Factors Influencing Cyanobacteria Blooms in Farmington Bay, Great Salt Lake, Utah

A Progress Report of Scientific Findings From the 2013 Growing Season

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CONTENT OF REPORT

The following findings of our study of the aquatic biota of Farmington Bay, with special focus on the factors influencing cyanobacteria blooms, represent a summary of the initial year of research. It is not intended to be a conclusive examination of nutrient effects on cyanobacteria blooms in Farmington Bay. Rather, the main goal of the first year of the study was to gain a broad understanding of the temporal and spatial characteristics of Farmington Bay aquatic biota and related abiotic factors. This first year of research was intended to provide a strong foundation for subsequent investigations that would delve into more detail on the causes and consequences of cyanobacteria blooms in Farmington Bay. The multi-year goals for the study are to discern the critical factors that influence the growth and development of cyanobacteria and to understand the effect(s) that such algal blooms have on the aquatic biota of Farmington Bay. The results are to be examined with particular respect to their adverse impacts, if any are identified, on the beneficial uses of Farmington Bay.

EXECUTIVE SUMMARY

The Importance of Farmington Bay and Regulatory Necessities

The potential impacts of cultural eutrophication on water quality and biota of Farmington Bay are a priority issue for government regulators, water resource managers, sewer districts, birding enthusiasts, and a host of other stakeholders in the Great Salt Lake ecosystem. The ecological quality of Farmington Bay is of substantial concern because it is a waterbody of extraordinary biological productivity and importance for the GSL ecosystem. Although Farmington Bay typically represents only 5.7% of the total area of the GSL, it is a critically important waterbody for the processing and cycling of nutrients and may contribute as much as 45% of nutrients into Gilbert Bay (Wurtsbaugh, Naftz and Bradt, 2008). Farmington Bay has a remarkably high capacity for primary and secondary productivity and is therefore capable of supporting large and diverse populations of zooplankton that in turn provide abundant foraging opportunities for nesting and migratory waterbirds and shorebirds. Farmington Bay supports a uniquely robust diversity of biota not found in other bays of the Great Salt Lake. Furthermore, Farmington Bay provides a vital linkage, and in a sense a buffering capacity, between urban development and the main bodies of the GSL (Gilbert and Gunnison Bays). Farmington Bay is, in short, a keystone contributor to the overall quality and ecological integrity of the GSL ecosystem and, in spite of cyanobacteria blooms in mid-summer, the bay continues to provide ecological functions that are essential for the maintenance of GSL ecosystem integrity throughout the year.

Our investigation focused on nutrient concentrations (nitrogen and phosphorous), algal and zooplankton population composition, size and dynamics, abiotic factors, and the linkages between trophic levels. The biota of Farmington Bay observed from March through November 2013 showed substantial spatial and temporal heterogeneity. Pronounced growth of diverse algal groups was documented throughout the study and supported similarly large populations of zooplankton species. "Boom-and-bust" cycles of abundance were recorded among the phytoplankton and zooplankton. The diversity and abundance of zooplankton across Farmington Bay provides for the well-characterized beneficial use of supporting waterbirds and shorebirds. Although there were demonstrable transitions from eutrophic to hypereutrophic conditions in the bay during the summer, the beneficial role of supporting avifauna was in evidence during nearly all sampling programs—although systematic counts were not conducted, thousands to tens-of-thousands of foraging waterfowl were routinely observed. Cyanobacteria blooms occurred from late May to September primarily in the central and northern regions of the bay. Coinciding with cyanobacteria blooms was evidence of competitive exclusion of other previously established algal groups such as chlorophytes and diatoms. *Trichocorixa verticalis* became the dominant zooplankter in June, July and August and appeared to facilitate a pronounced shift in the zooplankton assemblage as a result of predation pressure on vulnerable zooplankton prey and via competitive advantages conferred by other beneficial traits. Soluble/bioavailable inorganic forms of nitrogen and phosphorus were low throughout the bay with the exception of one or two sites located in the southern region of the bay in close proximity to sewage outfall canals and tributaries. Near site #7 (close to the Salt Lake County sewage outfall canal) nutrient levels differed significantly from other locations in the bay: they were always in excess of all other regions of the bay. The paucity of cyanobacteria blooms in the southern region of the bay, coupled with measureable inputs of nitrogen in this region, suggests that nitrogen levels were sufficient to diminish the competitive advantages of cyanobacteria blooms, whereas in the mid-bay nitrogen became a limiting factor thereby conferring a pronounced competitive advantage on nitrogen-fixing algae such as *Nodularia* and *Pseudanabaena*. Although there were times when the cyanobacteria blooms extended north to the causeway, there were other sampling time periods that suggested that other factors, such as salinity, might be limiting the growth and competitive edge for cyanobacteria.

The fact that hypereutrophic conditions, and cyanobacteria blooms, develop in Farmington Bay during the summer is irrefutable; such blooms have been clearly documented in our study and in previous research programs on Farmington Bay. Accompanying large accumulations of cyanobacteria are increases in cyanotoxins in the water column. However, direct harm to zooplankton populations via acute toxicity from the cyanotoxins was not readily apparent and necessitates further investigation in controlled toxicity studies with representative zooplankton species. The fundamental question with regard to the cyanobacteria blooms is whether or not their development translates into unacceptable levels of harm to other biota and as a consequence causes a demonstrable demise in desired beneficial uses of the bay.

The cyclical growth and dominance of cyanobacteria blooms in Farmington Bay may be viewed alternatively as trophic inefficiency in which the flow of energy and carbon from autochthonous primary producers is temporarily stalled vis-à-vis the production of extensive accumulations of inedible filamentous algae rather than as a definitive measure of harm to the GSL ecosystem. This trophic inefficiency is relatively short-lived and gives way to natural processes of deposition and subsequent decomposition by heterotrophic bacteria, which then usher in beneficial changes in the structure and abundance of algal and zooplankton assemblages in the bay. In spite of, or possibly as a result of, elevated nutrient input and subsequent eutrophic conditions in Farmington Bay, the bay boasts greater diversity, species richness, and total biomass per unit volume than is often reported in other regions of the GSL. The ability of Farmington Bay biota to coexist, and even thrive, when confronted with multiple cycles, within and between years, of cyanobacteria blooms may be a function of coevolutionary interactions between cyanobacteria and zooplankton grazers—interactions in which behavioral, genotypic and phenotypic variations that confer tolerance to cyanobacteria and cyanotoxins may have been selected among the Farmington Bay zooplankton.

Alternative views of Farmington Bay, and its associated cyanobacteria blooms, are suggested as a conceptual platform from which to examine, in much greater scientific detail, the remarkable resiliency and complexity of Farmington Bay biota, and also to serve as a restraint on the oft-cited inclination to immediately classify Farmington Bay as a harmed waterbody simply because of recording indicators of hypereutrophic conditions. In essence, our first year of research on Farmington Bay suggests that there are far more interesting ecological interactions taking place in the bay than a simple negative cause-and-effect relationship between cyanobacteria, its resident biota, and beneficial uses of the bay.

DETAILED SUMMARY OF MAIN FINDINGS

1. The pelagic biota and multiple abiotic factors of Farmington Bay were evaluated along a north-south transect that extended from the Antelope Island causeway to the southern shoreline of the bay. Single-site samples were collected from January through November and transect samples were collected from March through November.

2. Results from transect site assessments reveal a remarkable production of algal, zooplankton, and macroinvertebrate biomass in Farmington Bay. It is evident that the biological productivity of Farmington Bay supports a wide variety of ecological functions for the broader GSL ecosystem. It is also apparent that nutrient uptake, utilization and cycling in Farmington Bay serve an important role in the food web of the larger and more saline Gilbert Bay.

3. There was pronounced spatial and temporal heterogeneity in all abiotic elements and biotic assemblages assessed. Salinity gradients were identified along the north to south transect. Nutrient loading was highest in the southern region of the bay. The central region of the bay showed the highest biomass production. Macroinvertebrate assemblages were predominately defined by location in FB and season.

4. Of the nutrients commonly measured in limnological investigations, only nitrogen (N) and phosphorous (P) were measured specifically for this study. The forms of nitrogen measured were: TN, TKN, Nitrate/Nitrite, and Ammonia. The forms of phosphorous assessed included TP and Soluble Reactive Phosphorous (SRP). Soluble inorganic forms of N and P were rapidly depleted/assimilated once they entered the bay. Organic forms of N and P were recorded along all transect sites throughout the study.

5. Nutrient results suggest that inflow sources near site #7 were the most significant in terms of nutrient loading into the bay. Site #8 also showed substantial loading of P and to a lesser extent N. The TN:TP ratio of 9.25 suggests that the bay is nitrogen limited and is in the range indicative of phosphorous dominance.

6. Algal abundance and diversity demonstrated strong spatial and temporal dynamics; spring and early summer phytoplankton exhibited a distinctly different profile than later in the summer. The initial algal population structure was composed of diatoms, chlorophytes, and euglenophytes, but was later dominated by cyanobacteria. The cyanobacteria blooms began in May and by June cyanobacteria were the dominant algal group in the bay. Cyanobacteria continued to dominate until the end of the study in November, although there was a pronounced return of chlorophytes in July and August.

7. The most abundant cyanobacteria was *Nodularia,* followed by *Pseudanabaena*. The *Nodularia* bloom began in May then diminished in October and November. *Pseudanabaena* began its bloom in August and continued through October. Although the data are non-conclusive, it appears that cyanobacteria gain a competitive advantage over other algal species once the bioavailable forms of nitrogen are assimilated and nitrogen becomes a limiting factor for algal growth. Phosphorous levels appear sufficient to support the robust growth of cyanobacteria during summer months. It is, however, unclear how much of the bioavailable phosphorous is a function of contemporary loading versus internal cycling and mobilization of "legacy" phosphorous loads already present in the bay. Although it seems prudent to limit phosphorous loading in the bay in order to reduce the magnitude of cyanobacteria blooms it is not entirely evident that this alone would have an immediate beneficial outcome. The results also suggest that under current conditions of phosphorous input into the bay nitrogen reductions may in fact enhance the competitive dominance of nitrogen-fixing cyanobacteria and therefore promote the bloom of *Nodularia* and *Pseudanabaena*.

8. Algal biomass as indicated by chlorophyll-a concentration varied substantially throughout the study period. The peak measurement of chlorophyll-a occurred at the end of May with a maximum single site value of 506 ug/L. Average chlorophyll-a level across the bay was 114.6 ug/L and the minimum value recorded was 6.7 ug/L.

9. Water samples were analyzed for cyanotoxins. Of the two cyanotoxins examined, nodularin and anatoxin, only nodularin was found to be present in elevated levels. Nodularin concentrations were first observed in significant concentrations in May and reached peak concentration in July (62 ug/L). The average concentration across the bay for the entire study was 13.4 ug/L with a median value of 3.4

ug/L. Nodularin production followed a threshold model ("hockey stick") of presence in the water column and appeared to be a density-dependent relationship with *Nodularia* cell numbers (i.e., >10,000 cells per ml). No definitive correlation between nodularin concentration and adverse impacts on zooplankton were identified.

10. Dissolved oxygen (DO) was measured during the routine sampling programs only; hence diel changes were not recorded. The minimum DO measurement of surface water was 0.26 mg/L at site #3 on July 22nd. The average DO across the bay was 7.08 mg/L with a high of 17.3 mg/L being recorded in October when grazing pressure on phytoplankton had diminished substantially. The lowest DO recorded occurred during the subsequent sampling program after the peak chlorophyll-a measurement was recorded and may have reflected an increase in oxygen demands imposed on the system. Oxygen consuming biochemical decomposition processes by heterotrophic bacteria, zooplankton respiration requirements, reductions in oxygen generation via shading of subsurface phyto- and benthic algae, or the combination of these and other oxygen depleting chemical reactions may have contributed to the decline in oxygen during July. Aside from the decline in July, daily average DO levels appeared sufficient to support zooplankton population growth.

11. Salinity was consistently low in the southern region of the bay where it had a maximum range of 0.1% to 0.5%. Salinity increased along a south to north transect with an average across the bay of 1.4% and the highest value of 8.3% being measured at site #1—near the breach in the Antelope Island causeway. The maximum value for salinity roughly followed a north to south gradient: Site 1 (8.3%), Site 2 (4.5%), Site 3 (6.3%), Site 4 (2.8%), Site 5 (3.6%), Site 6 (1.7%), Site 7 (0.5%), and Site 8 (0.2%). Site 9, which is on the Gilbert Bay side of the Antelope Island causeway had an average of 11.1% and a maximum value of 14.0%.

12. Zooplankton and macroinvertebrates were found in abundance in Farmington Bay and predominantly included Rotifera—*Brachionus plicatilis*; Cladocera—*Moina macrocarpa*; Copepoda (Harpacticoid)—*Cletocamptus sp.*; Branchiopoda—*Artemia franciscana*; Insecta (Hemiptera)—*Trichocorixa verticalis*. From April until July there were tremendous numbers of zooplankton in Farmington Bay and in particular in the central region of the bay. However, coinciding with the emergence and maturation of the corixid *Trichocorixa verticalis* the diversity and abundance of other zooplankton plummeted and essentially never recovered until corixids abundance declined in September. There is strong evidence of a top-down influence of *T. verticalis* on the zooplankton composition of the bay. There may, however, be multiple other factors influencing the demise of zooplankton including food limitation, intra and inter-specific competition, predation by invertebrates other than corixids, predation by vertebrate species,

dissolved oxygen levels, cyanotoxins, other stressors that can serve to constrain zooplankton growth and development. Normal life span and generation times also exert an influence on the temporal pattern of zooplankton abundance and diversity.

13. The results from the first year of study were used to develop food web models. Although some interesting results were identified, and some significant findings of food web interactions were statistically revealed and supported, the food web models are in their preliminary stages and will be used primarily to identify data gaps and to tailor future research to more thoroughly document causal relationships among the abiotic and biotic elements of the bay.

