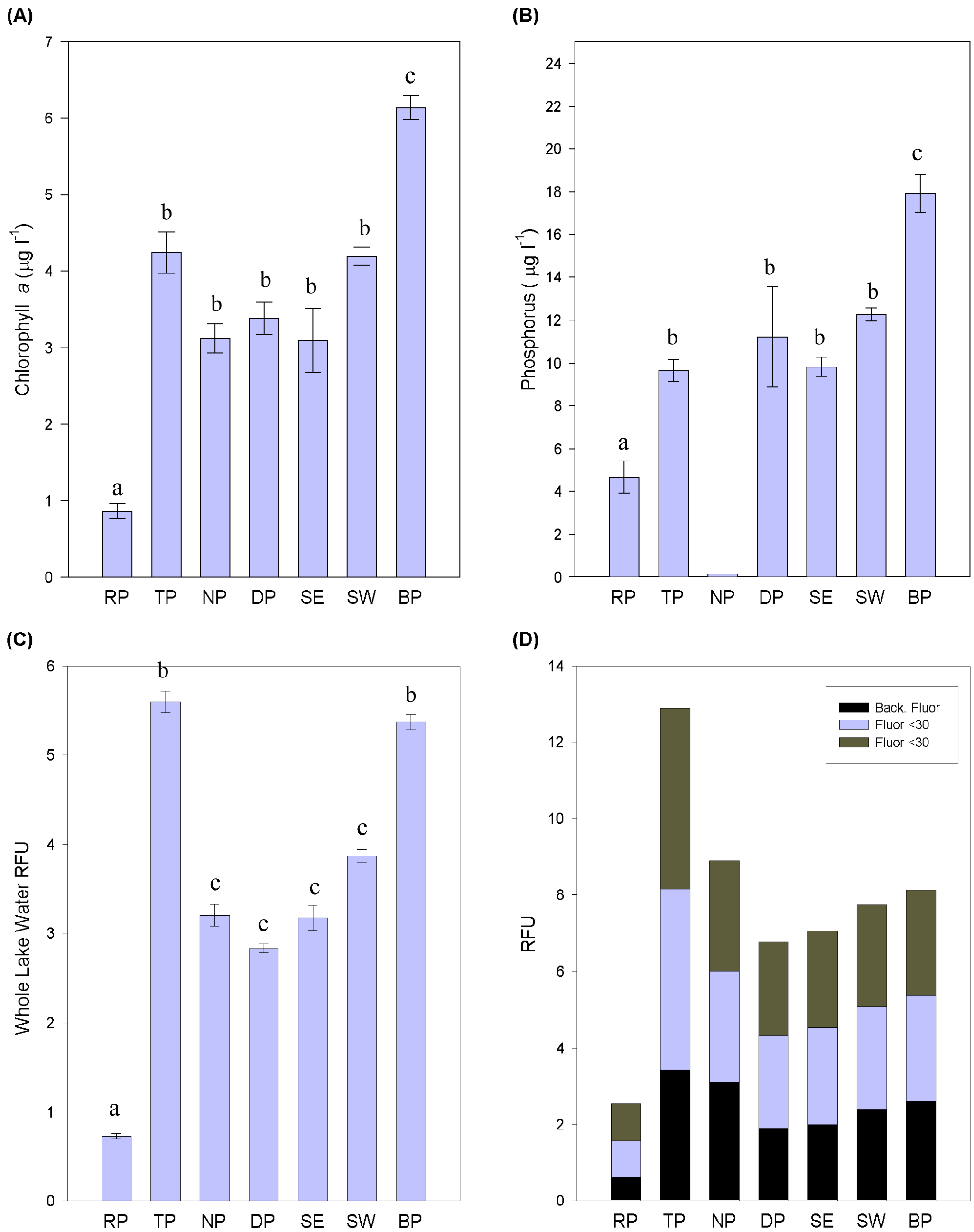

Fig. 8. Comparison of chlorophyll *a* concentration (A), phosphorus concentration (B), fluorescence (C) and pink end alkalinity (D) in six study lakes. Lakes are represented as follows: TP - Townhouse Pond, NP- Northeast Pond, DP - Depot Pond, RP - Russell Pond, SE - Swains lake East, and BP - Barbados Pond. Bars represent standard error.

