Biological Assessment of the Plankton in Vancouver Lake, WA

Stephen Bollens and Gretchen Rollwagen-Bollens
Washington State University Vancouver

Year One Annual Report

Introduction

The Vancouver Lake Watershed Partnership is interested in understanding the processes that lead to the formation, persistence and decline of cyanobacteria and other harmful algal blooms in Vancouver Lake and similar bodies of water. Vancouver Lake has experienced numerous nuisance blooms of cyanobacteria in recent years (e.g. Wierenga 2005, 2006), often necessitating closure of the Lake to recreational use. Indeed, there is growing evidence that the incidence of noxious cyanobacterial blooms in freshwater lakes and rivers is increasing worldwide, most often associated with increased nutrient inputs, i.e. eutrophication (e.g. Dokulil & Teubner 2000, Sellner et al. 2003, Yamamoto & Nakahara 2005). Excessive abundance or "blooms" of cyanobacteria may have detrimental effects on lake ecosystems and water quality, including development of surface scums, depleted oxygen levels, and (in some cases) production of toxins that can negatively affect aquatic life and humans (Carmichael 1992, Codd 1995, Sellner et al. 2003). This phenomenon is of great concern to water resource managers, particularly with respect to human health, as well as to the public whose use and enjoyment of these environments may be prohibited as a result.

With support from the Partnership, Washington State University Vancouver initiated an assessment of the planktonic assemblage and environmental conditions in Vancouver Lake as a first step in identifying and quantifying the factors that influence cyanobacterial blooms. This report summarizes the results from the first year of the assessment (March 2007 to February 2008), which was focused on three specific objectives: 1) to determine the abundance, distribution and taxonomic composition of cyanobacteria, algae and zooplankton in Vancouver Lake over a full annual cycle, 2) to initiate some preliminary investigations of the biotic (e.g., grazers) and abiotic (e.g., temperature, nutrients) factors influencing these blooms, and 3) to analyze the extant data on cyanobacteria blooms in Vancouver Lake for spatial and temporal patterns and trends in abundance, as well as provide a literature review.

Background

Vancouver Lake, in Clark County, WA, is a large, shallow lake in the lower Columbia River floodplain that is popular with the local community for swimming, boating, fishing and other recreational activities. Vancouver Lake is also an important habitat for a range of fish species, as well as migrating and resident waterfowl, raptors and songbirds. Up until the early 19^{th} century, Vancouver Lake was a relatively clear, moderately deep (6-8 m) lake flushed twice yearly by the spring and fall freshets of the Columbia River. Dam construction and diking along the south and west shoreline eliminated this natural flushing system, and urbanization in the surrounding drainage basin increased sedimentation rates, such that the lake shallowed to a depth of only 1 meter, on average, by 1981 and water quality was diminished (Gorini 1987).

In response to this, an artificial flushing channel was completed in 1983, along with dredging in the Lake, as a means to re-establish flushing by the Columbia River and improve water quality. However, average depth remains ~1 meter (range 0.8 to 2.5m, up to 4.5m at mouth of flushing channel) and water quality in Vancouver Lake remains quite poor, with high levels of dissolved nitrogen and phosphorus, high turbidity, and high pH (Wierenga 2005, 2006). Most notably, Vancouver Lake has experienced numerous summertime blooms of cyanobacteria over the past several years, often necessitating closure of the Lake to swimming and other recreational use. The blooms have been variable in intensity, however cyanobacterial abundance has met or exceeded the threshold established by the World Health Organization in three of the last four years, which led Clark County officials to close all uses of the Lake.

Vancouver Lake is one of many temperate, shallow lakes worldwide that are experiencing an increased frequency of noxious cyanobacteria blooms. Indeed, seasonal blooms of cyanobacteria and other algae are natural occurrences that have been documented in lakes of varying morphology and location for decades. All lakes evolve naturally through ecological succession from oligotrophic states (deep, clean and unproductive) to eutrophic states (shallow – due to long-term sedimentation – and infested with aquatic plants and phytoplankton) (Hutchinson 1973). However, numerous studies have demonstrated that the eutrophication process in lakes is being accelerated by human activity, through sewage and fertilizer inputs, deforestation, road construction, real estate development and other disturbances in lake watersheds, and is contributing to an increase in bloom frequency and intensity (e.g. Paerl 1988, Elser et al. 1990, Sellner et al. 2003 and references therein).

In particular, shallow lakes present a distinct set of characteristics and challenges with regard to the factors that contribute to algal blooms, as compared to deep lakes. By definition, shallow lakes are permanent standing bodies of water in which light may penetrate all the way to the bottom, sufficient to potentially support growth of aquatic plants over the entire basin – although turbidity often prevents this in practice (Wetzel 2001). Shallow lakes typically receive substantial loading of terrestrial-derived organic matter and nutrients, usually with low loss rates of these materials, such that the ratio of nutrient concentration to total water volume is very high. Moreover, in shallow lakes the proportion of water volume in direct contact with bottom sediments is much higher than in deep lakes, increasing the potential for contributions of sedimented nutrients to the dissolved pool (Wetzel 2001).

Also in contrast to deep lakes, shallow lakes may switch between different "stable states" that represent contrasting physical and biological conditions. Shallow lakes can be in a clear-water, macrophyte (large, submerged aquatic plants) dominated state, normally under low nutrient conditions, or a turbid state dominated by phytoplankton and high nutrient concentrations (Scheffer et al. 1993, Scheffer 1998). Many studies have documented the existence of these alternative stable states in shallow lakes (e.g. Moss et al. 1996, Korner 2001, Dent et al. 2002, Bayley & Prather 2003, Dokulil & Teubner 2003, Jackson 2003). The clear water state is maintained by the action of macrophytes, which outcompete phytoplankton for nutrients, reduce sediment resuspension, and provide a refuge for zooplankton against predation by fish (Schriver et al. 1995, Scheffer et al. 1997, Van den Berg et al. 1998, Blindow et al. 2002). The turbid state is stabilized by feedback mechanisms between cyanobacteria and turbidity. Under high nutrient conditions, dense blooms of filamentous cyanobacteria create shady conditions and out-compete phytoplankton for both light and nutrients (Scheffer et al. 1997). In addition, the absence of plants and the foraging behavior of benthic-feeding fish (e.g. carp) facilitate wind-driven resuspension of sediments to maintain the turbid conditions (Scheffer et al. 2003). But our understanding of how resilient these states are to switching from one condition to the other is incomplete and the subject of on-going research (Ibelings et al. 2007).

Vancouver Lake is currently in the turbid state, as are many other temperate, shallow lakes in North America. However, in many of these continually turbid shallow lakes (including Vancouver Lake) the phytoplankton is not dominated by cyanobacteria throughout the year. So the question remains about what factors contribute to rapid accumulation of cyanobacteria during summer and fall, as well as what may explain the demise of these blooms.

Investigations in a range of shallow lakes point to a multiplicity of factors that may influence the timing, frequency and intensity of cyanobacteria blooms, but rarely is only one factor responsible (reviewed in Dokulil & Teubner 2000 and Paerl & Fulton 2006). Elser (1999) describes a "pathway" by which noxious cyanobacteria blooms may come about, depending on a set of both abiotic and biotic factors, which provides a helpful construct for evaluating which factors may be most important under varying conditions, both in Vancouver Lake and in shallow lakes more generally. According to Elser's pathway, in order for a cyanobacteria bloom to begin there must first be high nutrient loading to the system. Moreover, according to Elser, if the ratio of nitrogen to phosphorus (N:P) in the nutrient load is low then cyanobacteria will be favored over algae (e.g. diatoms) due to their ability to utilize N_2-nitrogen. However, low N:P is usually not sufficient to stimulate cyanobacteria blooms in all cases. In Elser's pathway, light levels and hydrodynamic conditions must also be optimal – typically cyanobacteria colonies will proliferate in thermally stable water columns under moderate light levels (Scheffer 1997). Finally, according to Elser, the composition and structure of the pelagic food web, i.e. the abundance and composition of planktonic grazers such as cladoceran zooplankton and/or protozoans, will ultimately determine whether (given the above abiotic conditions) a cyanobacteria bloom will form.

Based on this potential pathway, and the previous research outlined above, our Vancouver Lake assessment therefore quantified the distribution, abundance and composition of the planktonic organisms (i.e. algae, cyanobacteria, and both protozoan and crustacean zooplankton) in the Lake, as well as a wide range of water quality data, including temperature, dissolved oxygen, secchi depth, and nutrient concentrations over an annual cycle and at locations distributed throughout the Lake.

Methods

The first year of the biological assessment of Vancouver Lake consisted of field sampling over several temporal scales. On a quarterly basis beginning in April 2007, 8 open-water locations in the Lake were sampled from the RV *Sea-Coug*. In addition, on a monthly (November – March), bi-weekly (April; October), and weekly (May – September) basis, water and plankton samples were collected from the Vancouver Lake Sailing Club dock (Figure 1, Table 1).

At each station and sampling time, the same field sampling procedures were followed: Temperature and dissolved oxygen profiles from the surface to the bottom were obtained using a Seabird Conductivity-Temperature-Depth (CTD) recorder (quarterly sampling from the RV *Sea-Coug)* or a YSI 85 probe (monthly/bi-weekly/weekly dock sampling). Relative subsurface light penetration was estimated by measuring the depth below the surface at which a Secchi disk was no longer visible.

Figure 1. Map of Vancouver Lake illustrating station locations for field sampling. Green shapes indicate open water stations. Site 1 is also the location of the Vancouver Lake Sailing Club dock.

Triplicate water samples were collected from the surface using a clean bucket, and subsamples taken for later laboratory analyses to measure nutrient concentration and chlorophyll *a* concentration. For nutrient analysis, 50-ml aliquots were obtained using a syringe equipped with a 0.45 µm filter, stored in a plastic vial and kept chilled until analysis. For chlorophyll *a* analysis, 20-100 ml aliquots were filtered over GFF filters, and the filters wrapped in foil and immediately frozen. Additional triplicate water samples were collected from the surface and subsamples preserved in 5% acid Lugol's solution, for enumeration and identification of cyanobacteria, algae and protozoan plankton.

Triplicate vertical zooplankton net tows were conducted to capture plankton >73 µm in size, with the net contents concentrated and preserved in 5-10% formalin. In addition, during quarterly sampling from the RV *Sea-Coug*, triplicate benthic samples were taken at each station using a petite ponar grab. Samples were passed through a 500 µm sieve, with the sieve contents fixed in 5-10% formalin and sent to the University of Washington for analysis.

Upon return to the laboratory, the water and plankton samples were processed and analyzed according to the following protocols: Subsamples of water for nutrient analysis were sent to the Marine Chemistry Lab at the University of Washington's School of Oceanography for determination of dissolved nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), phosphate (PO_4), and silicate (SiO_4) concentrations.

In order to measure chlorophyll concentrations, thawed GFF filters were placed in vials containing 20 ml of 90% acetone for 24 hours. The concentration of chlorophyll *a* suspended in the acetone was measured on a Turner Model 10 AU fluorometer, using the acidification method (Strickland & Parsons 1972).

To determine the abundance of planktonic protists and cyanobacteria, 1-10 ml aliquots of the Lugol's preserved water samples were settled overnight in Utermohl chambers, and the chambers examined using an Olympus CK-40 inverted microscope at 200-400x to enumerate and identify unicellular plankton ~5-150 µm in size. To determine the abundance and composition of the metazoan zooplankton, 5-25 ml aliquots of the formalin-preserved zooplankton net samples were examined using a Leica MZ-6 stereo microscope to enumerate and identify the metazoan taxa (e.g. cladocerans, copepods, rotifers). Aliquot size was varied to ensure a minimum of 300 individuals were enumerated per sample. Benthic invertebrate samples were examined using a Leica stereo microscope to determine numerical abundance and taxonomic composition. Individuals were identified to the lowest possible taxon.