PRINCIPAL INVESTIGATORS

- Brad Marden
- Theron Miller

PROJECT OBJECTIVE

To provide the Central Davis Sewer District (CDSD) and the Jordan River/Farmington Bay Water Quality Council with detailed scientific information on the causes and consequences of cyanobacteria blooms in Farmington Bay, Great Salt Lake, Utah.

SCIENTIFIC OBJECTIVES

1. Collect a systematic record of spatial and temporal changes in the biotic community and abiotic characteristics of Farmington Bay from March through November.
2. Identify key factors that influence phytoplankton, and in particular cyanobacteria, population size, composition and structure.
3. Evaluate spatial and temporal changes in the zooplankton population composition and abundance with respect to abiotic and biotic factors as well as predator-prey relationships.
4. Document the linkage between cyanobacteria blooms and cyanotoxin production in Farmington Bay and examine the effect(s) that cyanotoxins have on resident zooplankton.

DURATION OF PROJECT

March 1, 2013 to February 28, 2014

BACKGROUND AND JUSTIFICATION

It is well established that the Great Salt Lake (GSL) ecosystem serves multiple critical ecological and biological functions of hemispheric importance, influences the weather, and contributes substantially to the economy of Northern Utah (Paul and Manning, 2001). Although Farmington Bay has been studied intensively over the past few decades, there remains much uncertainty about the role of anthropogenic inputs and their impact on the ecology of the bay (Moser et. al., 2012; Goel and Meyers, 2009; Goel 2008; Schulle, 2008; Miller and Hoven, 2007). Of particular scientific and regulatory interest is the ecological response of Farmington Bay (FBay), to nutrient inputs from various sources including POTWs. Other researchers have examined nutrient loading into FBay periodically and their studies have shown high levels of nutrients (especially nitrogen and phosphorous) and substantial algal growth in response to elevated nutrient levels (Wurtsbaugh, Naftz and Brandt, 2009; Wurtsbaugh, 2008; Marcarelli et. al., 2005). These authors report extremely high levels of chlorophyll-a and cyanobacteria blooms and the subsequent establishment of hypereutrophic conditions in FBay as well as the presence of cyanotoxins. The USEPA along with the Utah State Division of Water Quality are under obligation to ensure that wastewater discharges into the Great Salt Lake are in compliance with the Federal Clean Water Act (CWA). Implementation and enforcement of the CWA is challenging giving the unique characteristics of the GSL and it requires an in-depth and site-specific understanding of the complex ecological responses of the GSL to nutrient inputs. The only site specific standard that exists to date for contaminants or nutrients input into the GSL is for selenium (Ohlendorf et. al., 2009; Brix and DeForest, 2004) and the multi-year process involved in this effort illustrates the importance and challenges of establishing such a site-specific standard. It is therefore of paramount importance to critically and systematically document and interpret the role that nutrients serve in the algal dynamics of FBay in order to provide a means for a prudent and ecologically sound process of establishing site specific nutrient standards for waste water discharged into FBay.

INTRODUCTION

The initial goal of this study is to rigorously document biotic and abiotic characteristics of FBay. Included in this multi-year objective is to record limnological conditions in FBay from the early stages of ice melt in March to the onset of winter in November. The goal is to have a continuous record of both biotic and abiotic conditions in the bay and to use this detailed record to understand the factors that lead to cyanobacteria blooms and eutrophic conditions in FBay. Particular emphasis is on the nutrients nitrogen and phosphorous, their spatial and temporal variations, and the correlation between nutrient concentrations and cyanobacteria blooms. The secondary and long-term goals of the project are to discern the effects that cyanobacteria blooms have on the biotic community and the adverse impacts, if any, that such blooms have on beneficial uses of the bay.

Objectives

The objectives were outlined as follows:

Objective #1. Collect a systematic record of spatial and temporal changes in the biotic community and abiotic characteristics of Farmington Bay from March through November.

Routine systematic assessment of biological and abiotic conditions will be completed on all surveys of FBay. These assessments will provide the foundation for understanding algal population dynamics and the factors that influence their growth. Nine sites along a north-south transect will be sampled and, due to the shallow water column, water will be collected from only a single depth (25 cm below the surface). Sampling will begin in March with the initial stages of ice-melt and will continue monthly or on a semimonthly basis until the end of November. During these routine sampling programs abiotic data will be recorded and biological samples collected.

Objective #2: Identify key factors that influence phytoplankton, and in particular cyanobacteria, population size, composition and structure.

Information collected under Objective #1 was used to statistically investigate the correlation, if any exists, between observed changes in the algal population size and structure with factors that potentially influence such changes. This field data can be used for the design of subsequent in-situ or laboratory experiments on the specific reaction of algal colonies to changes in nutrient concentrations. Although initially half of all algal and cyanobacteria samples collected will be analyzed (as a cost saving measure) a full suite of samples will be collected, preserved and stored for subsequent analysis if necessary.

Objective #3: Evaluate spatial and temporal changes in the zooplankton population composition and abundance with respect to abiotic and biotic factors as well as predator-prey relationships.

Information collected under Objective #1 will be used to statistically investigate the correlation, if any exists, between observed changes in the macroinvertebrate abundance, species composition, and age-class structure with factors that potentially influence such changes. Of particular interest is the relationship between macroinvertebrate population size and composition and algal population composition and abundance and the concentrations and extent of cyanotoxins, if they exist. Abiotic factors will also be analyzed in terms of their relationship and potential influence on macroinvertebrates in FBay.

Objective #4: Document the linkage between cyanobacteria blooms and cyanotoxin production in Farmington Bay and examine the effect(s) that cyanotoxins have on resident zooplankton.

While cyanobacteria blooms have been well documented in FBay, the production of cyanotoxins and their impact(s) on other biota in FBay has not been well understood. During this study the presence of cyanobacteria blooms, as indicated by dramatic changes in phycopigments, dissolved oxygen, and the presence of algal mats, will dictate that cyanotoxins assessments be included in the program. Concentrations of cyanotoxins will be analyzed in terms of algal population size and structure.

METHODS AND STUDY DESIGN

Study Area

The study focused Farmington Bay, Great Salt Lake, Utah. Farmington Bay is a highly unique body of water that provides many beneficial uses for the GSL ecosystem and for the surrounding areas. Some of these beneficial uses include, but are not limited to: habitat that supports a large number and diversity of avifauna, nutrient cycling essential for maintaining the biological integrity of the GSL, aesthetic value, supporting waterfowl reserves and hunting clubs, serving as a receiving water for treated sewage discharges, modulating ambient temperature fluctuations through its thermal mass, and reducing dust loads. Farmington Bay is an isolated bay of the GSL that is defined geographically by both natural and manmade features; it is bordered on the west by Antelope Island, on the north by the manmade Antelope Island causeway, on the east by extensive wetlands and urban areas, and to the south by a network of wetlands, waterfowl hunting clubs and managed water impoundments. Farmington Bay is a shallow basin and under the drought conditions of the last 15 years, it has a maximum depth of 1.3 meters and an average depth of 20-35 cm and has an area of approximately 135 km^2 during our study. Water entering Farmington Bay is primarily regulated and enters the bay via the Jordan River, sewage canals and the outflow from urban drainage basins. The bay also receives unregulated runoff water along its eastern and western margins. Farmington Bay is connected to the main body of the GSL (Gilbert Bay) by means of a breach in the Antelope Island rock causeway. This breach allows bidirectional flow of water to and from Farmington Bay depending on lake elevation, relative hydrological forces, and weather events. During spring runoff and throughout much of the year the flow is predominantly south to north; meaning from Farmington Bay into Gilbert Bay. However, wind events can dramatically alter the flow of water through the breach resulting in a north to south flow during certain times of the year. Abiotic and biotic features of Farmington Bay are characterized by high spatial and temporal diversity attributable to its shallow depth and the influence of bidirectional flow from the higher saline water of Gilbert Bay. There is generally a salinity gradient from south to north with the southern extension of the bay demonstrating relatively very low salinity (2-5 g/L) while the northern region near the causeway can achieve salinity concentrations approaching 100 g/L (Marcarelli, Wurtsbaugh, and Griset; 2009). This salinity gradient exerts a substantial influence on the population structure and composition of algae and zooplankton. Pronounced temporal changes in the biotic community of Farmington Bay have been documented by previous investigators and include dramatic shifts in algal species composition and abundance as well as substantial transitions in the population size and species composition of zooplankton. The bay often freezes in the winter and is typically ice free from mid-March to late December. The bay often exhibits eutrophic conditions (i.e., chlorophyll-a in excess of 400 ug/L and dissolved oxygen levels dropping to below 1.5 mg/L) during the summer months with eutrophic conditions corresponding to high abundance of cyanobacteria. Although characteristics of eutrophic conditions do exist, the extent to which these conditions exert an adverse influence on beneficial uses of the bay remains unanswered.

Sample Site Location

Sample site locations were assigned based on a north-south longitudinal transect that was established for previous scientific studies conducted by the Central Davis Sewer District and other investigators. Use of these site locations was chosen in order to afford an important degree of continuity from previous research investigations and because the existing site locations follow a biologically logical and defensible transect from north to south along the bay. Additionally, due to the shallow nature of the bay there are few other options (east-west) that can be reliably surveyed without undue risk of grounding. Of the nine sample sites used for this study eight of them were located in Farmington Bay and one additional site was located on the Gilbert Bay side (north) of the Antelope Island causeway breach that allows bi-directional flow between the bays.
The existing 8 Farmington Bay sites have a diversity of benthic environments and allowed for meaningful interpretations to be made with regard to the overall condition of the bay.

Frequency and Timing of Sampling

The sampling schedule was based on the following three goals: 1) collect samples beginning at the time of ice-melt from the bay; 2) sample more frequently during months when dramatic changes in algal blooms have been previously reported; 3) continue with sampling well into the late fall and the onset of winter. A total of 14 sampling programs were completed. Additionally, 28 single site samples were collected at Site #1. These were used for cyanobacteria and cyanotoxin assessments. Most research investigations in FBay have been limited to just a few systematic surveys and none have documented conditions throughout the entire spring and where therefore limited in their interpretive capabilities. The intent of this project was to have a full record of algal dynamics during the ice-free growth season and to evaluate the algal dynamics in relation to nutrient concentrations and zooplankton population size and structure and to augment this information with more frequent tracking of the cyanobacteria growth and cyanotoxin production.

Sample collection

Separate water samples were collected for nutrient, chlorophyll-a, and algal analysis. Cyanotoxin concentrations were determined for water samples collected for algal analysis. All water samples were collected in pre-cleaned 500 ml HDPE bottles. Bottles were filled to over-flowing and capped securely to minimize head space. All samples were immediately stored in the dark and on ice and were either preserved or shipped the same day of sampling via express overnight shipping. Samples for nutrient and chlorophyll analysis were shipped to Aquatic Research Laboratory in Seattle Washington. Samples for a combination of algal enumeration and cyanotoxin analysis were shipped same day of collection to GreenWater Laboratory in

Palatka Florida. Water samples used only for algal analysis were preserved using 1 ml concentrated Lugol's iodine solution, stored in the dark and on ice and then delivered to Rushforth Phycology in Orem Utah for phytoplankton identification, enumeration and biovolume determination.

Zooplankton were collected by means of a vertical net haul using a 50 cm diameter plankton net with a 65 micron mesh and affixed with a removable collection cup. Vertical net haul depth was recorded and used to calculate the total volume sampled in order to report zooplankton on a per volume basis (i.e., per liter). Zooplankton were rinsed from the collection cup into 4 liter containers, transported on ice, then subsequently isolated on 30 micron sieve and discharged into 475ml glass jars. A pH buffered formaline (10% solution) was added to a final formaline concentration of 5%. Samples were then immersed in an ice bath and delivered to Dr. Lawrence Gray, Utah Valley University in Orem Utah for zooplankton identification and enumeration.

SAMPLING PROGRAM

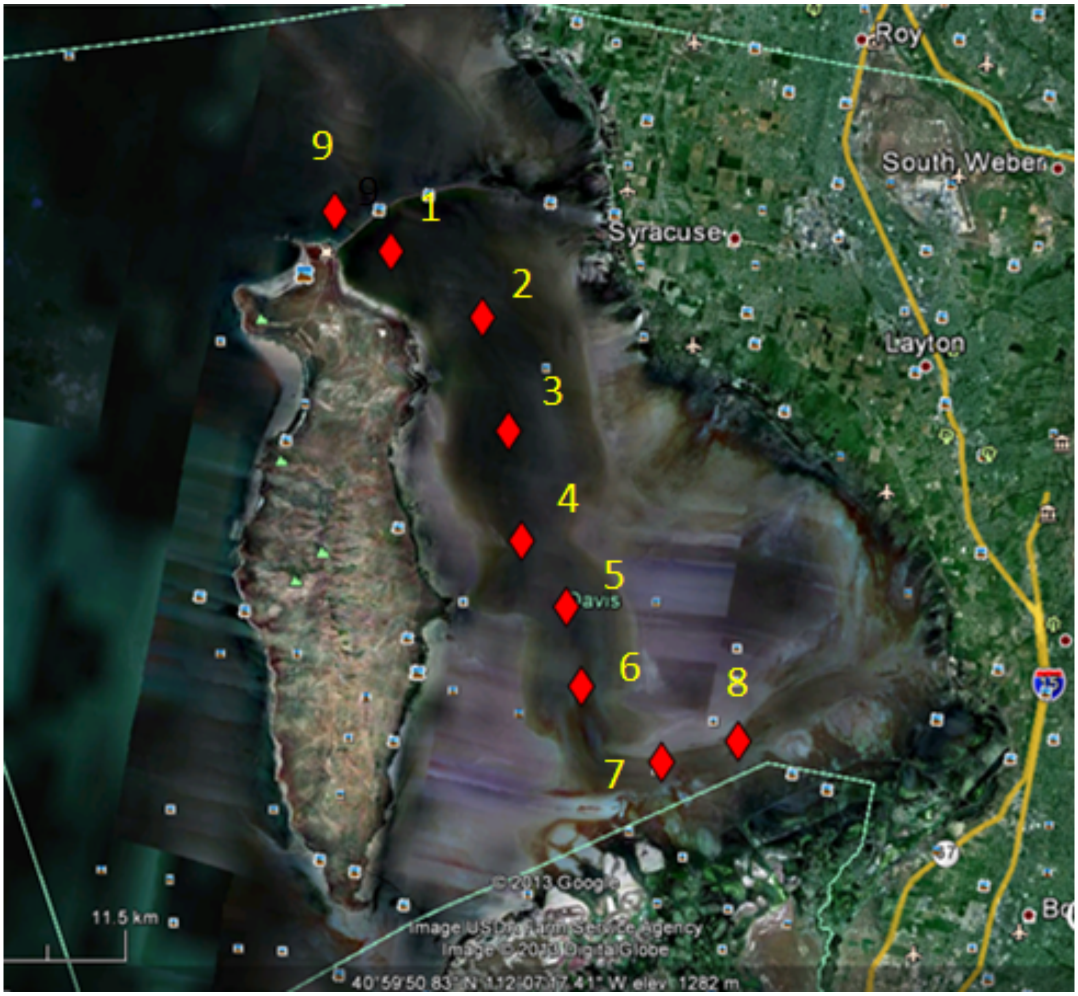
Sample Site Locations

- Farmington Bay
    - 9 locations
    - Sample sites follow transect
    - Specific locations coincides with previous scientific investigations
    - GPS coordinates
        - Site 1 N: 41.03.58 , W: 112.13.46
        - Site 2 N: 41.03.09 , W: 112.11.17
        - Site 3 N: 41.01.40 , W: 112.09.23
        - Site 4 N: 40.59.34 , W: 112.08.36
        - Site 5 N: 40.57.30, W: 112.07.36
        - Site 6 N: 40.55.33, W: 112.06.09
        - Site 7 N: 40.54.43, W: 112.02.39
        - Site 8 N: 40.55.12, W: 112.01.31