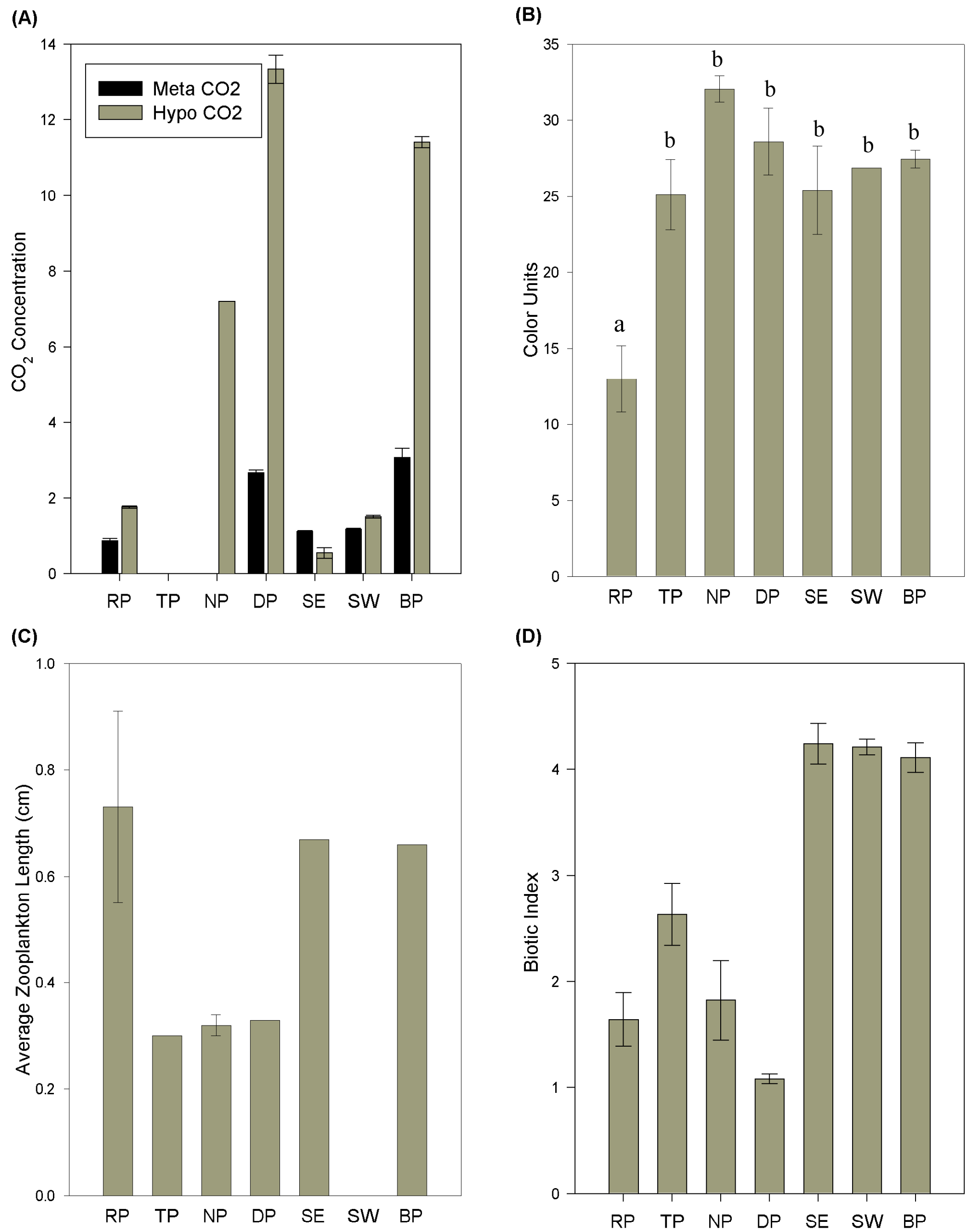

Fig. 9. Comparison of hypolimnetic carbon dioxide (A), epilimnetic carbon dioxide (B), color (C) and biotic index (D) in six study lakes. Lakes are represented as follows: TP - Townhouse Pond, NP- Northeast Pond, DP - Depot Pond, RP - Russell Pond, SE - Swains lake East, and BP - Barbados Pond. Bars represent standard error. Zooplankton body lengths were not measured for Swains Lake West.