Statistical analyses of spatial variability in plankton community composition across the 8 stations sampled in Vancouver Lake over the annual cycle were conducted using Kendall's tau correlation tests (Zar , SAS statistical software). All taxa that comprised >1% of total abundance in each sample were included in the analyses.

Results

During Year 1 of the Vancouver Lake Biological Assessment project, quarterly cruises with the RV *Sea-Coug* were conducted in April, July, October 2007, and February 2008. In addition, the Lake was sampled from the Sailing Club dock 37 times between March 2007 and February 2008 (Table 1).

Spatial Patterns

Water quality. Mean surface temperature, dissolved oxygen concentration, Secchi depth, chlorophyll *a* concentration, and surface concentrations of inorganic nitrogen (NO_3, NO_2, NH_4), phosphate (PO_4), and silicate (SiO_4) in general showed very little variation among the 8 sampling locations throughout the lake over the course of the year. The variation in these measured variables was the least in April/May 2007, with the exception of NH_4 concentration, which was substantially higher at the dock station and station 2 compared to the other 5 locations (Figure 2). In July 2007 water quality parameters were also consistent among stations 2-8, with elevated chlorophyll *a*, dissolved oxygen and NH_4 observed at the dock station (Figure 3).

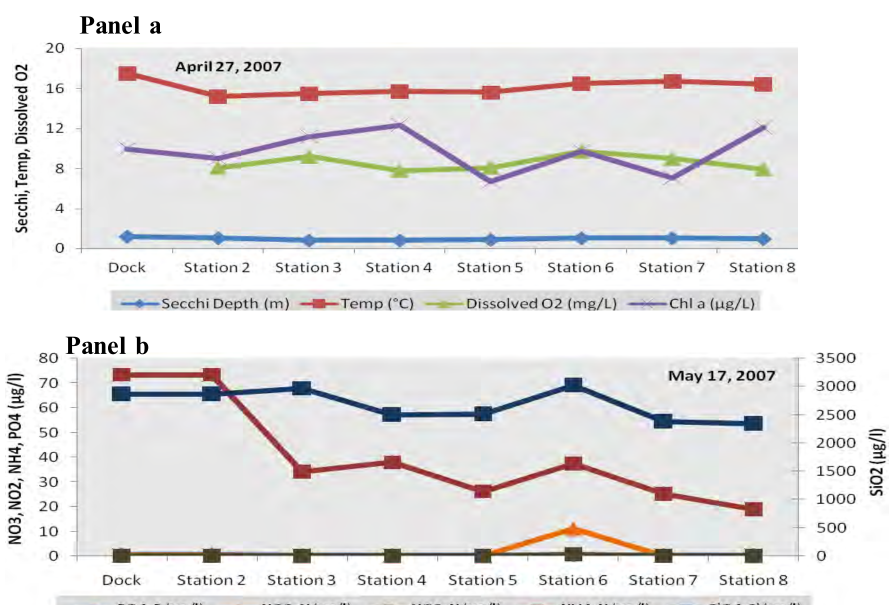


Figure 2. Panel a: Surface temperature, dissolved oxygen concentration, Secchi depth and mean surface chlorophyll *a* concentration measured from the RV *Sea-Coug* at 8 stations in Vancouver Lake on April 27, 2007. Panel b: Mean surface concentrations of dissolved inorganic phosphate (PO_4), nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), and silicate (SiO_2) collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on May 17, 2007.

During the wetter months of October 2007 and February 2008, water quality measures varied primarily at station 3 (outlet to Lake River) and station 6 (mouth of the flushing channel), locations where flows into the lake may be highest depending on tidal stage and precipitation. Values measured at the other lake stations during October and February were quite similar (Figures 4 and 5).

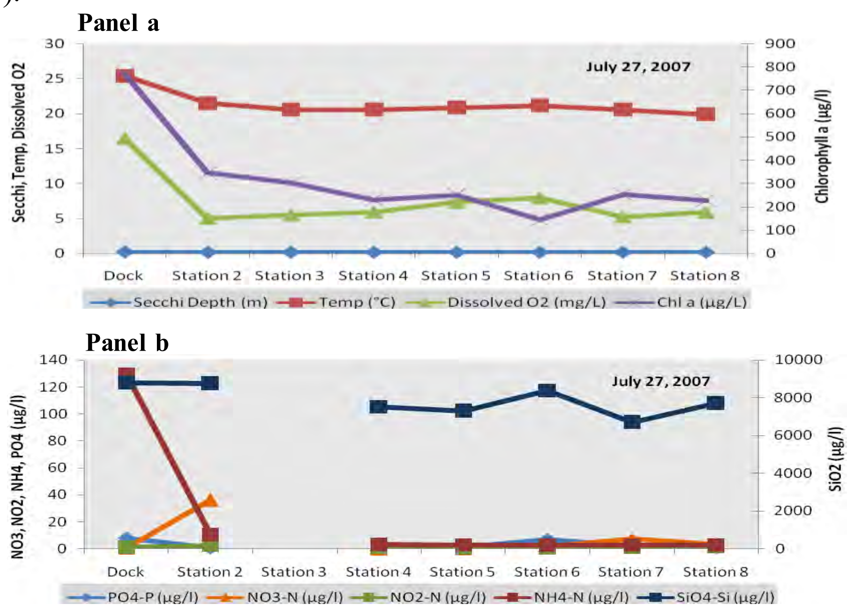


Figure 3. Panel a: Surface temperature, dissolved oxygen concentration, Secchi depth and mean surface chlorophyll *a* concentration measured from the RV *Sea-Coug* at 8 stations in Vancouver Lake on July 27, 2007. Panel b: Mean surface concentrations of dissolved inorganic phosphate (PO_4), nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), and silicate (SiO_4) collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on July 27, 2007.

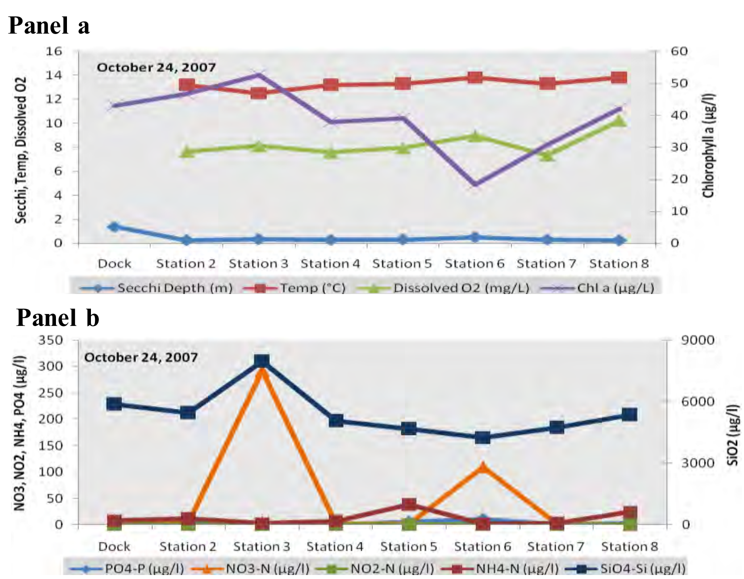


Figure 4. Panel a: Surface temperature, dissolved oxygen concentration, Secchi depth and mean surface chlorophyll *a* concentration measured from the RV *Sea-Coug* at 8 stations in Vancouver Lake on October 24, 2007. Panel b: Mean surface concentrations of dissolved inorganic phosphate (PO_4), nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), and silicate (SiO_2) collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on October 24, 2007.

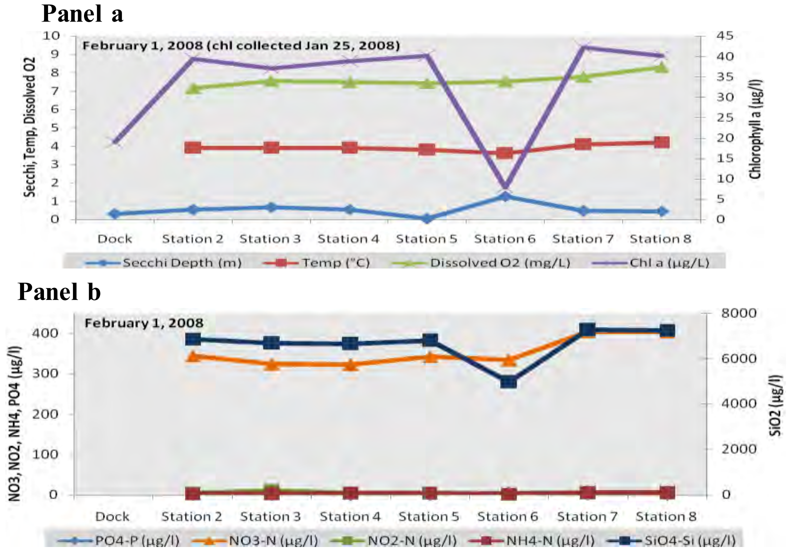


Figure 5. Panel a: Surface temperature, dissolved oxygen concentration, Secchi depth and mean surface chlorophyll *a* concentration measured from the RV *Sea-Coug* at 8 stations in Vancouver Lake on February 1, 2008 (note chlorophyll data collected on January 25, 2008). Panel b: Mean surface concentrations of dissolved inorganic phosphate (PO_4), nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), and silicate (SiO_2) collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on February 1, 2008.

Cyanobacteria and protist plankton abundance and composition. The abundance and composition of the unicellular plankton in the lake was somewhat variable among the 8 station locations during 2007-2008 (Table 2), however there was no consistent spatial pattern of compositional differences over the year. Statistical comparisons of rank order taxonomic composition of cyanobacteria and protist plankton collected at each quarterly sampling resulted in frequent significant correlations among stations (indicating very few significant differences in composition), but the pattern of similarity differed across seasons (Table 3). In April 2007 the relative composition of protist plankton and cyanobacteria showed little spatial variation, dominated mainly by cryptophyte and chlorophyte algae. Absolute abundance of protists and cyanobacteria was somewhat more variable, with higher abundances at stations 2 and 3, but total abundance did not vary by more than 50% across all locations (Figure 6). The relative composition of protists and cyanobacteria was highly consistent across the entire lake during July 2007, when the community was strongly dominated by a bloom of cyanobacteria (primarily *Anabaena flos-aquae*). In terms of absolute abundance, cyanobacteria were more abundant at the dock than the other locations in July, although abundances varied very little at the other stations (Figure 7).

In October 2007, cyanobacteria still comprised ~50% of the algal community throughout the lake, however diatoms and chlorophytes were also relatively abundant. Total abundance of cyanobacteria was again higher at the dock compared to other locations, except at station 6 (mouth of flushing channel) where all protist and cyanobacteria abundances were lower than elsewhere (Figure 8). During February 2008 the cold water community was dominated by diatoms, which accounted for 60-70% of the total abundance of protists and cyanobacteria. With respect to absolute abundance, there was very little variation between stations with the exception of station 6, where as observed in October 2007, abundances of all taxa were markedly lower than at the other stations (Figure 9).