- Ogden Bay
    - 1 location
    - Random location near area of Antelope Island Causeway breech entrance to the open water of Gilbert Bay.
    - GPS Coordinates:
        - Site 9 N: 41.04.02 , W: 112.14.00

- Transect Sample Schedule:
    1. March 14, 2013
    2. April 18, 2013
    3. May 13, 2013
    4. May 30, 2013
    5. June 10, 2013
    6. June 13, 2013
    7. June 25, 2013
    8. July 11, 2013
    9. July 22, 2013
    10. August 6, 2013
    11. August 26, 2013
    12. September 19, 2013
    13. October 17, 2013
    14. November 14, 2013
- Additional Single Site Sample Schedule:
    1. January 8, 2013
    2. January 22, 2013
    3. February 5, 2013
    4. February 19, 2013
    5. March 5, 2013
    6. March 12, 2013
    7. March 19, 2013
    8. March 26, 2013
    9. April 2, 2013
    10. April 9, 2013
    11. April 16, 2013
    12. April 23, 2013
    13. April 30, 2013
    14. May 7, 2013
    15. May 22, 2013
    16. June 4, 2013
    17. June 18, 2013
    18. July 2, 2013
    19. July 9, 2013
    20. July 16, 2013
    21. July 30, 2013
    22. August 14, 2013
    23. August 21, 2013
    24. September 4, 2013
    25. September 10, 2013
    26. September 24, 2013
    27. October 9, 2013
    28. November 6, 2013

Figure 1. Sample site (total N=9) locations in Farmington Bay (n=8) and in Gilbert Bay (n=1). Sample sites are designated along a predetermined transect through the bay and follow the midline for the 4196 elevation contour.



Routine Sample Site Procedures

- Routine Procedure:
    - Measure total depth
    - Secchi disk

    Measurements are taken at 25 cm depth include:
    - pH (YSI)
    - Temperature (YSI 550 temperature probe).
    - Salinity (refractometer)
    - Conductivity/TDS (Hach)
    - Dissolved oxygen (at intervals if depth is >50 cm)(YSI 550A)
    - In-vivo phytopigment measurement
        - Turner DataBank
            - Phycocyanin probe
    - Collect multiple 500 ml water samples for:
        - Nutrients
        - Complete algal assessment
        - Cyanobacteria
        - Chlorophyll-a
- Water samples treatment

    All water samples were pre-filtered through 500 or 125 micron sieves to remove zooplankton from the samples.
    - Nutrients
        - Preservative: none (samples are for immediate shipment)
        - Samples stored in HDPE bottle with eliminated head space.
        - Samples immersed in an ice bath and in the dark for transport to laboratory.
        - Samples transported to lab within 12h of completion of sampling program and shipped within 12 to 24 hours to analytical lab.
        - Samples were analyzed for NH_3, NO_3, NO_2, TKN, TP, Ortho-P
        - Samples were analyzed by Aquatic Research Inc.
        - Samples are prepared for nutrient analysis according to standard methods.
    - Algae (phytoplankton)
        - Preservative: concentrated Lugols solution .
        - Samples stored in HDPE bottle with eliminated head space. Samples immersed in an ice bath and in the dark for transport to laboratory.
        - Samples delivered to and analyzed by Rushforth Phycology.
    - Cyanobacteria
        - Preservative: none (samples are for immediate shipment)
        - Samples stored in HDPE bottle with eliminated head space. Samples immersed in an ice bath and in the dark for transport to Central Davis Sewer District for shipment or storage.
        - Samples shipped to GreenWater Laboratories within 12h of collection for immediate analysis.
    - Cyanotoxins
        - Preservative: None (samples are for immediate shipment)
        - Samples stored in HDPE bottle with eliminated head space. Samples immersed in an ice bath and in the dark for transport to Central Davis Sewer District for shipment.
        - Samples shipped to GreenWater Laboratories within 12h of collection for immediate analysis
    - Chlorophyll-a
        - Preservative: Magnesium Carbonate (lab).
        - Samples stored in HDPE bottle with eliminated head space.
        - Samples immersed in an ice bath and in the dark for transport to laboratory.
        - Samples shipped to laboratory within 24-48h.

- Samples analyzed by Aquatic Research Inc.

- Net haul samples treatment:
    - Macroinvertebrates
        - Vertical net haul from bottom of water column using a 50 cm diameter plankton net with 65 micron mesh and affixed with detachable collection cup.
        - Entire contents were judiciously washed from net and into receiving collection cup.
        - Collection cup contents repeatedly rinsed with filtered Farmington Bay water into 4 liter sealed container.
        - Samples immersed in an ice bath and in the dark for transport to laboratory.
        - Zooplankton were then isolated from 4-liter container by filtration through 30 micron sieve and then rinsed into glass specimen jar.
        - Preservative: Buffered Formalin was added to the specimen jar to a final concentration of 2.5% buffered formaline.
        - Samples were then transported to the laboratory of Dr. Lawrence Gray, UVU for identification and enumeration.
        - Sample identification and enumeration was carried out to the species level if possible. Enumeration includes population age class structure and fecundity assessments.

Analytical Methods

Cyanotoxin Measurements and Cyanobacteria Identification and Enumeration (GreenWater Laboratories)

Nodularins/Microcystins

- High performance liquid chromatography (HPLC) systems with photodiode array (PDA), fluorescence (FL), and mass spectrometry (M^{Sn}) detection.

Cyanobacteria Identification and Enumeration

- Samples were preserved with Lugols solution.
- Then Utermöhl counting chambers were constructed. Depending on the cell density of the sample settling towers of 5, 10 or 25 mL were used. Towers were secured to base using a thin film of high vacuum grease. Minimum settling times were 17 hours for 5 mL samples, 34 hrs for 10 mL samples and 74 hours for 25 mL samples.
- Enumerations were performed on a Nikon Eclipse TE200 inverted microscope equipped with phase contrast optics.
- A minimum of 400-600 natural units per slide were counted to give a 95% confidence interval of the estimate within +10% of the sample mean. QA/QC checks were performed at least once for every 10 samples counted and included a check for random distribution of cells (standard error among total number of natural units/field was calculated as the count was being performed with a goal of 15% or less) and a replicate count (goal being a difference between counts of 15% or less). New samples were prepared if samples failed to reach the QA/QC objectives.

Nutrients, Chlorophyll-a, pH, Salinity and Conductivity(Aquatic Research, Inc.)

- Ammonia: Automated Phenate, EPA# 350.1, Standard Method # 4500NH3H
- Nitrate/Nitrite: Automated Cadmium Reduction, EPA# 353.2, Standard Method # 4500NO3F
- Total Kjeldahl Nitrogen: micro-Kjeldahl, EPA # 351.1, Standard Method #4500NORGC
- Total Phosphorous: Automated Ascorbic Acid, EPA# 365.1, Standard Method #4500PF
- Soluble Reactive Phosphate: 0.45 micron filtration, EPA # 365.1, Standard Method #4500PF
- Salinity: Conductometric, Standard Method # 252OB
- pH: Potentiometric, EPA # 150.1, Standard Method #4500H+B
- Conductivity: Conductometric, EPA # 120.1, Standard Method #251OB

Analytical Laboratories

Nutrients, Chlorophyll-a, pH, Salinity and Conductivity

Aquatic Research, Inc.
3927 Aurora Avenue North
Seattle, WA
98103
Phone: 206.632.2715
http://www.aquaticresearchinc.com/contact.html
Certifications:

- Washington State Department of Ecology for the analysis of environmental and drinking water samples.
- State of California by the Department of Health Services Environmental Laboratory Accreditation Program (ELAP)

Cyanotoxins and Cyanobacteria Identification

GreenWater Laboratories
205 Zeagler Drive
Suite 302
Palatka, FL
32177
Phone: 386.328.0882
http://www.greenwaterlab.com/contactus.html

Phytoplankton Identification

Rushforth Phycology
4123 Bona Villa Drive
Ogden, UT
84403
801-376-3516
http://rushforthphycology.com/201.html

Zooplankton Identification

Dr. Lawrence Gray
Department of Biology
Utah Valley University
800 W. University Parkway
Orem, UT
84058
(801) 863-8558

Phytoplankton Identification and Enumeration

- Samples are filtered through a 1.2 micron pore filter
- Cells retained on the filter are resuspended in 5 ml of distilled water
- Subsamples are isolated placed in a Palmer Counting Chamber and viewed with a Nikon CF160 Infinity Optical System at 160X to 400X
- Identification is carried out to species level of taxa if possible and if species cannot be confirmed then identification is determined to genus level.
- Samples for diatom analysis are separately prepared using nitric acid digestion coupled with potassium dichromate staining.
- Diatoms are then slide mounted and identified using a Nikon Eclipse E200 microscope equipped with a Nikon CF160 optical system.

- Identification is to the lowest taxonomic level possible; species or genus level if possible, otherwise categorized according to centric or pinnate diatoms.
- Biovolume, relative abundance, and rank are determined or calculated along with cell counts.
- Detailed SOPs are available from Rushforth Phycology

Zooplankton Identification and Enumeration

- Samples are thoroughly mixed to ensure uniform distribution.
- Subsamples are then collected and dispensed into counting cells
- All zooplankton contained in subsamples are identified to lowest taxa possible.
- Age-class categories are identified, defined and enumerated according to standard procedures and distinctions.
- Gravid females are separately assessed.
- Biomass is calculated based on species composition and population size per liter.

Spatial and Seasonal Patterns of the Macroinvertebrate Assemblage in FB

Ordination techniques are often superior to hypothesis testing approaches for explaining relationships between multivariate ecological assemblages or communities (McCune and Grace 2002). In general, ordination is the ordering of objects along axes according to their (dis)similarities. The main objective of ordination is data reduction and expressing many-dimensional relationships into a small number of easily interpretable dimensions (axes on a plot). The strongest correlation structure in the data is extracted and is then used to position objects in ordination space. Objects that are close in the ordination space are generally more similar than objects distant in ordination space (McCune and Mefford 2011).

Several types of ordination exist; non-metric multidimensional scaling (NMS) was used for this analysis. NMS has been shown to be robust for ordination of species composition and is often more useful than other ordination techniques because, among other things, it avoids the assumption of linear relationships among variables. NMS is also the most widely accepted ordination technique used in community ecology (Peck 2010). NMS ordination permitted the visualization of the multidimensional relationships of the macroinvertebrate assemblages in our FBay dataset into a more easily visualized lower dimensional space. Dimensional reduction obviously creates some distortion in relationships between samples. The level of reduction in distortion is measured as ‘stress’; less stress equals less distortion.

Dry weight biomass (micrograms) of macroinvertebrate taxa were estimated from the literature and then calculated from the density (number/L) values in the data. Biomass data were then log generalized transformed prior to NMS analyses using PC-ORD (2011)(Version 6.0). Taxa biomasses were log generalized transformed[1] to dampen the influence of highly abundant taxa (e.g. Tricocorixid taxa) and to balance assemblage relationships with rare and uncommon taxa that occurred at low abundances (Gauch 1982; Efron and Tibshirani 1991; Cao et al. 1998). Taxa with ≤ 2 occurrences in the sixty- eight samples were also removed from the analyses, which resulted in nine taxa used in the final analyses. A Sorensen (Bray-Curtis) distance measure was used in the NMS analysis and run for 250 iterations using the real data and 250 iterations in randomized Monte Carlo simulations. The Sorensen distance measure is based on pairwise comparisons between all sample pairs, therefore NMS ordinations were rotated using varimax rotation to maximize variation along the axes, and extracted as univariate scores. Because standardized log-abundance variables are approximately normally distributed, axes are a linear combination of these variables, and are approximately normally distributed as well.

The best model was chosen based on scree plots and final significant stress values. Centroid labels were added to the ordination plots to better interpret the spatial and temporal macroinvertebrate assemblage relationships. Post- hoc proportion of variance represented by each axis was calculated based on the R^2 value between distance in the ordination space and distance in the original space. Individual macroinvertebrate taxa correlations with NMS axes were also calculated and those with strong correlations ($r > 0.50$) were added to the plots. Graphs of the relative proportion of the nine taxa per sample in ordination space were also made. Correlations between salinity and NMS axes were also made. Missing salinity measurements ($N = 12$) were averaged per site before correlating with NMS axes.