Table 6. Correlations between phosphorus concentrations and phytoplankton parameters.

	p-value	r^2 value
Whole lake water fluorometry	0.001	0.856
< 30 fraction fluorometry	0.004	0.836
> 30 fraction fluorometry	0.006	0.807
Chlorophyll *a* concentration	<0.001	0.982
Phytoplankton biotic index	0.001	0.914

1980 would be the same as those found in this study. Also, lakes often have different classifications based on the different parameters examined. It is important to realize that trophic levels of lakes must be thought of as a gradient, with one lake having more eutrophic characteristics than another, instead of thinking of the classification as an all or nothing basis.

Diagnostic Summary

Most of the lakes in the study were borderline meso- and oligotrophic, except for Russell Pond, which was oligotrophic. Statistical correlations were found between measurements of phytoplankton concentration (fluorescence, chlorophyll *a* concentration, phytoplankton biotic index) and phosphorus concentrations. Zooplankton communities were extremely different in size and species composition across the lakes, with two clear groups emerging. One group composed of the Milton Three Ponds, had a significantly ($p<0.05$) smaller mean zooplankton length, dominated by the small Cladoceran *Bosmina* and virtually no *Daphnia*. The other remaining lakes had a large zooplankton length, low concentrations of *Bosmina* and high concentrations of the large grazer *Daphnia*. A comparison of lakes, excluding Barbadoes due to its high nutrient content and subsequent influence on zooplankton populations, found large differences between the two groups of lakes.

Two main conclusions were reached. First, was that a bottom-up effect could be seen in the study lakes. Although phosphorus levels were low, correlations were found between the phosphorus levels and various parameters representing the size and abundance of the phytoplankton community. Depot Pond had a phytoplankton community typical of the nutrient levels found. Second, the influence of a planktivorous fish, Alewife, could be seen in the characteristics of the zooplankton communities. A top-down influence was controlling the size and structure of zooplankton populations.

Although the area immediately surrounding Depot Pond is moderately populated and roads pass near many of the lakeshores, the lake appears only moderately impacted by humans. The pH of the epilimnion was a neutral 7 and the phosphorus levels were intermediate. However, a great deal of danger exists for human impact to seriously affect the health of the lake. Heavy metals were not sampled for in this study, but may be present in high numbers due to the proximity of roads to the lakeshore. Data found in the Milton Ponds Water Quality Monitoring Program for 1996 (Craycraft and Schloss 1996) showed that peak specific conductance in 1996 was at around 65 mS cm^{-1} near the bottom. In 1997 this measurement increased to about 83 $\mu S\ cm^{-1}$. The reason for such an increase in specific conductivity might be due to an overall increase of dissolved salts and other ionized matter.

The area immediately surrounding Depot Pond is moderately to highly populated by houses. Increases in specific conductance could be the result of faulty septic or infiltration units, salt runoff from adjacent roads and highways, or from fertilizers and other pollutants. With a community of people living on and around its shores, the danger exists for sewage or wastewater pollution to add nutrients to the lake and cause a shift in the producer trophic level; thus, changing the entire food web. Soil erosion from surrounding areas aid in the amount of pollutants entering the system. Steps should be taken to maintain a buffer strip along the lake shore. Nutrient runoff that would normally empty into the pond could be absorbed by the surrounding buffer zone. The low alkalinity of Depot Pond does not allow for much buffering, making the lake susceptible to the effects of acid rain. Even a small change in pH can cause grave changes in lake chemistry and biotic composition.