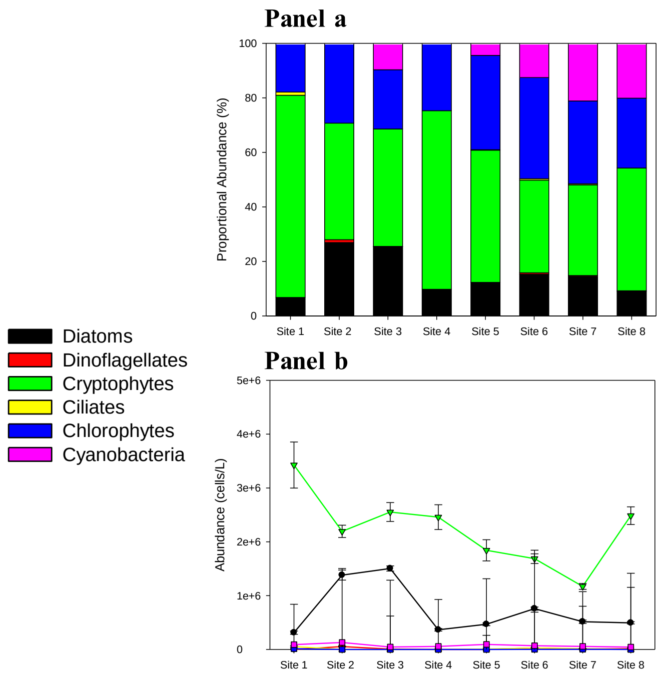


Figure 6. Panel a: Relative abundance of major taxonomic groups of protist plankton and cyanobacteria collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on April 27, 2007. Panel b: Absolute abundance of major taxonomic groups of protist plankton and cyanobacteria collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on April 27, 2007.

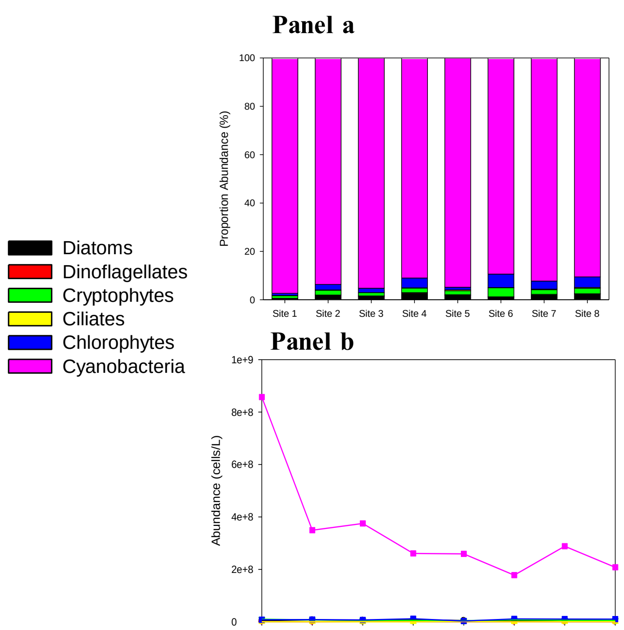


Figure 7. Panel a: Relative abundance of major taxonomic groups of protist plankton and cyanobacteria collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on July 27, 2007. Panel b: Absolute abundance of major taxonomic groups of protist plankton and cyanobacteria collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on July 27, 2007.

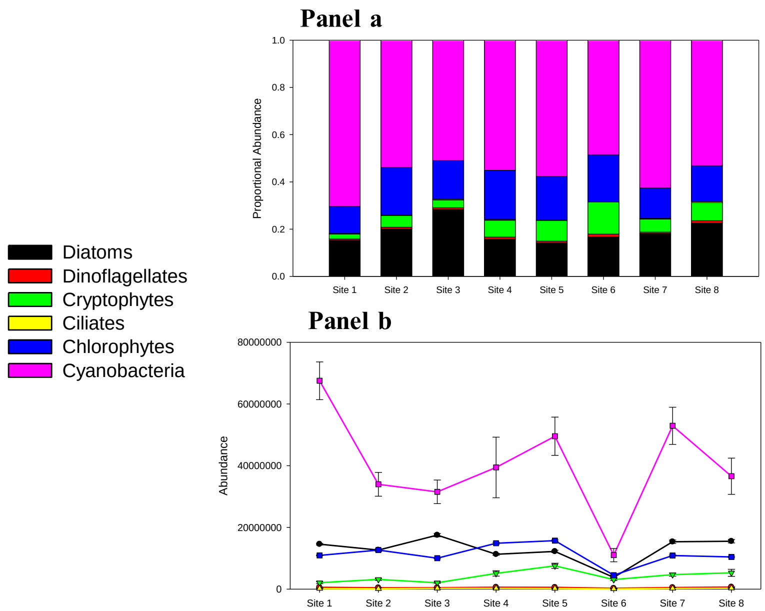


Figure 8. Panel a: Relative abundance of major taxonomic groups of protist plankton and cyanobacteria collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on October 24, 2007. Panel b: Absolute abundance of major taxonomic groups of protist plankton and cyanobacteria collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on October 24, 2007.

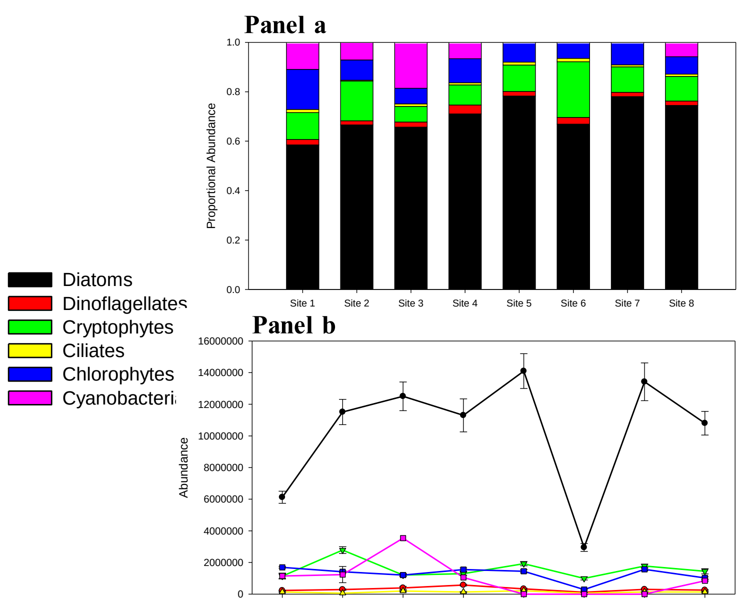


Figure 9. Panel a: Relative abundance of major taxonomic groups of protist plankton and cyanobacteria collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on February 1, 2008. Panel b: Absolute abundance of major taxonomic groups of protist plankton and cyanobacteria collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on February 1, 2008.

Metazoan zooplankton abundance and composition. The metazoan zooplankton community in Vancouver Lake is relatively low in species diversity, dominated primarily by *Daphnia retrocurva* (a cladoceran “water flea”), *Diacylcops thomasi* (a copepod), and three species of rotifer (*Polyarthra* sp., *Asplancha* sp., *Brachionus* sp.). Over the course of the year, the community shifted from relative dominance of cladocerans, to copepods, to rotifers (Table 4). Statistical analyses of zooplankton community composition across the Lake during each seasonal cruise showed highly significant correlations between each sampling station, indicating the zooplankton community to be essentially uniform throughout the Lake (Table 5).

In April 2007, *Daphnia retrocurva* and other cladocerans comprised ~40% of the community throughout the lake, with several life stages of copepod comprising much of the remainder. Total abundance of these groups did not vary substantially between stations, although *D. retrocurva* and young copepods were more abundant at stations 2 and 7 (Figure 10). During the cyanobacteria bloom in July 2007, the zooplankton community consisted nearly entirely of juvenile and larval copepods, dominated by *Diacyclops thomasi*, with little variation from station to station. However, overall abundance of copepods did vary somewhat among the 8 stations, although without a consistent pattern (Figure 11).

During the fall and winter (October 2007 and February 2008), rotifers were more common, accounting for ~40-50% of the zooplankton community across all lake stations. In October there was very little variability in overall abundance of zooplankton (Figure 12); however in February 2008 zooplankton abundance was higher at station 2 (mouth of Burnt Bridge Creek) and lower at station 6 (mouth of the flushing channel) (Figure 13).

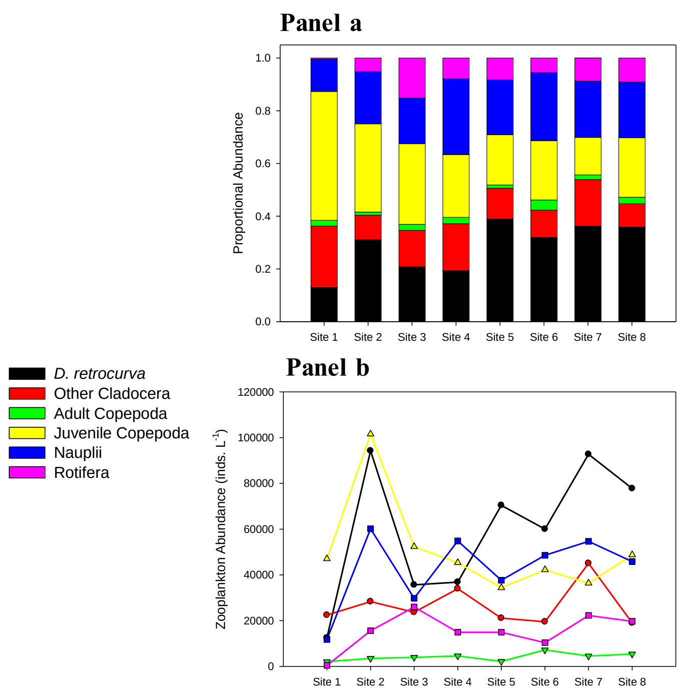


Figure 10. Panel a: Relative abundance of major taxonomic groups of metazoan zooplankton collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on April 27, 2007. Panel b: Absolute abundance of major taxonomic groups of metazoan zooplankton collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on April 27, 2007.

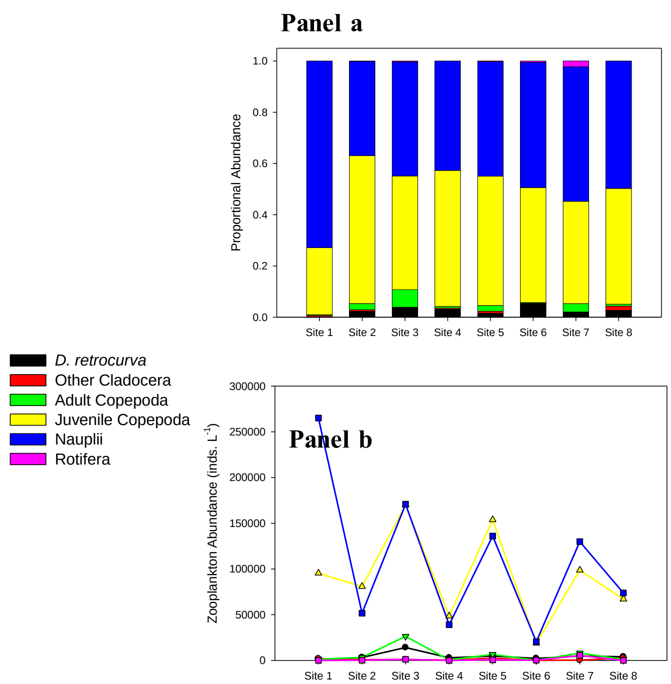


Figure 11. Panel a: Relative abundance of major taxonomic groups of metazoan zooplankton collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on July 27, 2007. Panel b: Absolute abundance of major taxonomic groups of metazoan zooplankton collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on July 27, 2007.