Macroinvertebrate Assemblages relationships to environmental variables

MRPP (multi-response permutation procedure), a non-parametric method, was also used to formally test the null hypothesis of no spatial and temporal differences in macroinvertebrate assemblage groups. MRPP has the advantage of not requiring distributional assumptions such as multivariate normality and homogeneity of variance and is often superior to MANOVA (McCune and Grace 2002). As is NMS, MRPP is one of the more useful ordination methods for analyzing multivariate ecological data. A Euclidean distance measure was used in this MRPP analysis. The chance-corrected within-group test statistic, *A* (and associated p-value) was used to evaluate the hypothesis of no difference in the groupings (McCune and Grace 2002).

Food web analysis

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[1] See Appendix 1 for description of log generalized transformations

Structural Equation Modeling (SEM) methods

Structural Equation modeling, SEM is a combination of a large number of statistical models used to evaluate the validity of proposed relationships using empirical data and is related to path analysis. Statistically, SEM represents an extension of general linear modeling (GLM) procedures, such as ANOVA and multiple regression analysis (Acock 2013). One of the primary advantages of SEM (vs. other applications of GLM) is that it can be used to study the relationships among latent constructs that are indicated by multiple measures. SEM typically takes a confirmatory (hypothesis testing) approach to the multivariate analysis. The causal pattern is specified *a priori*. The goal is to determine whether a hypothesized theoretical model is consistent with the data collected. The consistency is evaluated through model-data fit, which indicates the extent to which the postulated network of relations among variables is plausible (Acock 2013). SEM is a large sample technique (usually $N > 200$) and the sample size required is somewhat dependent on model complexity, the estimation method used, and the distributional characteristics of observed variables.

We used SEM based on our limited data more as an exploratory but somewhat confirmatory model to help us construct cursory food web models. We used maximum likelihood with missing values with a maximum of 200 iterations using the SEM package in STATA 13. We did not evaluate or validate the model further because we only wanted to begin exploration of the paths between variables and to help us to understand the food web dynamics and to construct more realistic models after we collect and assimilate additional data. We attempted to link the top down effects of phytoplankton (measured as non- cyano cells and PTox cells)(primary producers) on nutrients (measured as SRP and TIN) in our first model but we did not have enough data points and a viable model could not be generated (remember in SEM models the more links and complex a model is the more data points are necessary) We then created an SEM with only bottom up effects of nutrients on phytoplankton, top down and bottom up effects between phytoplankton (primary producers) and zooplankton (primary consumers), and top down and bottom up effects between zooplankton and corixids (secondary consumers).

The food web model thus constructed has some limited interpretive value for the initial research results, but it provides an excellent framework for identifying data gaps, causal relationships and interactions, and for revising experimental design for subsequent field research as well as devising and implementing mesocosms or complimentary laboratory projects to further determine causal relationships, interactions, and relevant linkages among and within trophic levels of the food web.

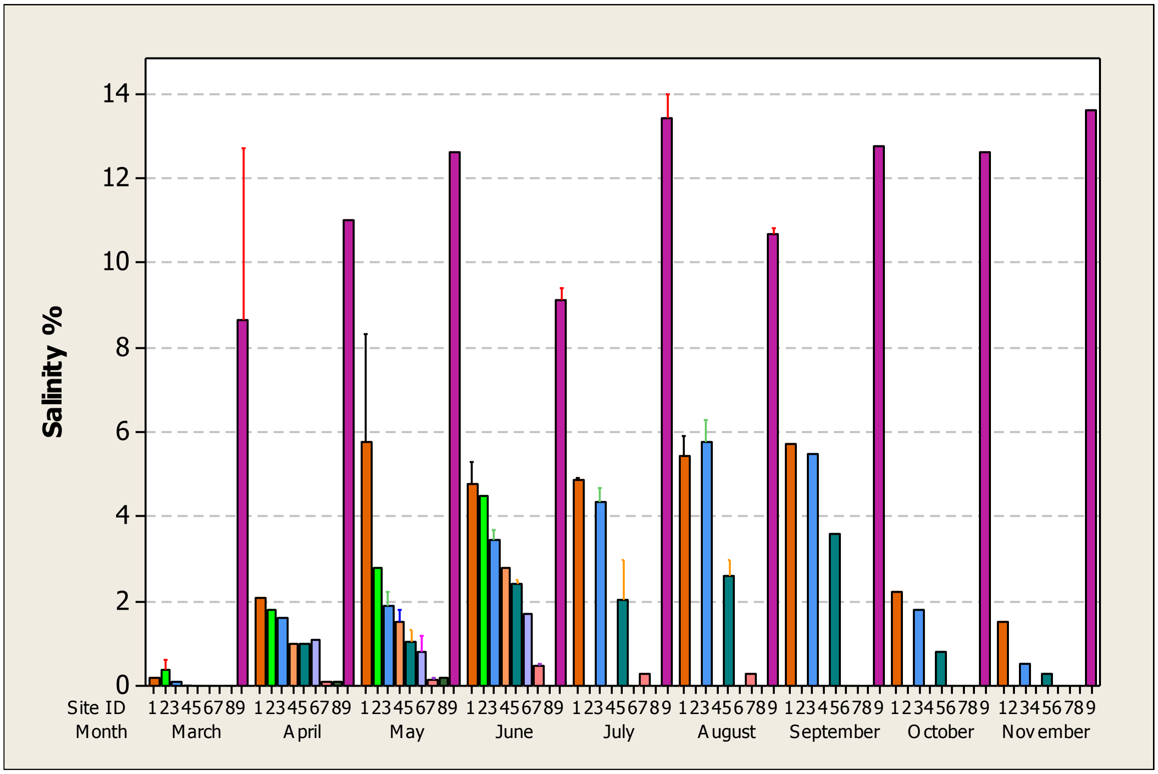
RESULTS

Abiotic Characteristics

Salinity and Conductivity

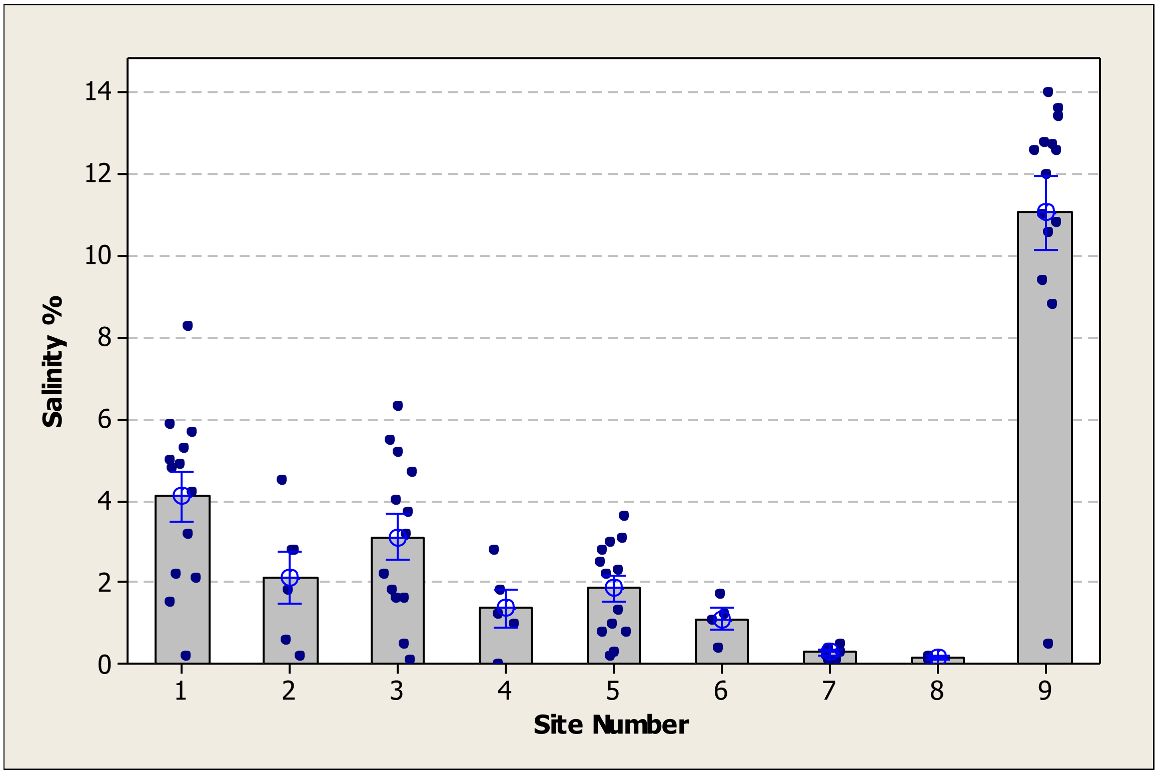
Salinity varied both spatially and temporally across Farmington Bay throughout the course of the study period. Salinity was highest in the sites located in the northern region of the bay demonstrating influence from bidirectional flow of water from Gilbert Bay into Farmington Bay. Within each sample period this north-south spatial gradient was observed (Figure 2).

Figure 2. Spatial and temporal results for salinity in Farmington Bay. Samples are taken from 25 cm depth at each location and 1-2 times per month. Site number 9 is on the Gilbert Bay side of the Antelope Island causeway. Sites 1-8 follow a north to south transect.



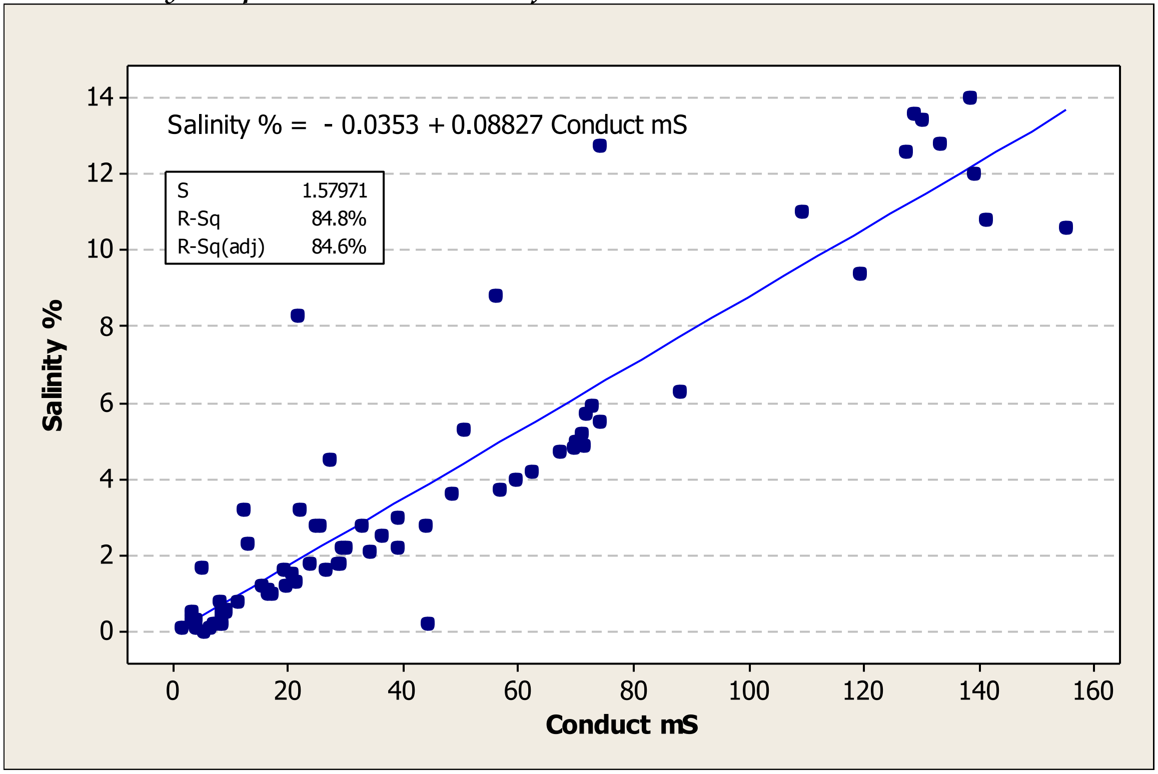
There was also a temporal component to the salinity of Farmington Bay water samples in which the salinity increased from a low during spring thaw followed by an increasing trend that reached its peak salinity in August and September. Salinity then decreased thereafter as a function of precipitation and inflow of runoff water into the bay. Site #9 showed the greatest range of salinities: with a low of 0.5% and a high of 14.0%. The low value corresponded to a surface sample during spring ice melt. The range at site #9 thereafter fell between 8.8% and 14.0%. The pattern of salinity at site #9 is a function of the substantial influence of Gilbert Bay salinity coupled with transient changes linked to wind events (i.e., low value during July due to substantial and prolonged wind). The spatial pattern of salinity varied in a site specific manner: the southern sites showed the lowest degree of variability while, not surprisingly the northern sites were the most variable (Figure 3).

Figure 3. Within-sample location salinity measurements. The pattern of variability consistently reflected sample site location within the bay. Sample location proximity to the Antelope Island causeway, and the breach that provides bidirectional flow between the bays, had a distinct influence on site salinity: it established a North-South gradient of salinity across Farmington Bay.



Conductivity was also recorded as a surrogate measure of dissolved solids in the water samples. The conductivity measurements correlated with salinity % assessments (R^2=84.6%)(Figure 4). Conductivity measurements retain value for comparative purposes with other saline water bodies and for an more detailed understanding of the osmotic conditions that the algae and zooplankton are subjected to throughout the bay.