Care should be taken to prevent the introduction of additional phosphorus into the watershed of the lake. Planning boards should be careful when allowing additional homes and camps to be built on or near the lake. Development will continue if allowed, and a reasonable amount of caution should be taken. Pollution leading to acid rain is difficult to control because it does not originate close to where it falls to the ground. The only way this problem could be addressed would be to ensure that New Hampshire fought to limit pollution emissions. Factories and plants hundreds of miles away would cause most acid rain problems tht would appear in this area.

Future studies should continue to examine the impact of *Alosa* on the zooplankton community and test for trends toward eutrophication. Vertical sampling of the zooplankton and length determination can indicate the integrity of zooplankton communities. Phosphorus levels appear to be a good indicator of the status of phytoplankton. Further tests relating chlorophyll *a* concentrations, fluorescence and the biotic index to this limiting nutrient would provide data for lakes with low levels of phosphorus, perhaps bolstering the data at the low end of the curve and providing more accurate correlations to make predictions. Also, testing must be performed regularly throughout the entire year to so as to ensure the collection of representative and comprehensive data.

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Appendix A: Lake Sampling Data Set

					Zooplankton			
		Chlorophyll *a* mg L-1	Phosphorus mg L-1	SDD m	Body length mm	NPBI -	Kext -	CDOM CPU
RP	Average	0.86	4.65	11.03	0.69	1.60	0.26	12.99
	SE	0.10	0.75	0.19	0.17	0.21	0.02	2.18
NP	Average	3.12	-	3.50	0.32	1.75	0.28	32.04
	SE	0.19	-	1.15	0.02	0.47	-	0.87
TP	Average	4.24	9.65	3.77	0.30	2.65	0.61	25.11
	SE	0.27	0.52	0.02	-	0.32	0.09	2.29
DP	Average	3.38	11.20	4.62	0.33	1.05	0.75	28.58
	SE	0.21	2.33	0.04	-	0.07	0.03	2.18
BP	Average	6.14	17.92	2.10	0.66	4.08	0.59	27.42
	SE	0.16	0.89	0.15	-	0.23	0.04	0.58
SLE	Average	3.09	9.82	3.68	0.61	4.20	0.59	25.40
	SE	0.42	0.46	0.09	-	0.31	0.05	2.89
SLW	Average	4.19	12.24	4.00	-	4.15	0.75	26.85
	SE	0.12	0.30	-	-	0.18	0.10	0.00

		Alkalinity		**Fluorescence**			**CO2**		**DO**	
		Grey end mg CaCO3	Pink end mg CaCO3	WLW RFU	<30 mm RFU	>30 mm RFU	Metalimnetic mg L-1	Hypolimnetic mg L-1	Epilimnetic mg L-1	Hypolimnetic mg L-1
RP	Average	0.27	0.30	0.73	0.97	-0.23	0.88	1.77	8.03	8.67
	SE	0.03	0.06	0.03	0.03	0.03	0.05	0.03	0.09	0.03
NP	Average	4.40	5.67	3.53	2.90	0.63	-	4.80	7.97	0.14
	SE	0.12	0.07	0.19	0.10	0.09	-	2.40	0.26	0.01
TP	Average	5.87	6.58	5.60	4.73	0.87	-	-	-	-
	SE	0.57	0.51	0.12	0.07	0.07	-	-	-	-
DP	Average	4.92	5.28	2.87	2.52	0.35	2.67	13.33	6.87	1.93
	SE	0.09	0.04	0.06	0.04	0.05	0.07	0.37	0.28	0.72
BP	Average	8.40	-	5.37	2.77	2.60	3.07	11.40	10.53	1.97
	SE	0.50	-	0.09	0.19	0.10	0.24	0.15	0.24	0.09
SLE	Average	-	0.70	3.20	2.53	0.67	1.12	0.56	8.64	8.00
	SE	-	0.06	0.16	0.18	0.06	0.02	0.14	0.07	0.06
SLW	Average	-	-	3.87	2.67	1.20	1.18	1.52	7.00	7.00
	SE	-	-	0.07	0.03	0.06	0.02	0.04	0.40	0.23