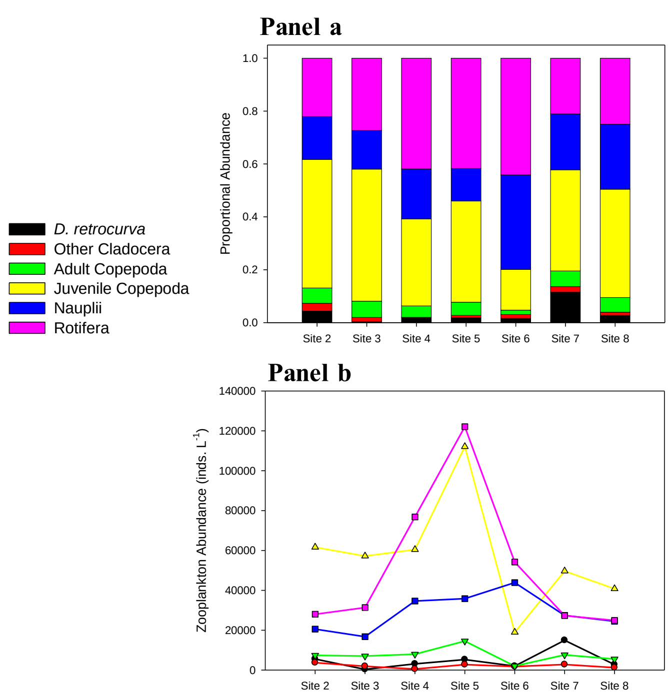


Figure 12. Panel a: Relative abundance of major taxonomic groups of metazoan zooplankton collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on October 24, 2007. Panel b: Absolute abundance of major taxonomic groups of metazoan zooplankton collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on October 24, 2007.

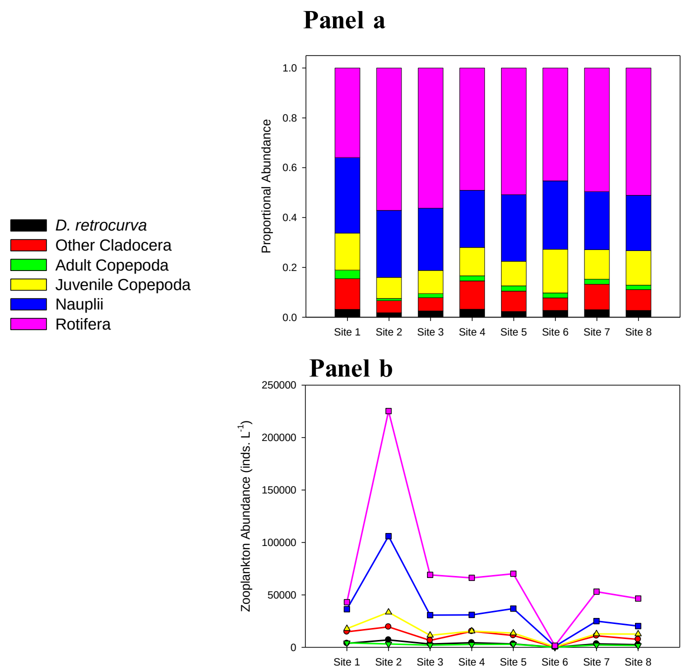


Figure 13. Panel a: Relative abundance of major taxonomic groups of metazoan zooplankton collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on February 1, 2008. Panel b: Absolute abundance of major taxonomic groups of metazoan zooplankton collected from the RV *Sea-Coug* at 8 stations in Vancouver Lake on February 1, 2008.

Benthic invertebrate abundance and composition. One component of the Vancouver Lake Biological Assessment was designed to assess the biotic structure of the Lake's benthic habitat as well as potential prey resources available to foraging predators, including juvenile salmonids. In the initial survey of benthic infauna in the Lake, between three and five benthic ponar grab samples were collected monthly at each of eight stations in April, July and October 2007 and February 2008 (Table 6).

From the 97 benthic samples processed from the survey, 20 taxa were identified; oligochaetes, nematodes, midge larva of the family Chironomidae and ostracods were the most commonly encountered taxa by frequency of occurrence (Table 7). Planktonic invertebrates were present in the core samples, including *Daphnia spp*., *Leptodora spp*. and cyclopoid copepods, but were most likely sampled incidentally in the water column and were therefore not included in the data analysis.

The numerical composition of the benthic taxa was consistently dominated (58-76%) by oligochaetes (Table 8). Little difference existed in the percent numerical composition of benthic taxa between stations for a given sampling period (Figure 14). Oligochaetes were the dominant taxa in April and July 2007 at every station.

Oligochaetes are commonly reported as dominant taxa in benthic cores from the lower Columbia River estuary (McCabe and Hinton 1993; Lott 2004), but not commonly reported in the diets of juvenile Chinook salmon in this system. All stages of Chironomidae (particularly emerging adults) occur in the diets of juvenile salmon in the lower estuary (Lott 2004) but were not found to be abundant in the Lake relative to the other taxa.

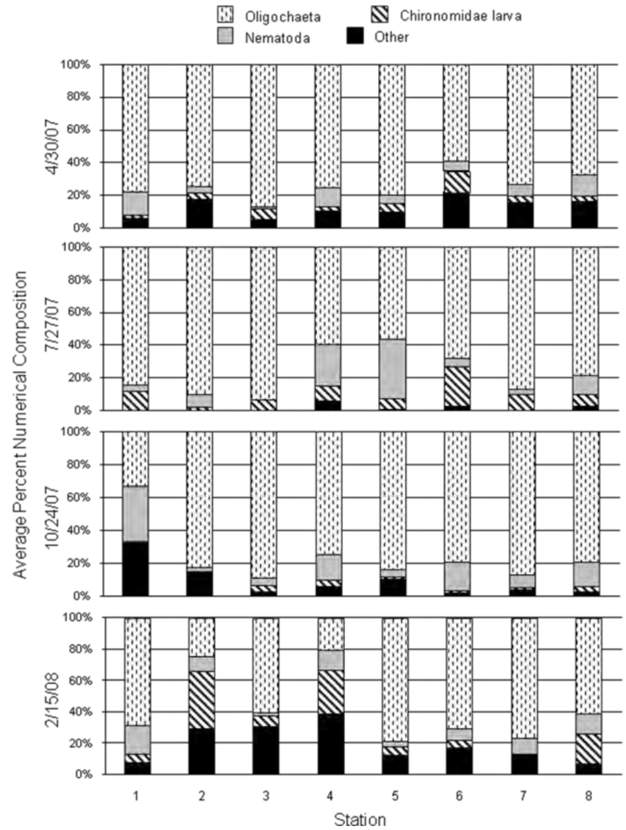


Figure 14. Average percent numerical composition of benthic taxa by date and station, April 2007 to February 2008.

Temporal Patterns: Annual Cycle

Year one of the Biological Assessment was the first time Vancouver Lake had been sampled on a consistent basis over the course of an entire annual cycle. The sampling frequency was weekly during summer and fall 2007, the typical algal and cyanobacteria bloom period, and bi-weekly or monthly during the spring and late fall 2007 and winter 2008. The data from this relatively high frequency sampling show very strong seasonal patterns in both the physical/ chemical and biological components of the Lake's planktonic ecosystem.

Water quality. Surface temperature, surface dissolved oxygen concentrations and Secchi depth measurements taken from the Sailing Club dock from March 2007 to February 2008 reflect the typical pattern for temperate lakes. Surface temperatures were elevated (>20^{o}C) in July and August, and generally lowest (<5^{o}C) in December and January. Concentrations of dissolved oxygen showed peaks in April/May and again in July/August, but remained somewhat consistent throughout the remainder of the year. Secchi depth, an indirect measure of overall water clarity, was deepest (i.e. highest water clarity) during April and May, and shallowest (<0.4 m) during summer months (Table 1, Figure 15a).

A seasonal signal was also evident in the concentrations of inorganic nutrients present in samples collected from the Sailing Club dock over the year, although different mineral nutrients peaked in concentration at different times. Ammonium (NH_4) and silicate (SiO_4)levels were highest during July 2007, and slowly decreased to near detection limits (in the case of NH_4) by

September 2007 through February 2008. This pattern closely mirrored the variation in chlorophyll *a* concentration over the summer and fall. Inorganic dissolved phosphate (PO_4) also peaked in summer, but was most abundant in August and early September 2007, with nearly undetectable concentrations for the remainder of the year. By contrast, concentrations of nitrate (NO_3) were highest during the late fall and winter, with a maximum peak exceeding 700 mg/L in late December 2007 associated with a significant rain event, and virtually undetectable during the late spring and summer (Figure 15b).

Panel a

Panel b

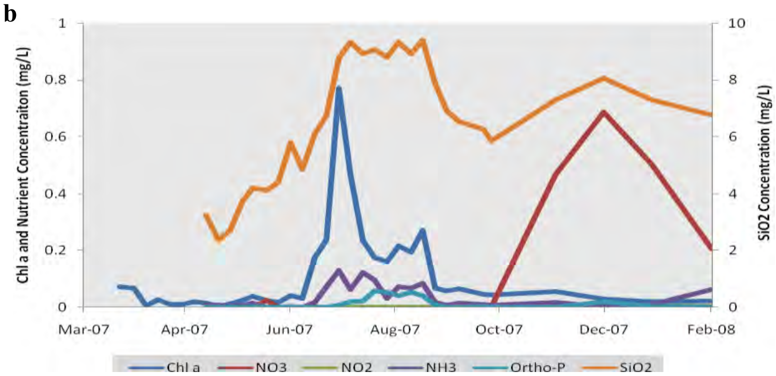


Figure 15. Panel a: Surface temperature, dissolved oxygen concentration, and Secchi depth measured from the Vancouver Lake Sailing Club dock between March 2007 and February 2008. Panel b: Mean surface chlorophyll *a* concentration and mean surface concentrations of dissolved inorganic phosphate (PO_4), nitrate (NO_3), nitrite (NO_2), and ammonium (NH_4) collected from the Vancouver Lake Sailing Club dock between March 2007 and February 2008.

Cyanobacteria and protist plankton abundance and composition. A strong seasonal pattern was also clearly evident in the abundance and biomass of the major taxonomic groups of planktonic protists and cyanobacteria in Vancouver Lake. In terms of overall abundance of individuals, cyanobacteria cells dominated the community of unicellular plankton by an order of magnitude from late July to late September 2007, with a peak of >8 * 10^6 cells/mL in August 2007. The pattern closely mirrored the concentration of chlorophyll *a* pigment in the Lake (Table 9, Figure 16). However, other important protist plankton groups, in particular other autotrophic protists (i.e. "algae"), also showed summer peaks in abundance. Green algae ("chlorophytes"), especially *Dictyosphaerium* and *Scenedesmus*, showed a very large peak (>6 * 10^5 cells/mL) in September 2007, and cryptophytes (particularly *Cryptomonas* and *Mallomonas*) peaked in August 2007. In addition, diatoms (primarily *Aulacosira*, *Cyclotella* and *Nitzschia*) showed a variable "boom-bust" pattern of high and low abundance from April through October 2007, but abundances never exceeded 2 * 10^5 cells/ml (Table 9, Figure 17).

With respect to the total carbon biomass of each group of unicellular plankton, cyanobacteria still dominated the assemblage during their peak of abundance in August 2007, however diatoms (due to their larger volume and carbon content per individual cell compared to other unicellular plankton) were the dominant autotrophic group in September and October 2007 (Table 9, Figure 18). Notably, the biomass and abundance of all unicellular plankton was substantially lower throughout the winter and early spring of 2007/2008 (Figures 17 and 18).