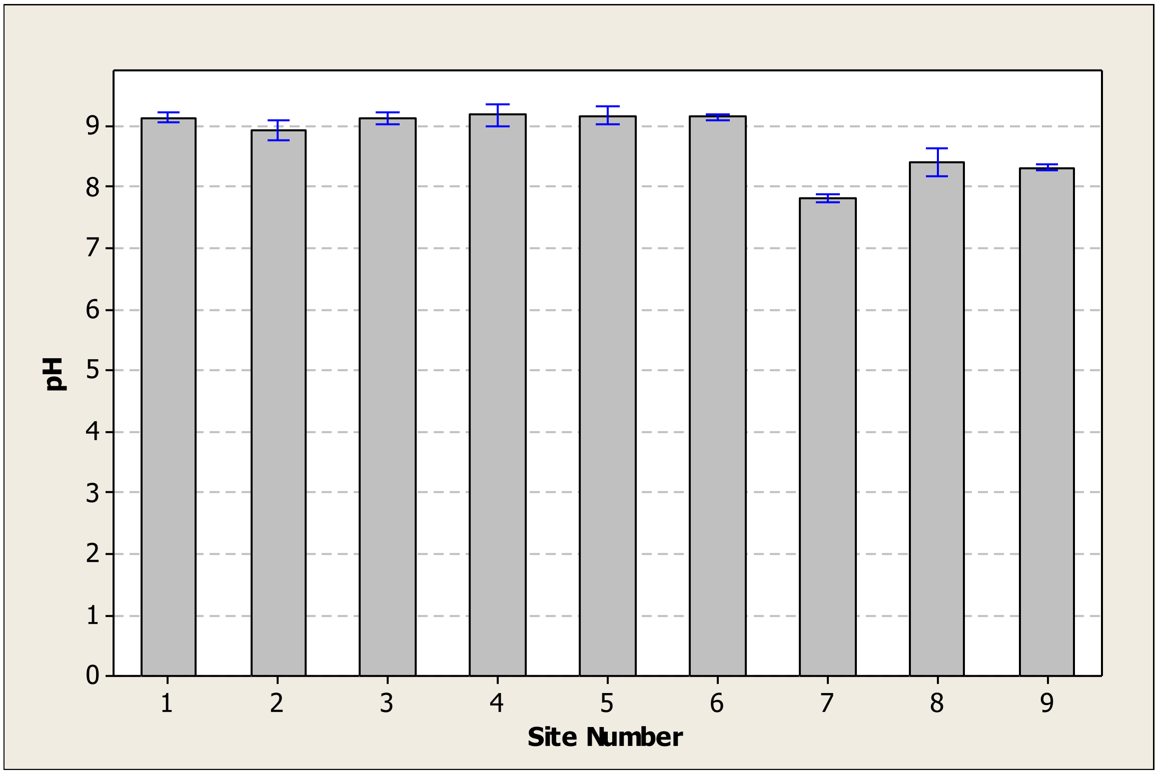
Figure 4. Comparison of conductivity and salinity measurements for samples collected on Farmington Bay. There was a strong positive correlation between the two measurements. Salinity was done by temperature corrected refractometer measurements.



pH

The pH of Farmington Bay was relatively uniform for sites distant from sources of runoff or tributary inflow. The pH across sites 1-6 maintained a stable mean measure between 8.93 and 9.14. Sites 7 & 8 showed the influence of inflow waters with lower pH than other samples for the bay. For these two sites the average pH was between 7.82 and 8.40. Site #9 was, as expected, lower than the pH in the bay, and likely reflected the buffering capacity of Gilbert Bay coupled with diminished algal growth (i.e., less uptake of CO_2). The pH at this site varied from 8.09 to 8.60 with an average of 8.31.

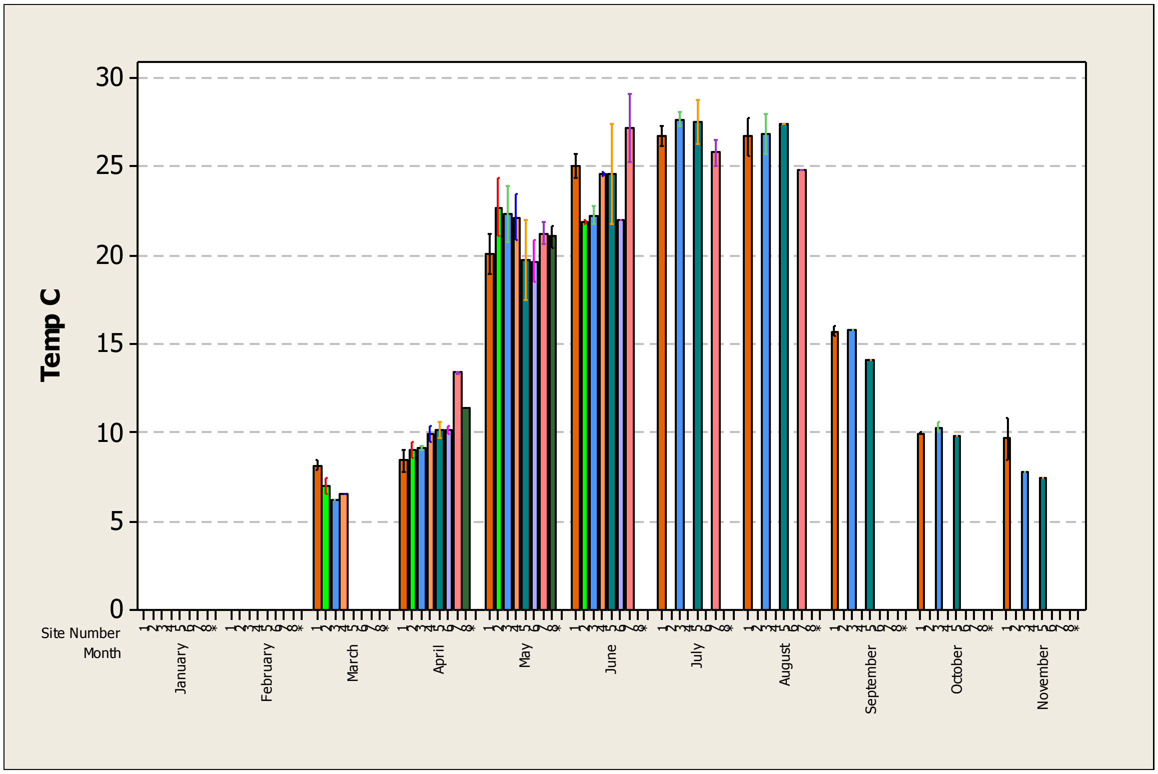
Figure 5. The average pH of Farmington Bay sample locations. Notable changes in pH occurred at the southern region of the bay near inflow sources.



Temperature

Over the course of the project water temperature within Farmington Bay was between 6.2 and 29.2 degrees Celsius. During April the shallower sites located in the southern region of the bay warmed more quickly than the somewhat deeper sites in the northern region of the bay. Similarly these shallow sites cooled off more quickly during September through November. The average water temperature peaked in July with an average temperature of 27.5 C. Water temperature was recorded only during transect sampling programs and diel temperatures were not recorded. The bay had warmed to 23.0 C by May 13th, but a prolonged storm coupled with multiple days of wind lowered the temperature in the bay by 5.3 C to an average temperature of 17.8 C on May 30th. The bay warmed again and reached 25.3 C by June 10th.

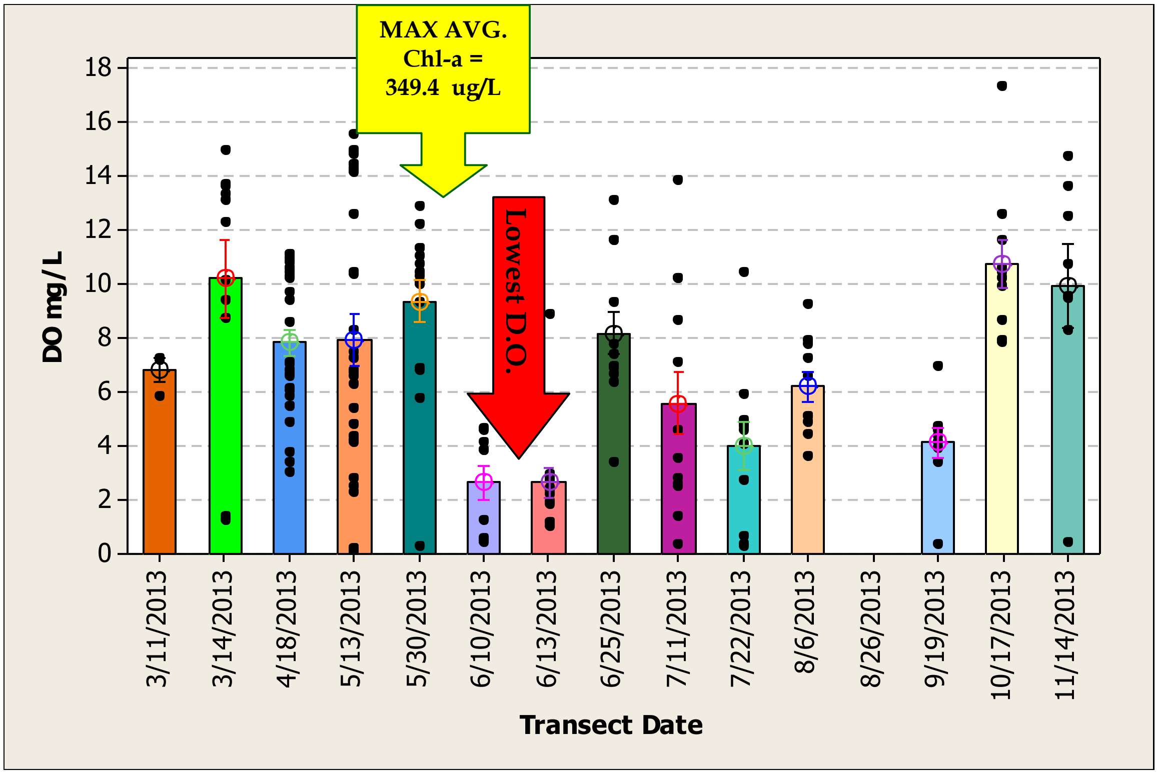
Figure 6. Within-sample location water temperature taken at 25 cm depth below the surface. Water temperature exhibited the typical pattern of warming and cooling for a shallow body of water. The maximum temperature for 2013 was cooler than previous summers in which the maximum temperature can exceed 30 degrees Celsius.



Dissolved Oxygen

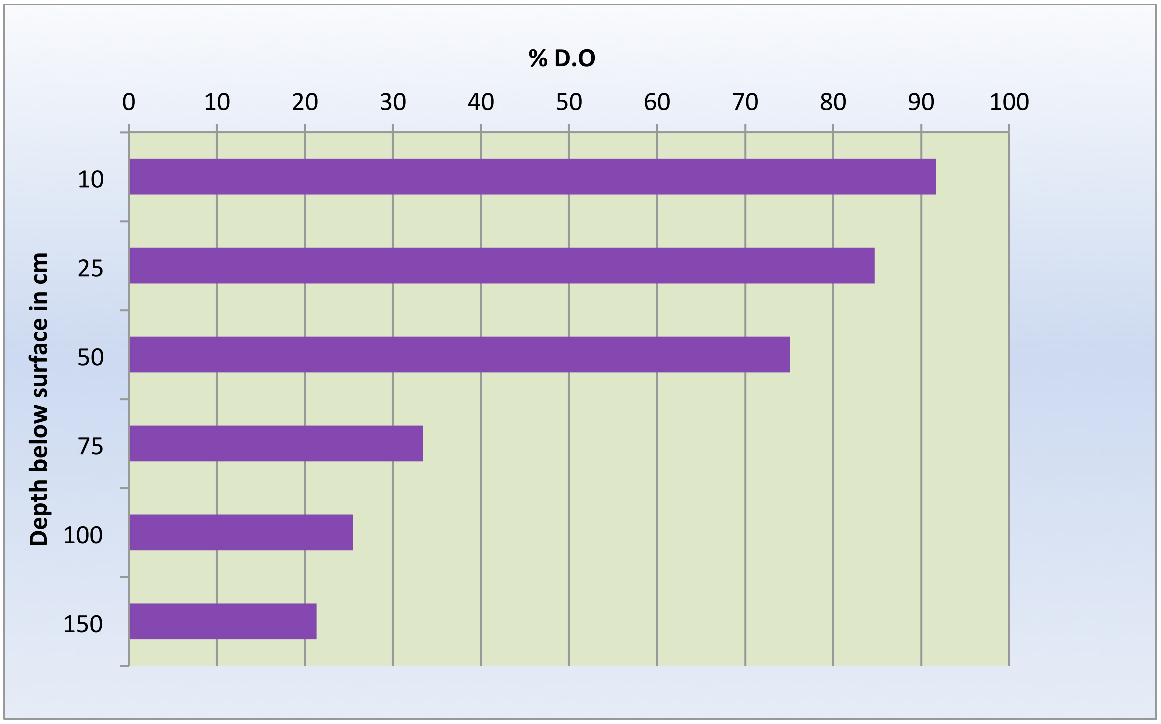
Dissolved oxygen levels in Farmington Bay did not show a distinct temporal and spatial pattern of variation as had been observed for other abiotic factors. Dissolved oxygen levels in the water column during the sampling program were generally adequate to support most oxygen dependent zooplankton (e.g., >2.0 mg/L). However, there was one time period of oxygen depletion that occurred during the June 10-13 sampling programs. Average DO during this week was just 2.6 mg/L. This time frame followed the initial peak and subsequent decline in *Nodularia* abundance. This decline in *Nodularia* is characteristically associated with sedimentation and elevated bacterial decomposition of algal cells, which increases oxygen demand and can result in rapid depletion of DO throughout the water column. Dissolved oxygen levels in the water column increased thereafter resulting in average dissolved oxygen levels across the bay that were between 2.6 and 10.7 mg/L. Peak levels were either in the early spring, at a time of low zooplankton biomass, or in November after grazing pressure from zooplankton had subsided.

Figure 7. Dissolved oxygen measurements by sample program date for Farmington Bay. A distinct decrease in dissolved oxygen occurred in early June and occurred shortly after the initial peak and collapse of cyanobacteria.



Dissolved oxygen exhibited vertical stratification at sites that were greater than one meter in depth. For example, on March 13, 2013 the DO at 25 cm to 50 cm depth were all greater than 10 mg/L. At 75 cm depth this declined to 6.9 mg/L (i.e., 26% saturation) and at depths of 1 meter or more the dissolved oxygen declined to between 0.09 to 2.5 mg/L (i.e., ≤20 % saturation). Diel changes in DO were undoubtedly taking place, and may have exerted an influence on the observed pattern, yet such daily fluctuations were not documented. Observations during the study did not indicate lethal depletion of DO, with the exception of the pronounced reduction in DO values during early June. Instrument failure prevented the measurement of DO for the August 26th sampling program.

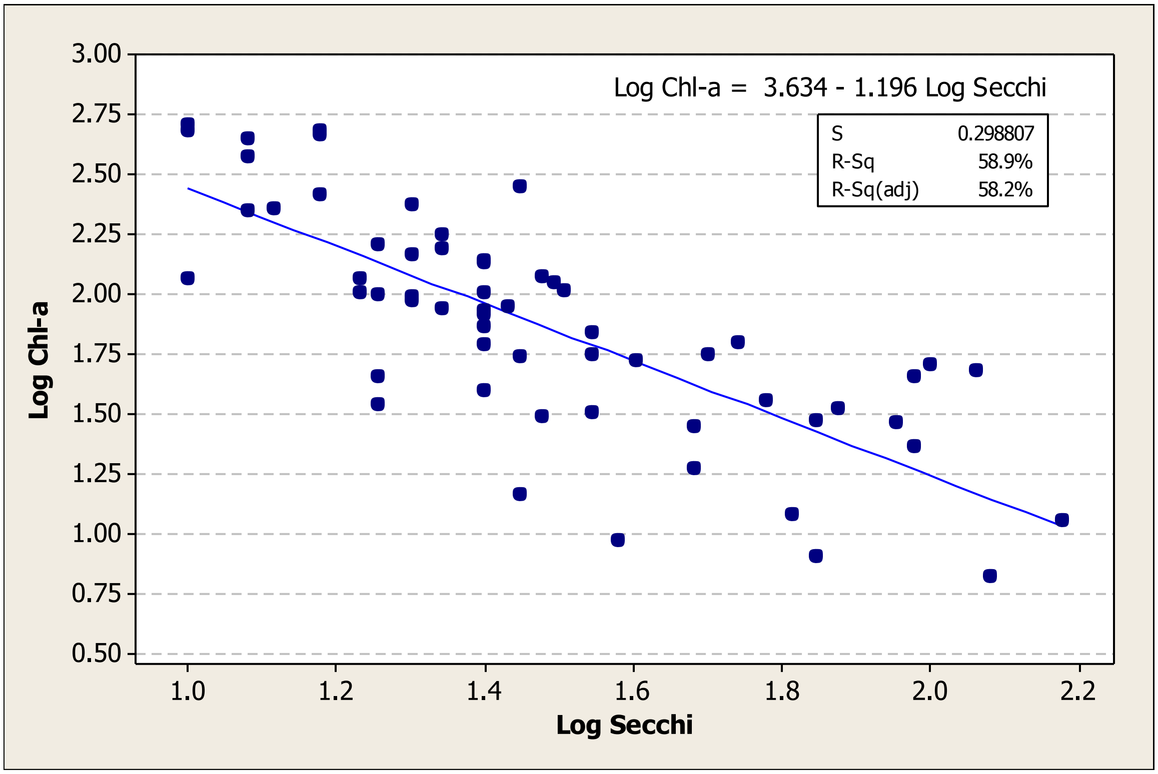
Figure 8. Vertical stratification of dissolved oxygen observed on May 13, 2014 at site #1. This location was one of the relatively deeper regions of the bay and was proximal to the Antelope Island causeway and breach. Stratification is likely the result of hypersaline water of Gilbert Bay forming a lens of denser water beneath the Farmington Bay water. This stratification may result in oxygen depleting reactions with hydrogen sulfide found in sediments in this region of the bay.



Chlorophyll-a and Secchi Depth

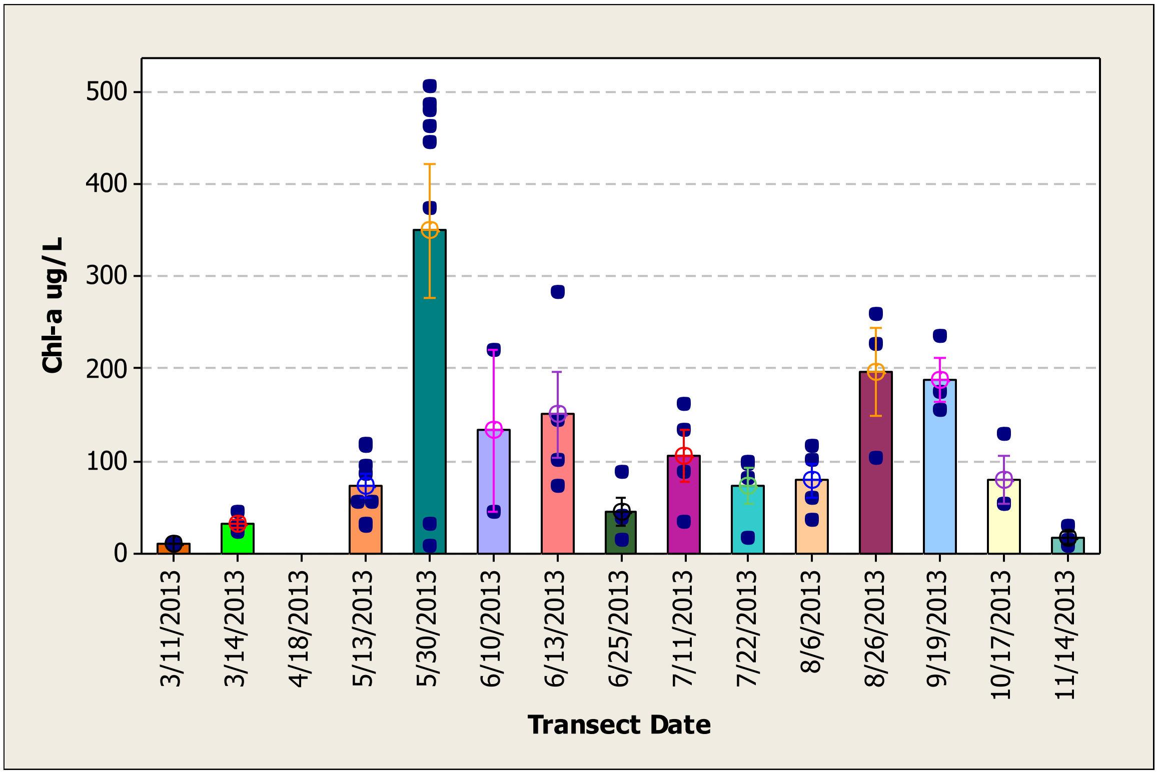
Transparency in the water column as measured by secchi disk showed consistently low light penetration into the water column. Average secchi depths measurements were between 20 and 43 cm. The maximum light penetration into the water column in Farmington Bay during the study was 150 cm at site #2 on March 11, 2013 shortly after the ice had cleared from the northern region of the bay. Sites 5 and 6 (mid-bay) had the lowest transparency measurements with an average depth of just 20 cm and 21 cm respectively. Secchi depth and chlorophyll-a levels exhibited a linked relationship (Fig 8.0; R^2 = 58.9%) suggesting that diminished light penetration is attributable to chlorophyll producing algal cells rather than other sources of turbidity such as inorganic and organic particulate matter.

Figure 9. Chlorophyll-a concentration and secchi depth exhibit an inverse relationship; with increasing transparency chlorophyll-a values decrease in a log-linear manner.



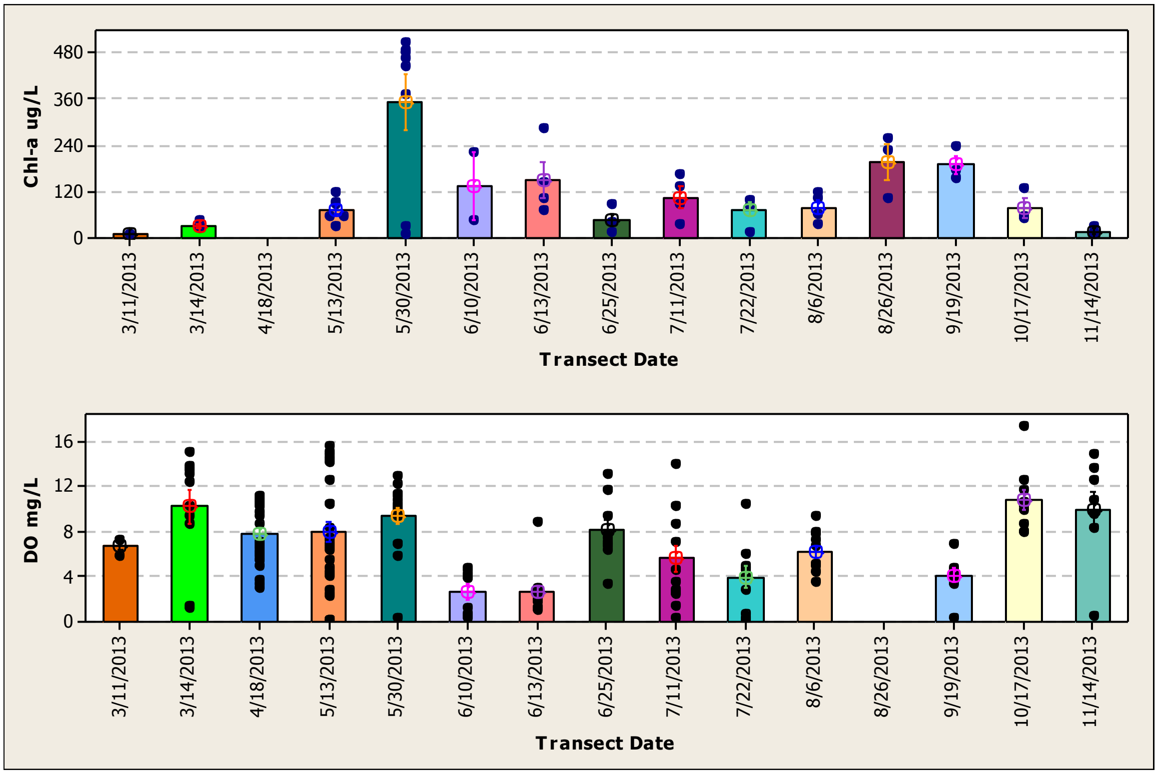
Chlorophyll-a concentrations in Farmington Bay were consistently high relative to values typically encountered in Gilbert Bay (peak values in Gilbert Bay are often ≤40 ug/L). Chlorophyll-a values for Farmington Bay exhibited the lowest levels both at the beginning and the end of the research program (Figure 10). On March 11, shortly after the melting of surface ice, the average concentration was only 9.01 ug/L. Coinciding with algal blooms in the bay, chlorophyll-a levels increased in a pronounced manner and by May 30th it reached the hypereutrophic level of 349.4 ug/L average concentration. The site-specific peak level measured on this date was 506.0 ug/L. Algal production was taking place at an exponential growth rate during this time period and the primary algal group responsible for the Chl-a increase was the cyanobacteria. The lowest dissolved oxygen levels recorded throughout the summer followed this maximum production of chlorophyll-a. The decline in dissolved oxygen occurred two-weeks later during the subsequent sampling programs on June 10-13th, thus exhibiting a classic pattern of eutrophication of a water body: exponential algal growth followed by a rapid collapse of the population (*Nodularia* cells per liter declined by 72.5% between May 30th and June 13th) coupled with depletion of oxygen by bacterial degradation processes. It is notable that DO concentrations did recover from the depletion event quickly by July 11th and between July and October levels returned to between 4.0 mg/L and 10.7 mg/L.

Figure 10. Chlorophyll-a concentrations for surface water samples were well above levels typically seen in Gilbert Bay throughout the summer. Extremely high levels of chlorophyll-a occurred in late May indicating hypereutrophic conditions. This peak in chlorophyll-a levels preceded a transient depletion of dissolved oxygen in the water column.



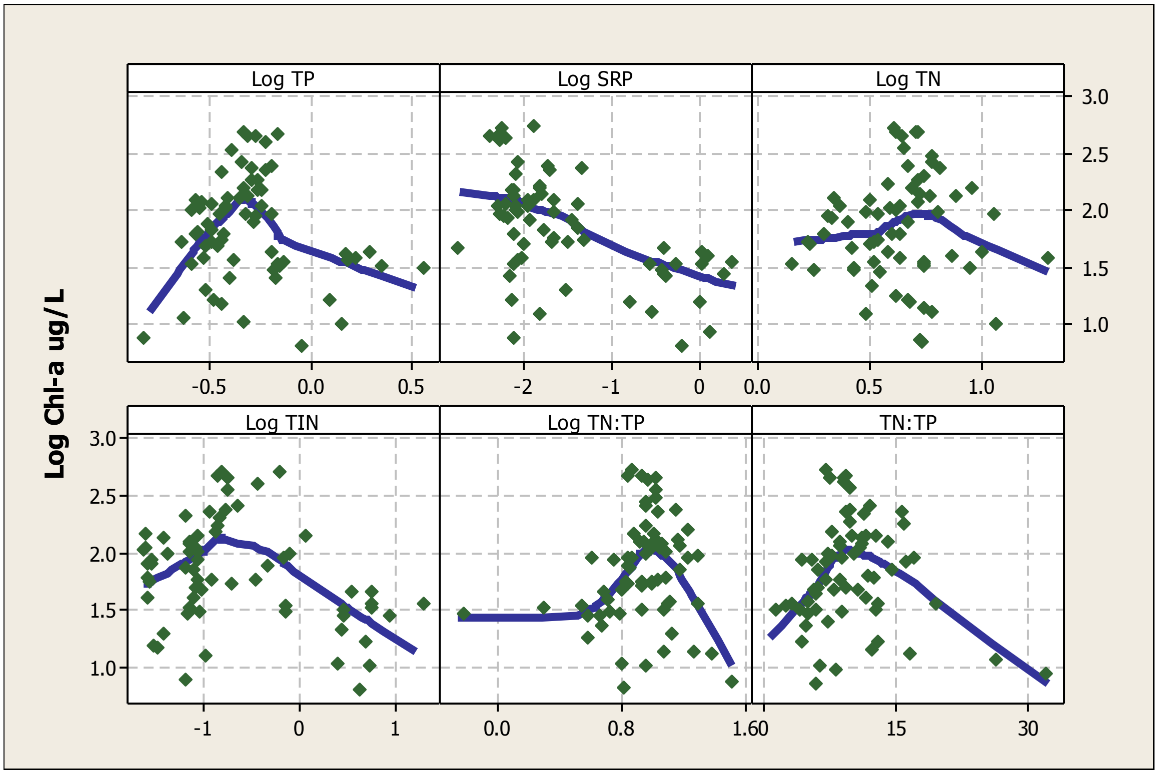
The combined results of chlorophyll-a and dissolved oxygen allows for a further comparison of the interrelationship of these two measures of water quality and biological productivity. Figure 11 shows these two assessments compared in a temporal sequence. A regression of these two parameters does not show a significant relationship, however the impact of phytoplankton biomass on dissolved oxygen is a delayed effect resulting from the demise of excess algal biomass and the subsequent consumption of available oxygen via bacteria activity during decomposition.