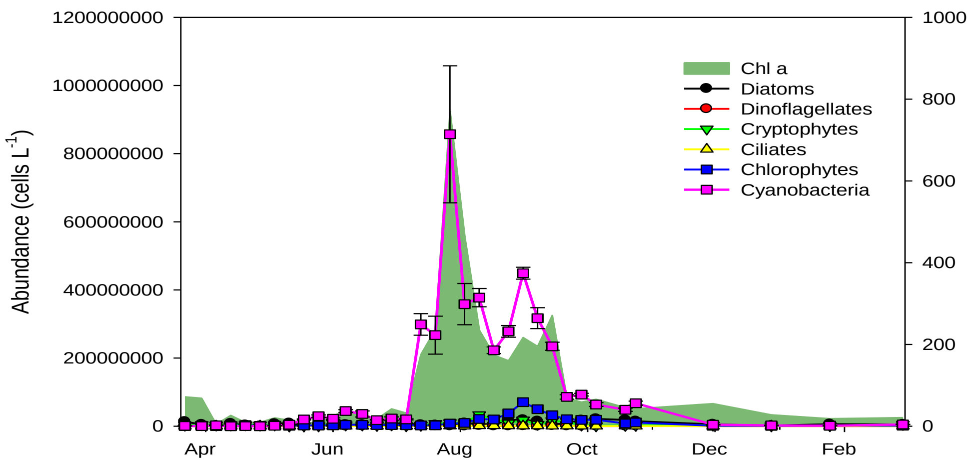


Figure 16. Mean abundance of major taxonomic groups of protist plankton and cyanobacteria collected from the Vancouver Lake Sailing Club dock between March 2007 and February 2008. Green shaded area represents mean surface chlorophyll *a* concentration measured over the same period.

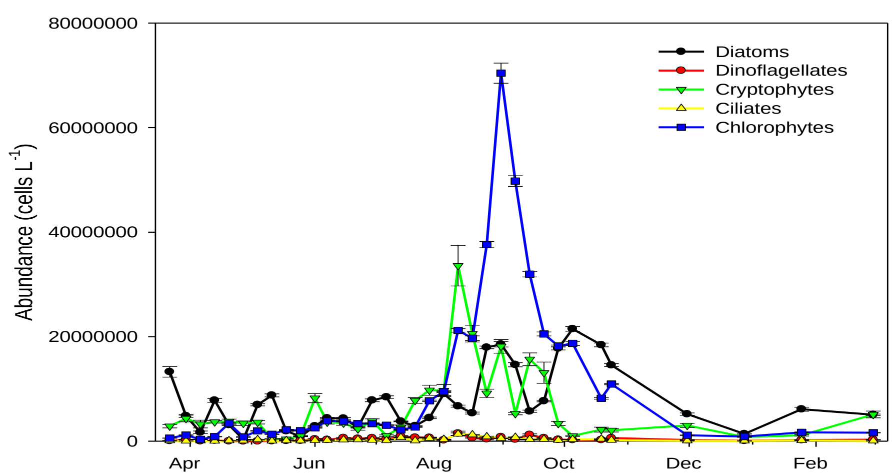


Figure 17. Mean abundance of major taxonomic groups of protist plankton (without cyanobacteria) collected from Vancouver Lake Sailing Club dock between March 2007 and February 2008.

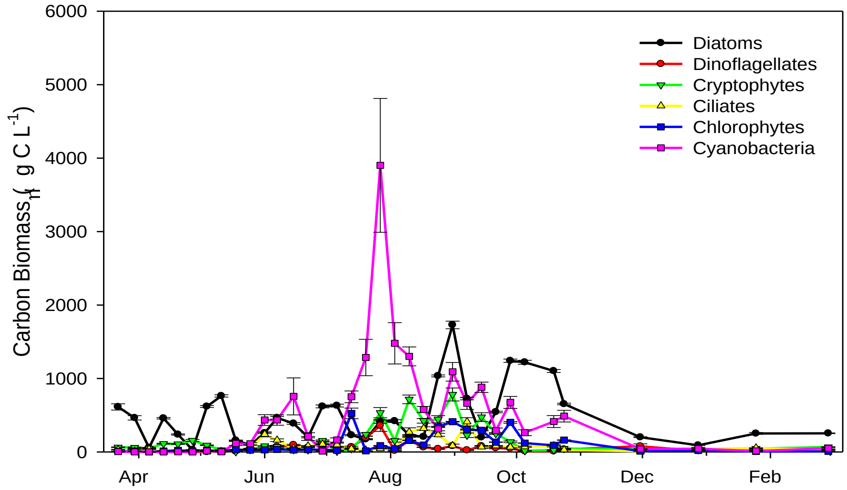


Figure 18. Mean biomass of major taxonomic groups of protist plankton and cyanobacteria collected from the Vancouver Lake Sailing Club dock between March 2007 and February 2008.

The cyanobacterial assemblage itself was strongly dominated by just one species, *Anabaena flos-aquae*, particularly during the primary bloom of chlorophyll *a* observed in July/August 2007, although other cyanobacteria taxa were also present and at times were very abundant. These other cyanobacteria species, in particular *Microcystis* sp. and *Aphanizomenon flos-aquae*, were highest in abundance during September and, along with diatoms, contributed to a secondary peak in chlorophyll *a* concentration (Figures 16 and 19). However, due to the very small individual cell size (~2-4 micron diameter) of the non-*Anabaena* cyanobacteria taxa, the overall carbon biomass of the cyanobacteria assemblage during the secondary bloom was actually apportioned roughly evenly between *Anabaena flos-aquae* and *Aphanizomenon flos-aquae* (Figure 20).

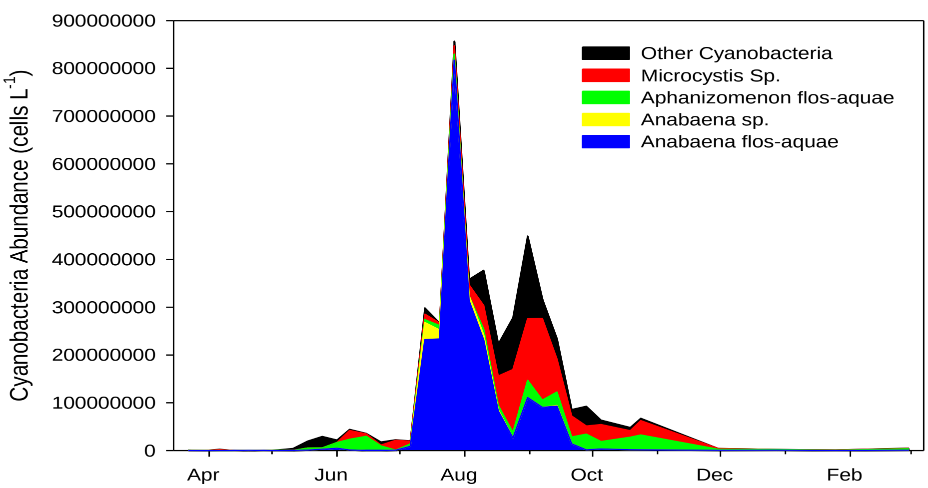


Figure 19. Mean abundance of the major cyanobacteria taxa collected from Vancouver Lake Sailing Club dock between March 2007 and February 2008.

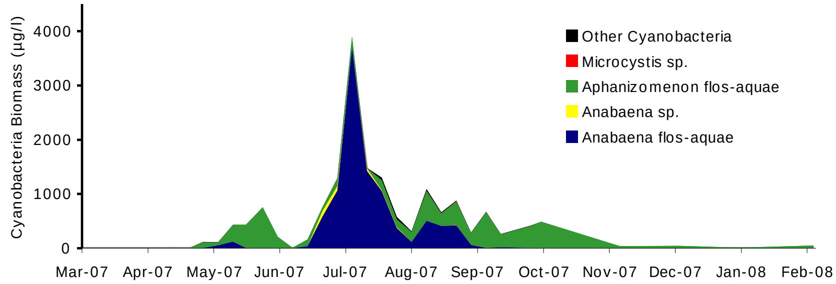


Figure 20. Mean biomass of the major cyanobacteria taxa collected from Vancouver Lake Sailing Club dock between March 2007 and February 2008.

There is clearly a compositional shift in the unicellular plankton community between winter, spring and summer in Vancouver Lake. From December 2007 to February 2008 diatoms and cyanobacteria comprised roughly the same proportion of the total community, with contribution from cryptophytes, and in spring diatoms and cryptophytes increased in proportion to cyanobacteria. However, from June through October the abundance of unicellular plankton was dominated by cyanobacteria (Figure 21a). With respect to the proportional biomass of these groups, however, diatoms comprised a larger proportion of the total community biomass throughout the year, and the contribution of dinoflagellates and heterotrophic ciliates became more apparent (Figure 21b).

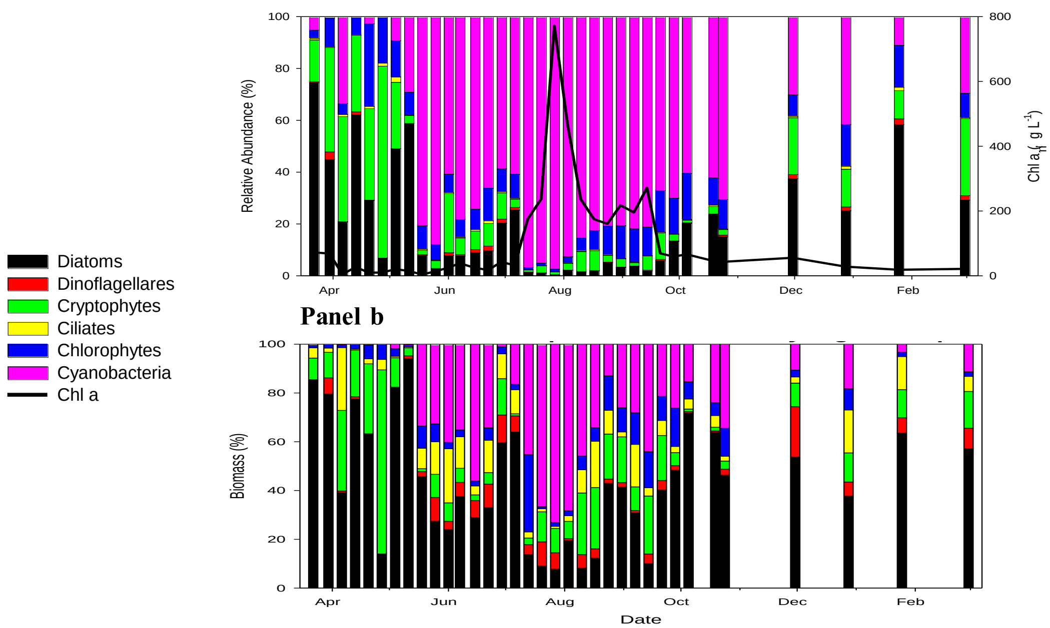


Figure 21. Panel a: Relative abundance of major taxonomic groups of protist plankton and cyanobacteria collected from Vancouver Lake Sailing Club dock between March 2007 and February 2008. Black line indicates mean chlorophyll a concentration measured over the same period. Panel b: Relative biomass of major taxonomic groups of protist plankton and cyanobacteria collected from the Vancouver Lake Sailing Club dock between March 2007 and February 2008.