Figure 11. Combined results for dissolved oxygen and chlorophyll-a. Values are shown on a temporal scale based on the timing of sample programs.



Chlorophyll-a concentration is a useful surrogate measure of algal biomass and therefore should reflect phytoplankton responses to nutrient availability, uptake and utilization coupled with other factors, such as sunlight, competition, grazing pressure and other factors that regulate algal growth rates. Chlorophyll-a levels were evaluated in terms of their relationship to soluble phosphorous and nitrogen. Comparisons were made on log-transformed data in order to enhance recognition of relationships, if any were present. There were no conclusive correlations between Chl-a levels and the measured nutrient levels. However there is a peak in Chl-a production corresponding to a TN:TP ratio of 9.6:1 (TN:TP) Peak algal biomass production at low TN:TP ratios are recognized as indicators of ecosystem responses to nitrogen limitation and adequate phosphorous levels in which nitrogen fixing bacteria are favored over other algal groups. Such ecosystem responses are characteristic of eutrophic and hypereutrophic systems. The Chl-a levels were positively correlated with total numbers of *Nodularia* cells per liter (R^2 = 47.9%). The relationship between Chl-a and other algal groups was not as evident.

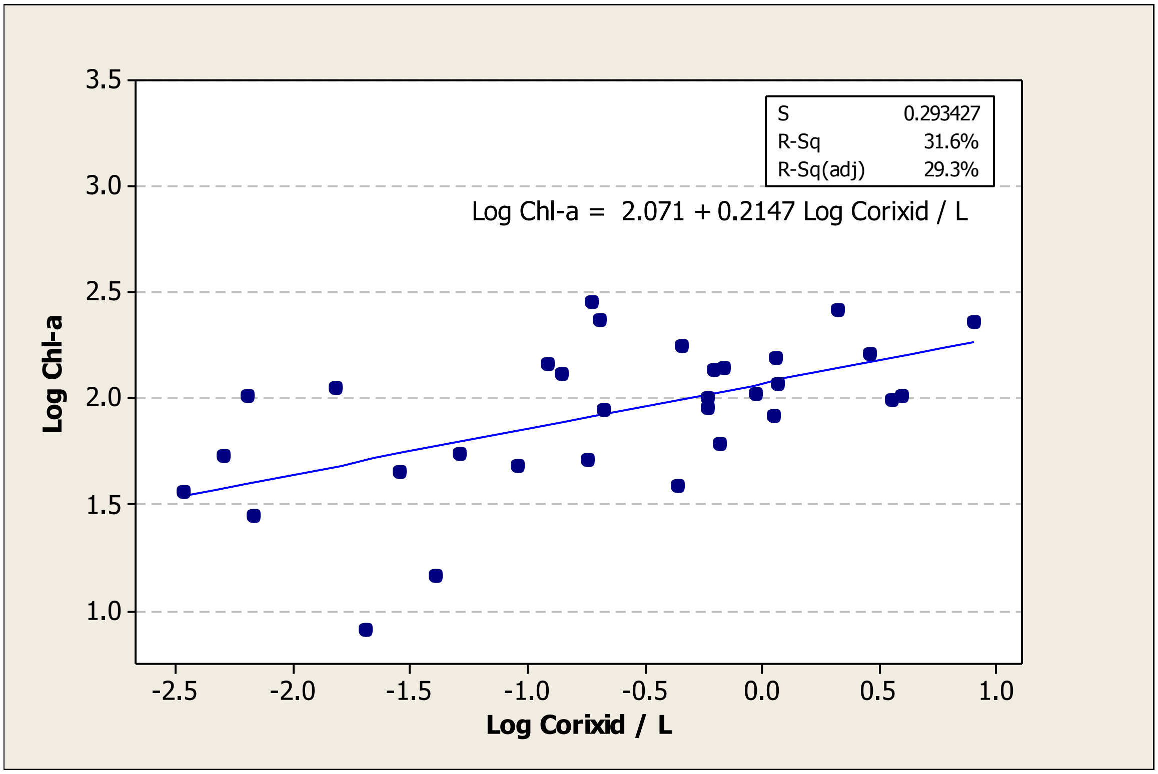
Figure 12. Chl-a levels are evaluated in terms of nutrient concentrations in collocated samples. No clear correlation is established, yet there is a general tendency for the algal population to achieve maximum chl-a production at a ratio of TN:TP near 9:1. The ecosystem response to TN:TP suggests eutrophic conditions prevail in the bay. Note that Chl-a is depicted to both the logarithmic function of TN:TP and also directly with TN:TP. All others are log:log comparisons.



Interestingly changes in chlorophyll-a levels also corresponded to increasing numbers of corixids, suggesting that corixid predation may be exerting a top-down influence on trophic structure and food web interactions (Figure 13). Although the data suggest a trophic influence on algal blooms resulting from *Trichocorixa* predation on algal grazing zooplankton, this correlation is likely an oversimplification of the complexity of inter- and intra-specific competition by algal species for niche dominance, nutrient availability, light/shading effects and shifts in grazing pressure. It is, however, logical that if corixids are preying upon the algal grazing species of zooplankton then there may be a diminution of grazing pressure on the algae. More detailed relationships and interactions are also likely to be occurring at the species level of algal groups and zooplankton, but are not readily apparent within the diverse mixture of biota collected during periodic sampling of the bay.

Figure 13. Relationship of Trichocorixa verticulatis abundance and chlorophyll-a concentration in the water column of Farmington Bay. Log transformed data were used to evaluate the possible trophic influence of corixid abundance, and therefore predation pressure, on algal grazing

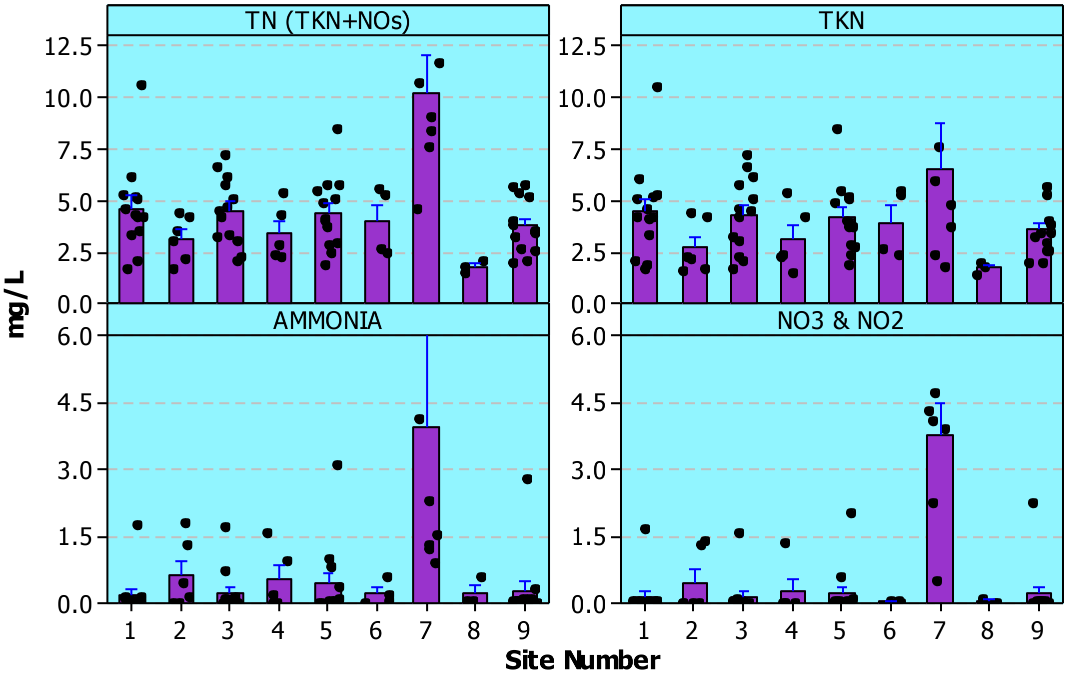
zooplankton. The results suggest an influence on algal productivity by increasing numbers of mature Trichocorixa.



Nutrients

Water samples collected along the transect gradients were analyzed for key nutrients; the list included total Kjeldahl nitrogen, nitrate, nitrite, ammonia, total phosphorous, and soluble reactive phosphorus. The results of these analyses provided an impression of the spatial heterogeneity that occurs in Farmington Bay with respect to nutrient loads. Nutrient inflow sources are primarily located along the eastern and southeastern margins of the bay where the discharge of treated wastewater from sewage treatment facilities in Davis and Salt Lake counties reach the bay. Sites 7 & 8 are located in close proximity to inflow sources containing post-treatment urban wastewater from Salt Lake City and multiple cities in Davis County. Site 7 (influenced by the Salt Lake City sewer canal) was consistently high relative to other sample site results for various forms of nitrogen. Site 8 (receiving water from discharges associated with Davis County waste water treatment facilities) typically showed the highest concentration of phosphorous. Results for nitrogenous compounds are shown in Figure 14. Bioavailable forms of nitrogen such as nitrate, nitrite and ammonia were found in substantial concentrations at site #7 near the Salt Lake County (Salt Lake City) wastewater discharge canal. These forms of nitrogen are generally assimilated rapidly by developing biota. Average levels of bioavailable forms of nitrogen were spatially similar across sites 1-6 when evaluated over the full time frame of the ice-free time period on Farmington Bay. The nitrate & nitrite concentration was between 0.01 and 6.57 mg/L with a collective average of 0.52 mg/L. Ammonia fell between 0.01 and 16.29 mg/L and exhibited an overall average of 0.65 mg/L. If we omit the high concentration associated with site #7 the upper limit for nitrate & nitrite is 2.26 mg/L and for ammonia it is 3.01 mg/L. The organic fraction of nitrogen expressed as total Kjeldahl nitrogen (TKN) fell between 1.35 mg/L and 19.33 mg/L (again at site #7). Without inclusion of site #7 the upper limit was 10.55 mg/L at site #1. The TKN average was 4.06 mg/L. Total nitrogen had a lower limit of 1.44 mg/L and an upper value of 19.82 mg/L, and excluding site #7 the highest value was 10.57 mg/L. The bay-wide average for the entire ice-free period for all sites was 4.58 mg/L. This value may be an underestimate of the nitrogen load in the bay because evaporative loss of volume precluded access to sites 7 & 8 from September to the end of the study, thereby rendering it impossible to collect samples at the location that had previously demonstrated the highest values.

Figure 14. Nitrogen concentrations in Farmington Bay shown according to sample location. Pronounced spatial heterogeneity existed at the southern region of the bay where treated wastewater sources exert their influence on receiving waters of the bay. In particular, site #7 is located proximal to the Salt Lake City wastewater canal and as a result this particular sample site exhibited elevated levels of multiple chemical forms of nitrogen. TKN and TN share the same scale whereas the scale for ammonia and nitrate & nitrite is half the TKN scale.



The spatial heterogeneity of nitrogen levels in Farmington Bay water samples were observed during each sampling program and the pattern was relatively consistent over time; there were substantially higher concentrations in the southern portion of the bay of organic forms of nitrogen and rapid depletion of inorganic forms down to the limits of detection as sampling progressed northward. Figures 15a, 15b and 15c show the pattern of various forms of nitrogen over spatial and temporal scales. In all cases the highest values occurred at site 7. At this location TN, NO_3&NO_2, and ammonia had pronounced concentrations during each time period. The decline at this location after September is attributable to the lack of access to these sites late in the summer as a result of declining water elevation. Of particular relevance is the rapid diminution of NO_3&NO_2 that occurs beyond site #7. The results suggest that there is rapid uptake of these readily absorbed forms of nitrogen and that they are incorporated into biological molecules. Total nitrogen shows depletion along the south to north transect as well, but the organic forms of nitrogen (i.e., TKN) remains at moderate levels in the water samples (generally above 2.5 mg/L).

Figures 15a, 15b and 15c. The temporal and spatial pattern of nitrogen concentration in Farmington Bay is shown for Total Nitrogen (15a), Nitrate+Nitrite (15b) and ammonia

(15c). In all cases the concentration exhibited high spatial and temporal variability with the highest concentrations occurring in the southern regions of Farmington Bay and particularly in the site #7 results. Ammonia and the nitrate + nitrite fractions diminished rapidly at sites located distant from the SLC sewer canal. Access to sites 6, 7 & 8 became problematic as summer progressed and the elevation of Farmington Bay declined. Notice that the Z-axis has differing scales for each of the forms of nitrogen. Site #9 is on the Gilbert Bay side of the Antelope Island causeway.

Figure 15a. Spatial and temporal pattern of total nitrogen.