Metazoan zooplankton abundance and composition. Various life stages of the copepod *Diacyclops thomasi* (naupliar larvae, juvenile copepodids and adults) were nearly always present in Vancouver Lake over the 12-month period from March 2007 to February 2008, and were the dominant zooplankton taxon during the summer bloom period. However, in autumn and winter rotifers (mainly *Polyarthra*, *Asplanchna*, *Brachionus* and *Keratella*) were often the most abundant zooplankters. In addition, during spring and early summer cladoceran taxa, particularly *Daphnia retrocurva*, was at times important with respect to zooplankton abundance (Table 10, Figure 22).

Figure 23 shows the proportional contribution of the major life history stages of copepods, rotifers and cladocerans to total zooplankton abundance, which illustrates the seasonal compositional shifts that occurred over the year. During winter months, rotifers and cladocerans were the two dominant groups. From March to May the copepod population increasingly dominated the assemblage, with more juvenile forms and relatively fewer nauplii. However, the cladoceran *Daphnia retrocurva* quickly became numerically dominant in May and June prior to the large cyanobacterial bloom in July, when cladocerans virtually disappeared and copepod nauplii and juveniles comprised >90% of the community from that point throughout the rest of the summer.

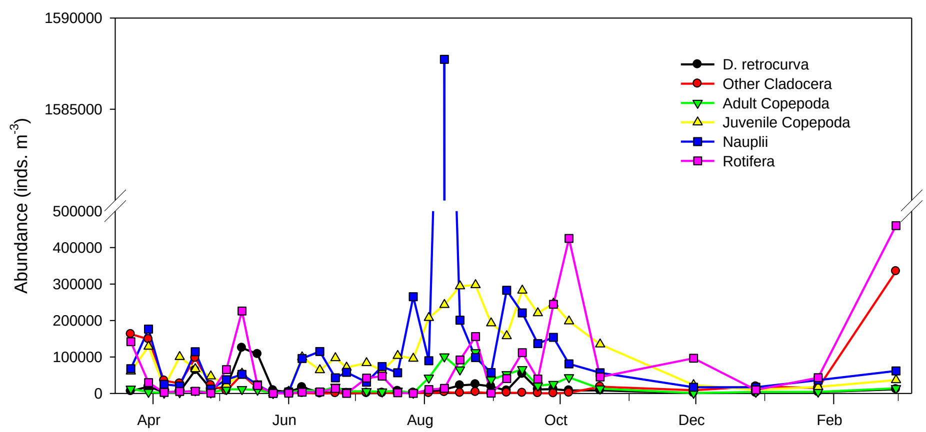


Figure 22. Mean abundance of major taxonomic groups of metazoan zooplankton collected from Vancouver Lake Sailing Club dock between March 2007 and February 2008.

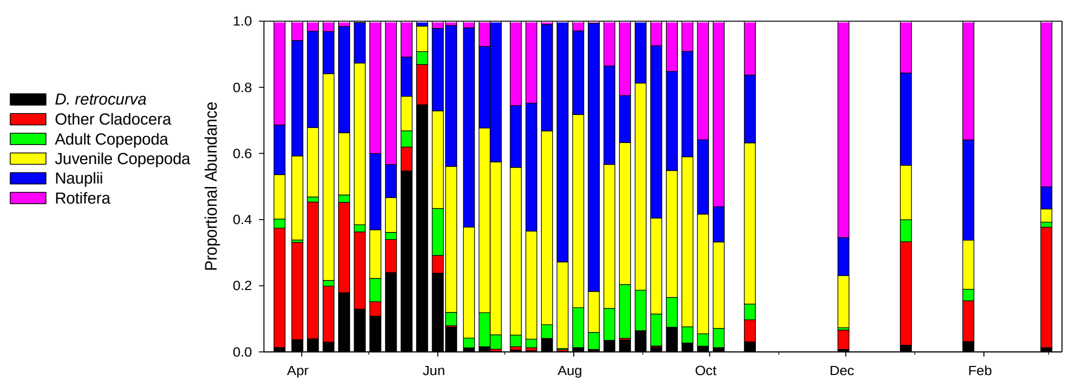


Figure 23. Relative abundance of major taxonomic groups of metazoan zooplankton collected from Vancouver Lake Sailing Club dock between March 2007 and February 2008.

Temporal Patterns: Inter-annual Cycle (2003 – 2008)

Clark County Public Works has provided support for seasonal volunteer monitoring of Vancouver Lake since 2003. In summer 2007 the volunteer monitoring coincided with the first year of the Partnership-supported WSUV Biological Assessment. Below we present the County monitoring data from 2003 to 2007, along with our Assessment results from 2007-2008, to illustrate inter-annual trends in water quality and plankton abundance and composition. Note that County monitoring samples were collected a minimum of 1000 feet from shore, but were not targeted to any particular location within the Lake. The Biological Assessment data were all collected from the end of the Vancouver Lake Sailing Club dock.

Water quality. Surface temperature, dissolved oxygen concentration and Secchi depth conditions during summer/fall measured by both projects in Vancouver Lake remained quite consistent from year to year between 2003 and 2007. Summer water temperature highs were ~20°C each year, with peaks up to 25°C. Dissolved oxygen concentrations and Secchi depth were more variable from year to year, although the range observed (dissolved oxygen: 5-10 mg/l; Secchi depth: 0.2-1.6 m) was roughly the same over time (Tables 1 and 11, Figure 24).

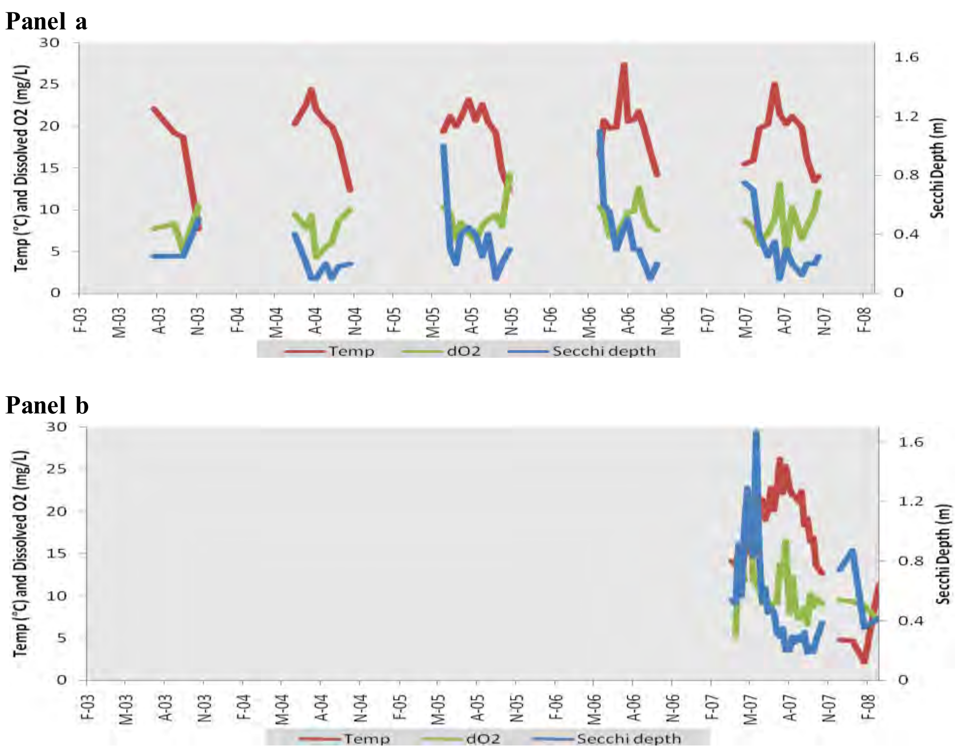
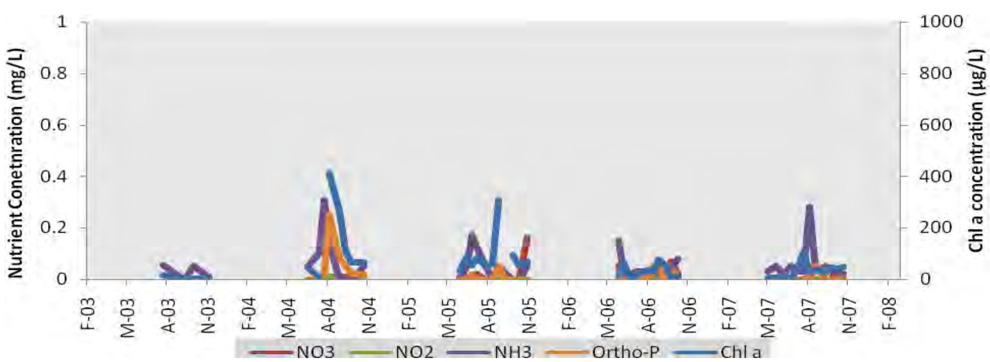


Figure 24. Panel a: Surface (0.5 m) temperature, dissolved oxygen concentration and Secchi depth measured by Clark County volunteers/staff at various off-shore stations in Vancouver Lake between July-October in 2003, 2004, 2005, 2005 and 2007. Panel b: Surface temperature, dissolved oxygen concentration and Secchi depth measured by WSUV staff from the Vancouver Lake Sailing Club dock between March 2007 and February 2008.

In contrast, surface nutrient concentrations were quite variable both within and between years from 2003 to 2007. Overall dissolved inorganic nutrient concentrations were lowest in 2003 and 2006, and there was no discernable chlorophyll bloom evident in either of those years. However, during 2004 and 2005, when chlorophyll *a* peaks of up to 350 micrograms/L were observed in County monitoring samples, nutrient concentrations (especially NH_4, PO_4 and NO_3) also showed summer peaks, although not always coincidental with highs in chlorophyll (Table 11).

In 2007, the results are somewhat different between the County monitoring data and the WSUV Biological Assessment data. The timing of maximum chlorophyll *a* concentration are aligned between the two data sets, however chlorophyll concentrations of as high as 750 micrograms/L were measured in July by WSUV, compared to ~100 micrograms/L by the County. This likely reflects the higher frequency of sampling in the Biological Assessment project, in which bloom peaks are more likely to be detected, but could also suggest a difference in the sensitivity of the detection methods used in both projects. Most notably, NO_3 concentration measured from WSUV sampling at the Sailing Club dock in winter 2007/2008 was substantially higher than measured earlier in 2007, or in any of the summer/fall monitoring samples from 2003-2007, suggesting winter sampling is important to characterizing the variation in nutrient concentrations over time in the Lake (Figure 25).

Panel a



Panel b

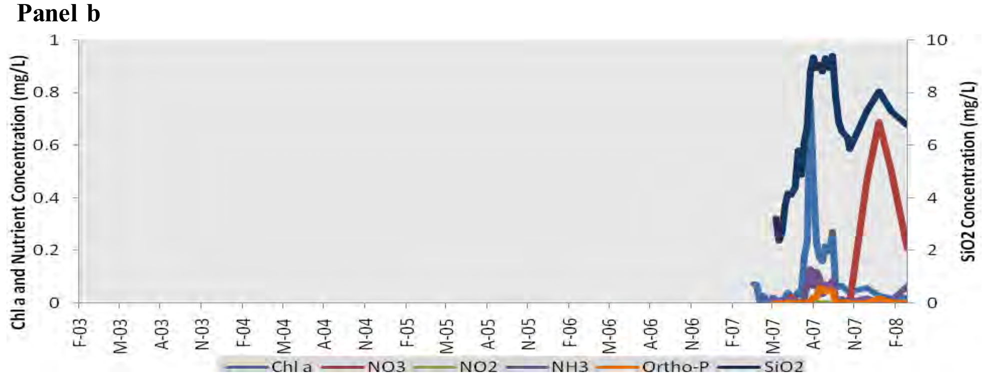


Figure 25. Panel a: Surface (0.5m) concentrations of dissolved inorganic nutrients measured by Clark County volunteers/staff at various off-shore (>1000 feet from shore) stations in Vancouver Lake between July-October in 2003, 2004, 2005, 2006 and 2007. Panel b: Surface concentrations of dissolved inorganic nutrients measured by WSUV staff from the Vancouver Lake Sailing Club dock between March 2007 and February 2008.

Cyanobacteria and protist plankton abundance and composition. From 2003 to 2007 summer/fall unicellular plankton abundance measured from the County monitoring program in Vancouver Lake varied by ~50%, with highest abundances in 2004 and 2006 (Tables 12 and 13, Figure 26a). This is not consistent with the inter-annual variability in chlorophyll *a* concentration, in which highest values were recorded in 2004 and 2005 (Figure 24a). However, the composition of unicellular plankton did remain comparable from year to year, with cyanobacteria the dominant taxa, especially in 2004. The WSUV Biological Assessment data also shows clear numerical dominance by cyanobacteria in summer/fall 2007, however total abundance of all cyanobacteria and protist plankton groups was observed to be nearly a full order of magnitude higher (Figure 26b/c). This is largely due to a difference is sample processing and enumeration protocols between the two projects: in the County monitoring program preserved samples were transferred to flat slides, and cyanobacteria and other colonial algae were counted by number of colonies (which can include many individual cells), while WSUV samples were settled overnight in counting chambers and every individual cyanobacteria and protist plankton cell was enumerated. The relative proportions of each taxonomic group at each coincident sampling time were actually quite similar between the two projects.

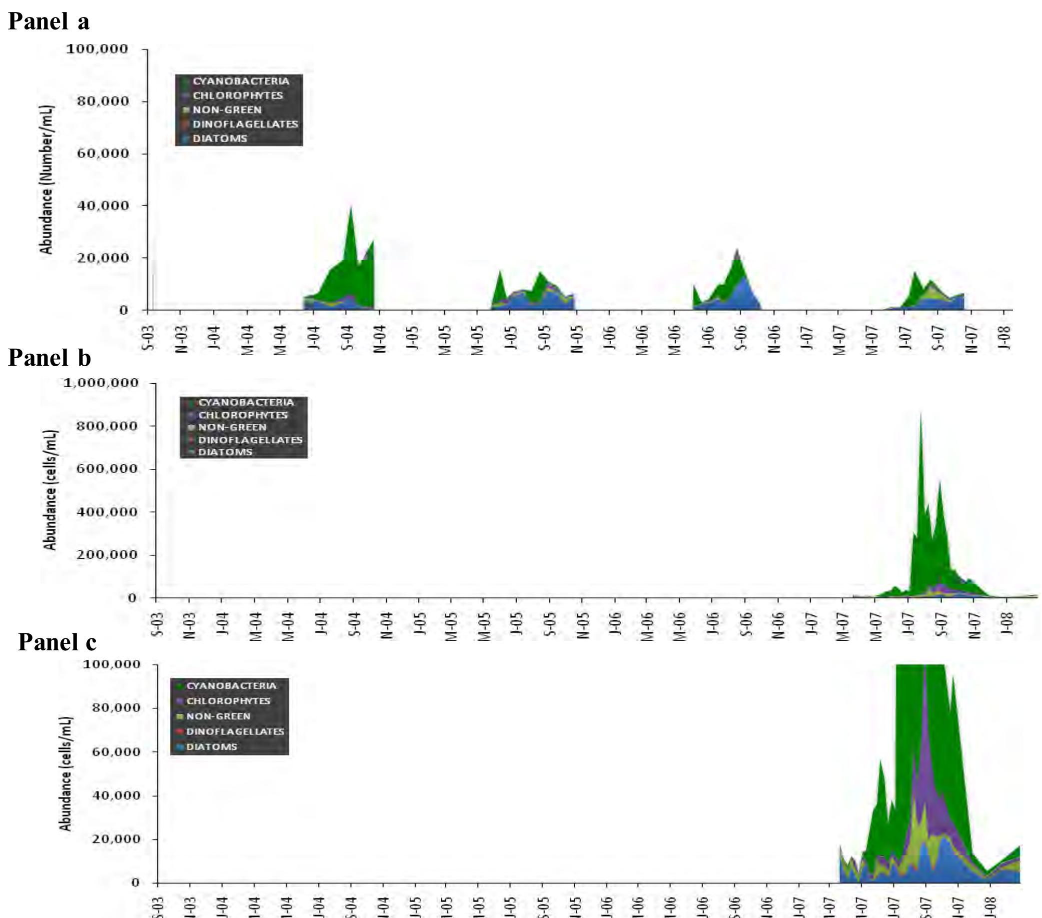


Figure 26. Panel a: Abundance of major taxonomic groups of photosynthetic protist plankton and cyanobacteria collected by Clark County volunteers/staff at various off-shore stations in Vancouver Lake between July-October in 2003, 2004, 2005, 2006 and 2007. Panels b/c: Abundance of major taxonomic groups of photosynthetic protist plankton collected by WSUV staff from the Vancouver Lake Sailing Club dock between March 2007 and February 2008. Note change of scale in panel c to highlight non-cyanobacteria taxa abundance (but same as panel a).

While cyanobacteria were consistently the dominant taxonomic group of unicellular plankton in Vancouver Lake with respect to abundance, the composition of the cyanobacteria community did vary substantially on an inter-annual basis between 2003 and 2007. The County monitoring data showed the cyanobacteria bloom in 2004 to have been first comprised primarily by *Anabaena flos-aquae* in early summer, but then shifted to dominance by *Aphanizomenon flos-aquae* during the later very large bloom in September/October. Similarly, the bloom of 2005 had two peaks, each consisting of either *Anabaena* or *Aphanizomenon*, but the first peak in June was primarily *Aphanizomenon* and the second peak in September consisted of *Anabaena*. The 2006 cyanobacteria bloom was exclusively *Aphanizomenon*, while the 2007 bloom was primarily dominated by *Anabaena flos-aquae*, as observed in both the County monitoring data and the results of the WSUV Biological Assessment (Tables 9, 12, and 13, Figure 27a/b/c).

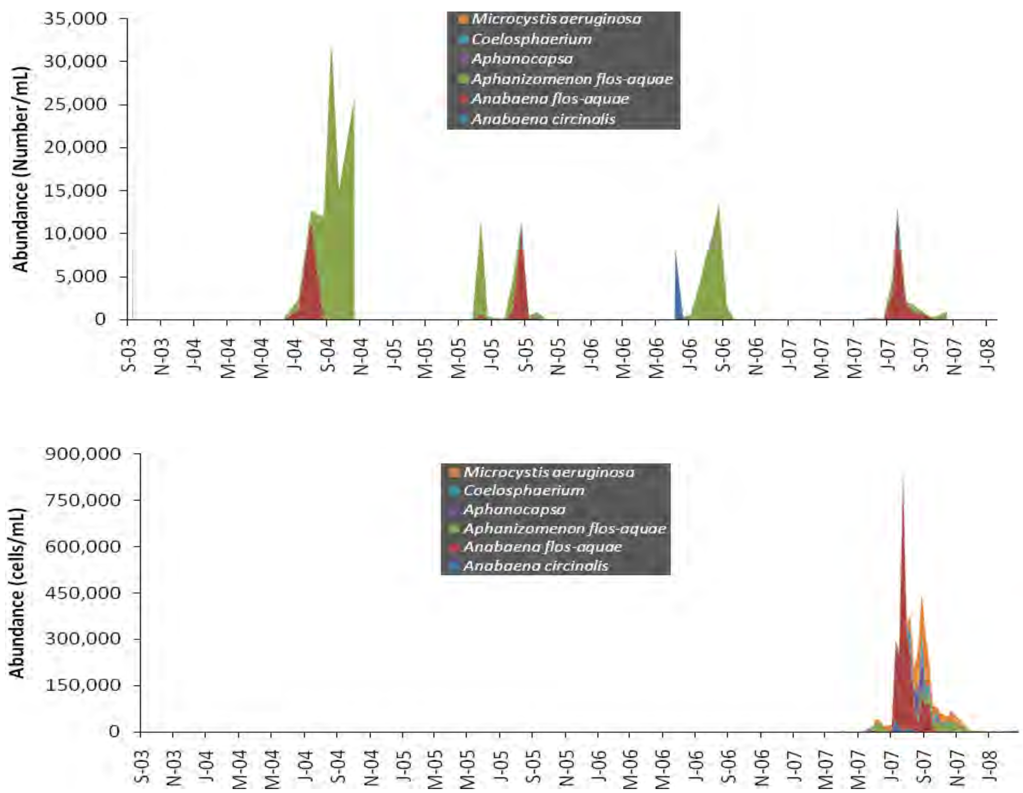


Figure 27. Panel a: Abundance of major cyanobacteria taxa collected by Clark County volunteers/staff at various off-shore stations in Vancouver Lake between July-October in 2003, 2004, 2005, 2006 and 2007. Panels b: Abundance of major cyanobacteria taxa collected by WSUV staff from the Vancouver Lake Sailing Club dock between March 2007 and February 2008. Note change in scales on the vertical axes of the two panels.

Potential species interactions

A secondary component of the WSUV Biological Assessment was to conduct preliminary investigations of the abundance and composition of the potential planktonic grazers that could be consuming cyanbacteria in Vancouver Lake. Information about the abundance of potential grazers provides important clues as to the possible trophic interactions between cyanobacteria and other heterotrophic plankton (although these potential interactions can only be assessed through experimentation under controlled conditions, e.g. in future years' studies).

Cyanobacteria abundance vs. potential protist plankton grazers. There were two groups of protist plankton observed in Vancouver Lake which may have the potential to consume cyanobacteria: heterotrophic ciliates and dinoflagellates. Ciliate abundance was generally low when cyanobacteria abundance was low, but showed a dramatic increase in abundance following the large bloom of cyanobacteria in July/August 2007 (Figure 28). Similarly dinoflagellate abundance peaked after the large bloom in cyanobacteria, however dinoflagellates were also abundant in spring and late fall, when cyanobacteria numbers were very low (Figure 29). These data are suggestive of a possible trophic interaction, particulary between cyanobacteria and ciliates.

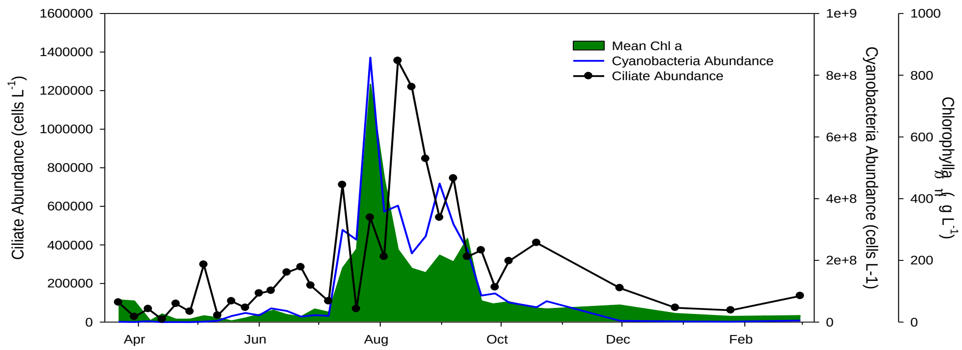


Figure 28. Mean cyanobacteria abundance compared to mean ciliate abundance measured from the Vancouver Lake Sailing Club dock between March 2007 and February 2008. Green area represents mean chlorophyll *a* concentration over this period.

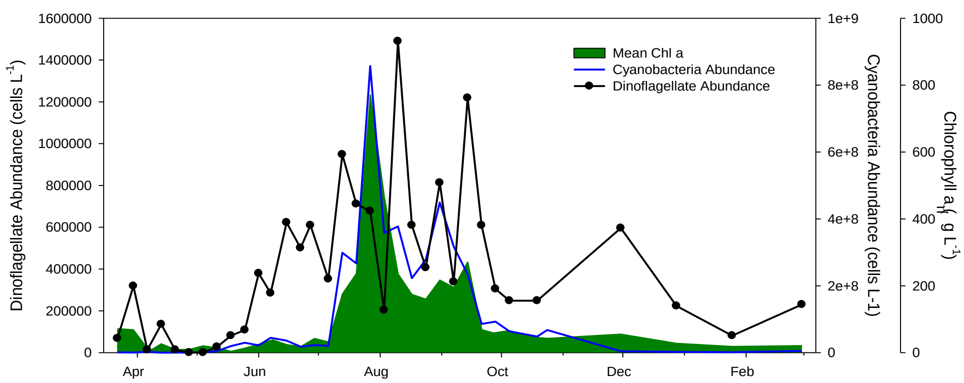


Figure 29. Mean cyanobacteria abundance compared to mean dinoflagellate abundance measured from the Vancouver Lake Sailing Club dock between March 2007 and February 2008. Green area represents mean chlorophyll *a* concentration over this period.

Cyanobacteria abundance vs. potential metazoan zooplankton grazers. There were three groups of zooplankton with the potential to consume cyanobacteria: cladocerans, copepods and rotifers. Neither of the two cladoceran species present in the Lake, *Daphnia retrocurva* and *Eubosmina coregoni*, appeared to have a relationship with cyanobacteria that suggested strong trophic coupling. *Daphnia retrocurva* were mainly abundant during May 2007, several weeks prior to the increase in cyanobacteria (Figure 30); and *Eubosmina coregoni* were highly abundant in February and March, but were undetectable in samples collected throughout the summer of 2007 (Figure 31).

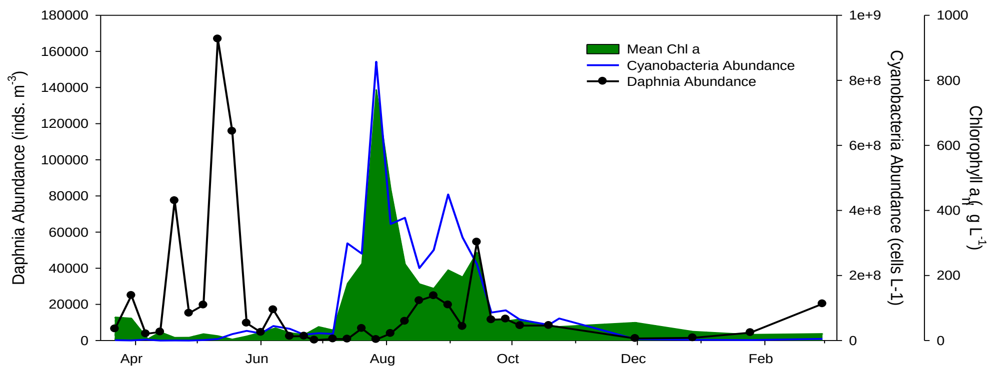


Figure 30. Mean cyanobacteria abundance compared to mean abundance of *Daphnia retrocurva* measured from the Vancouver Lake Sailing Club dock between March 2007 and February 2008. Green area represents mean chlorophyll *a* concentration over this period.

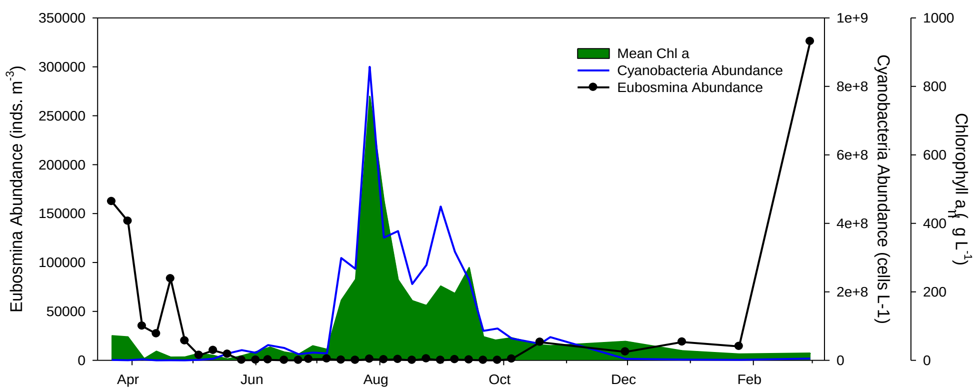


Figure 31. Mean cyanobacteria abundance compared to mean abundance of *Eubosmina coregoni* measured from the Vancouver Lake Sailing Club dock between March 2007 and February 2008. Green area represents mean chlorophyll *a* concentration over this period.

Similar to the cladoceran species, rotifer abundance did not stongly correlate with cyanobacteria abundance, but was instead somewhat variable throughout the year, suggesting a limited trophic relationship between cyanobacteria and rotifers (Figure 32).

However, in contrast to the cladocerans and rotifers, the abundance of all life history stages of copepods did show a strong relationship to cyanobacteria abundance, with low numbers throughout the year, except for a substantial peak just following the bloom of cyanobacteria in July/August 2007 (Figure 33). Thus copepods, along with ciliates and possibly dinoflagellates, are suggested to be important grazers of cyanobacteria, although this remains to be determined experimentally.

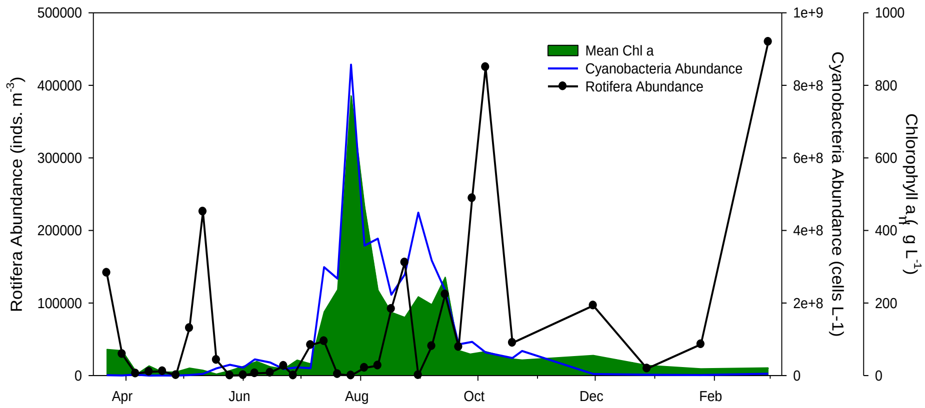


Figure 32. Mean cyanobacteria abundance compared to mean rotifer abundance measured from the Vancouver Lake Sailing Club dock between March 2007 and February 2008. Green area represents mean chlorophyll *a* concentration over this period.

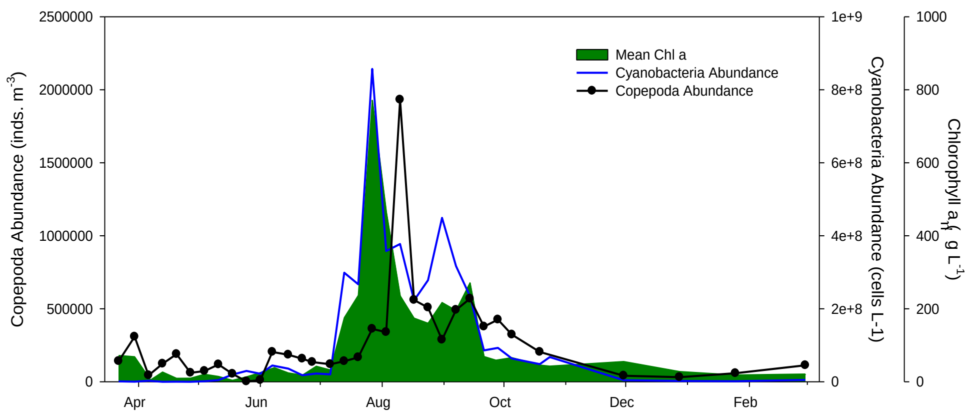


Figure 33. Mean cyanobacteria abundance compared to mean copepod abundance measured from the Vancouver Lake Sailing Club dock between March 2007 and February 2008. Green area represents mean chlorophyll *a* concentration over this period.

Summary and Significance

Year one of the WSUV Biological Assessment has provided a unique and unprecedentedly detailed picture of the water quality and plankton distribution, abundance and composition in Vancouver Lake over a full 12-month period. Several significant trends are evident from these results. First, there is on average little spatial variability in water quality and plankton abundance across the Lake. During periods of higher flow, such as in winter and early spring, there were some differences observed between stations near the flushing channel and the mouth of Burnt Bridge Creek, however these differences were not consistent. This suggests that samples collected from only one station, or at best a small number of stations, are likely to be sufficient to characterize conditions in the Lake as a whole at that time period. This has significant implications for planning of future monitoring of the Lake.

The second important trend illustrated by the results of this study is the significant seasonal signal in all measured parameters, both physical/chemical and biological. The summer/fall cyanobacteria blooms have been observed for several years, however these Biological Assessment data show that many other planktonic groups have a similar summer peak in abundance, including potential grazers of cyanobacteria such as ciliates and copepods. Notably, the wintertime sampling revealed that some other planktonic groups, including rotifers and cladocerans, have their highest abundances in the period from December to March.

In addition, monthly sampling through the late fall, winter and early spring revealed a substantial increase in nitrate concentration without a comparable increase in the other inorganic nutrient species. This may be evidence of higher run-off during the rainy season, but also suggests that conditions for autotrophic plankton growth could be substantially different during the winter, and may merit further examination.

Finally, these Biological Assessment results for year one provide an expanded data set to augment Clark County's volunteer monitoring program to discern inter-annual variations in water quality and plankton abundance. These data demonstrate that summer/fall blooms of cyanobacteria have been fairly consistent since 2003, however the magnitude and composition of these blooms has varied from year to year, which in turn suggests that the underlying causes (be they abiotic or biotic) may also vary between years.

Recommendations

The first year of this Biological Assessment has provided substantial new information about the spatial and temporal patterns of the physical and biological factors which may be influencing cyanobacteria blooms in Vancouver Lake. However, these results also raise new questions about the particular processes and mechanisms which may underly these patterns. Thus, we make several recommendations for further study to better understand the dynamics of cyanobacteria blooms.

First, at least one more full year of high frequency sampling from the Sailing Club dock will provide a critical comparison to the first year, and help to clarify whether trends observed in 2007-2008 are anomalous or repeated in 2008-2009, and thus are indicative of longer-term inter-annual trends. The lack of significant spatial variability within the Lake over four broad-scale surveys suggests that sampling only at the dock will provide a reliable indication of the conditions throughout the Lake.

Second, the highly suggestive correlations between the abundance of cyanobacteria and several potential grazer populations indicate that focused experimental studies to examine ingestion rates and prey selection by these grazers are critical to determining whether and how these groups may be directly and/or indirectly controlling cyanobacteria growth in the Lake.

Finally, we recommend maintaining and expanding the coordination between the Biological Assessment project and other public and private entities focused on investigating various topics in the Lake, including the Department of Health and the new Salmon Creek watershed group.

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