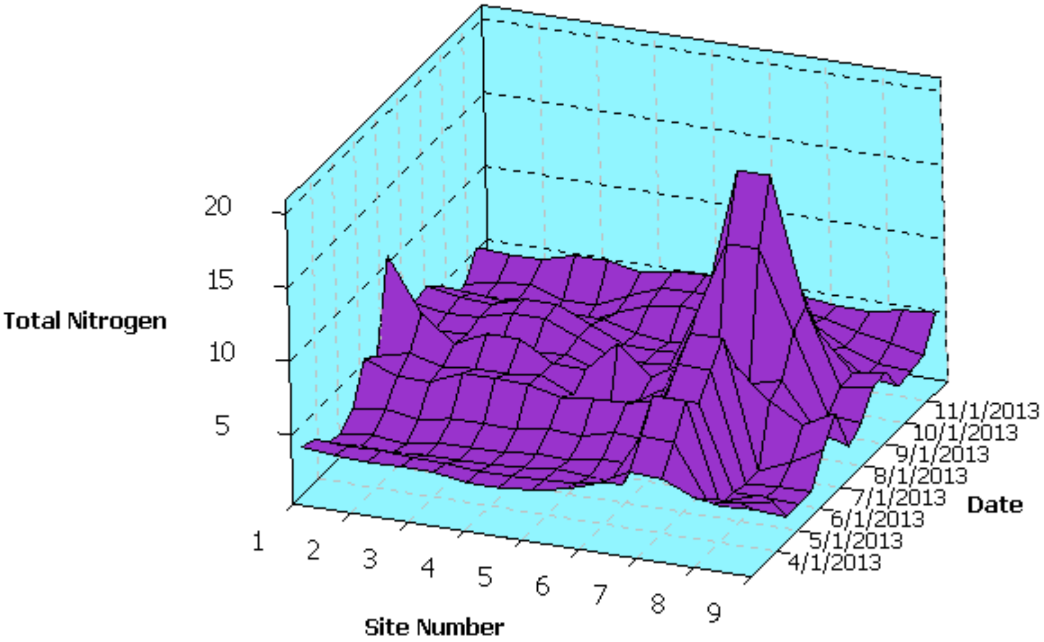


Figure 15b. Spatial and temporal pattern of nitrate & nitrite.

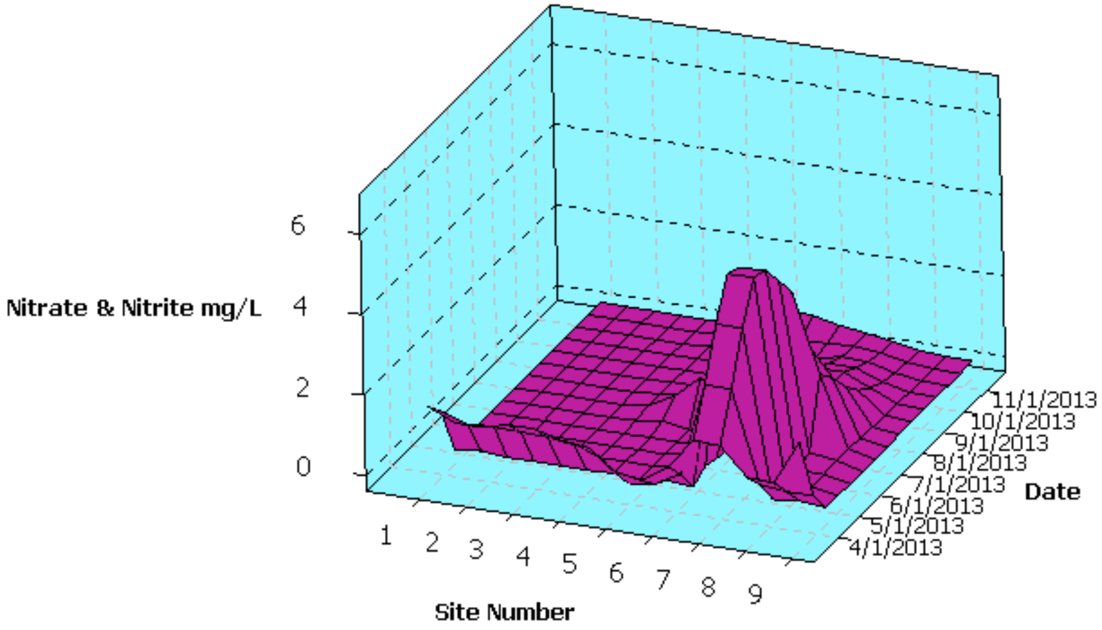
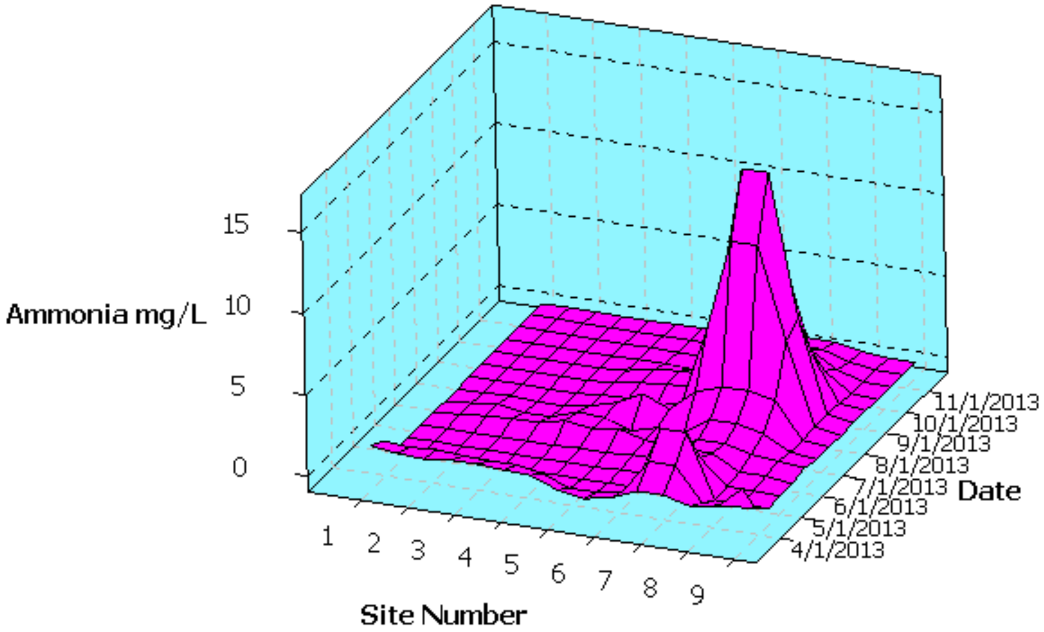
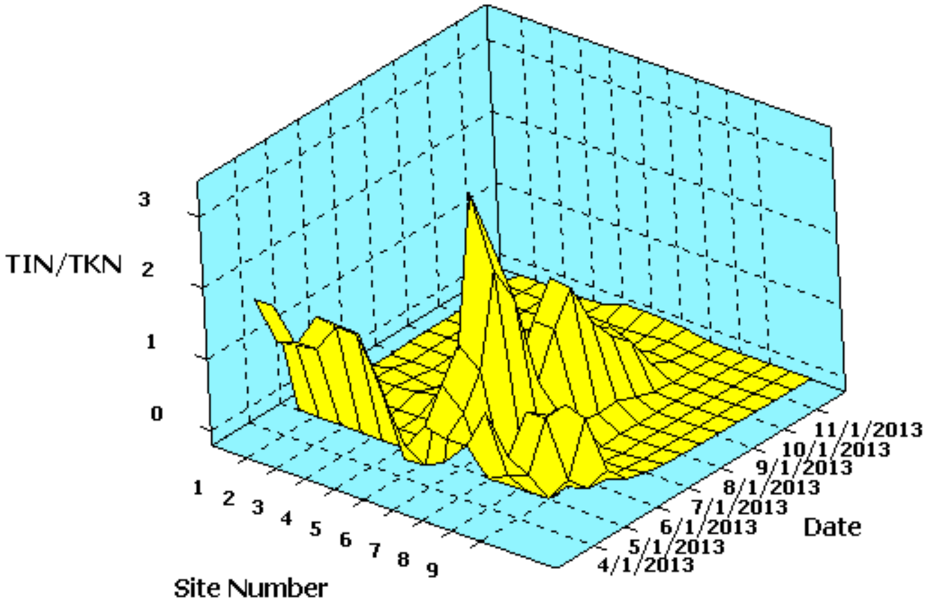


Figure 15c. Spatial and temporal pattern of ammonia.



The ratio of inorganic nitrogen to TKN similarly exhibited the highest percentage of inorganic forms near site 7 and the discharge area for the sewer canal. There was also a higher percentage of inorganic nitrogen available at the end of ice melt and in the early spring. Once the various phytoplankton groups began to grow in earnest in mid-April the presence of inorganic forms of nitrogen in the northern region of the bay remained low indicating rapid uptake and depletion of bioavailable inorganic forms of nitrogen (Figure 16).

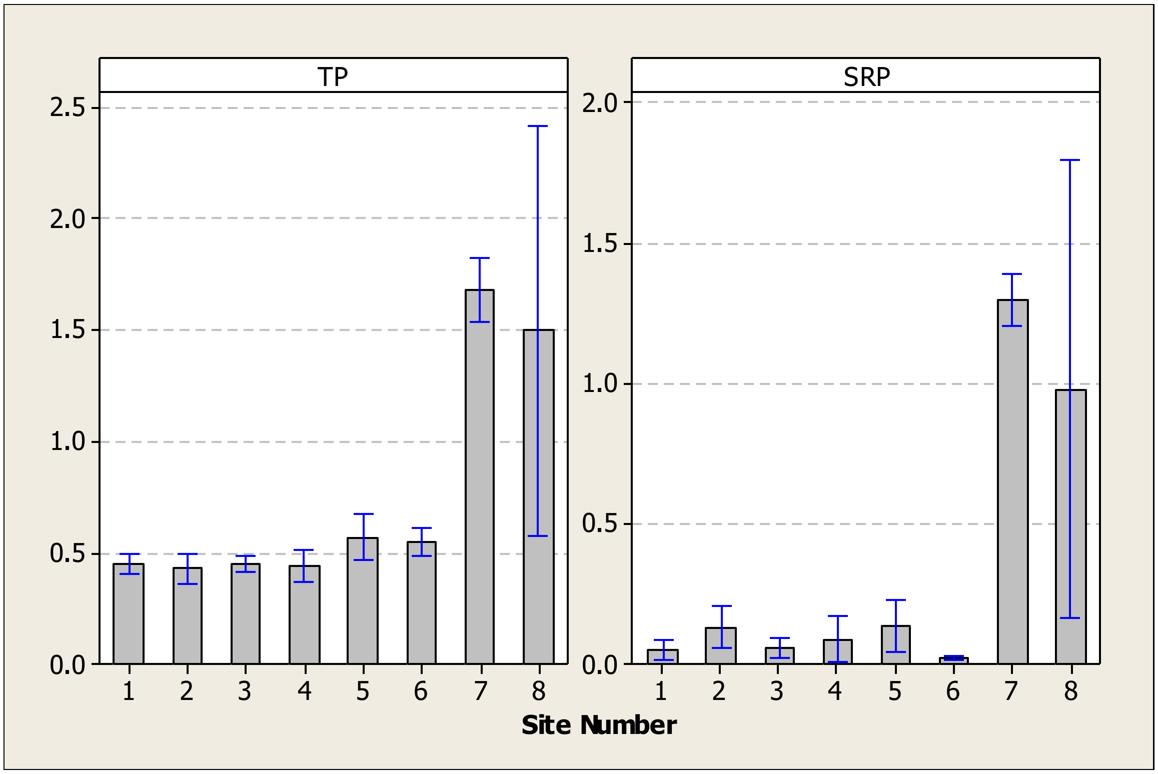
Figure 16. The percentage of inorganic nitrogen to TKN was explored over the course of the study period and spatially across each sample location. Analogous to the results already detailed for bioavailable forms of nitrogen the percentage of inorganic nitrogen drops off precipitously along a south-north transect. The presence of inorganic forms of nitrogen in the northern portion of the bay were found at similar levels to the southern bay in early spring and shortly after the melting of winter ice.



Phosphorous

In an analogous manner to the pattern of nitrogen concentrations in Farmington Bay, phosphorus exhibited spatial heterogeneity across all sample locations (Figure 17). Of particular interest are sites 7 & 8 which, at least when they were accessible, had the highest total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations relative to other locations in the bay. Total phosphorus concentrations across the bay had an average of 0.61 mg/L with a range of 0.16 mg/L to 3.33 mg/L. SRP concentrations were much lower, as anticipated, as this form of phosphorous is readily assimilated by biota and diminishes from source water rather quickly, and showed an average bay-wide value of 0.23 mg/L. The low end of SRP was at the limit of detection and the upper limit was 2.611 mg/L. Excluding sites 7 and 8 from the data gives a maximum value for the open water of Farmington Bay of 1.80 mg/L for TP and 1.147 mg/L for SRP.

Figure 17. Average phosphorus concentrations in Farmington Bay listed by sample location for the entire study time period are shown. Consistently the source of P for Farmington Bay was along the southeastern margins of the bay and in association with sites 7 & 8.



Phosphorous assessments in the southern region of the bay indicate that biological uptake and utilization of available P in the Northwest Oil Drain and along other discharge sources is proceeding at a rate insufficient to convert inorganic P to organic forms prior to discharge into the bay. Some of the measurements of SRP near site #7 approach those in the Northwest Oil Drain prior to reaching FBay. For example, upper-end SRP measurements for site #7 were: 1.25 mg/L to 1.65 mg/L (Figure 18b). The concentrations recorded in our study, and in particular near sites 7 and 8 should be compared with canal and other source concentrations in order to link total load estimates for the bay with observed water column values.

Figures 18a and 18b. The temporal and spatial pattern for total phosphorous (TP) (18a) and soluble reactive phosphorous (SRP) (18b). The concentration exhibited high spatial and temporal variability with the highest concentrations occurring in the southern regions of Farmington Bay and particularly in the site #7 and #8 results. SRP fractions diminished rapidly at sites located distant from these sites. As was the case for nitrogen assessments, the limitations of access to sites 7&8 became problematic as summer progressed. Site #9 is included in the graphs even though it is located on the Gilbert Bay side of the Antelope Island causeway.

Figure 18a. Spatial and temporal pattern of total phosphorous.

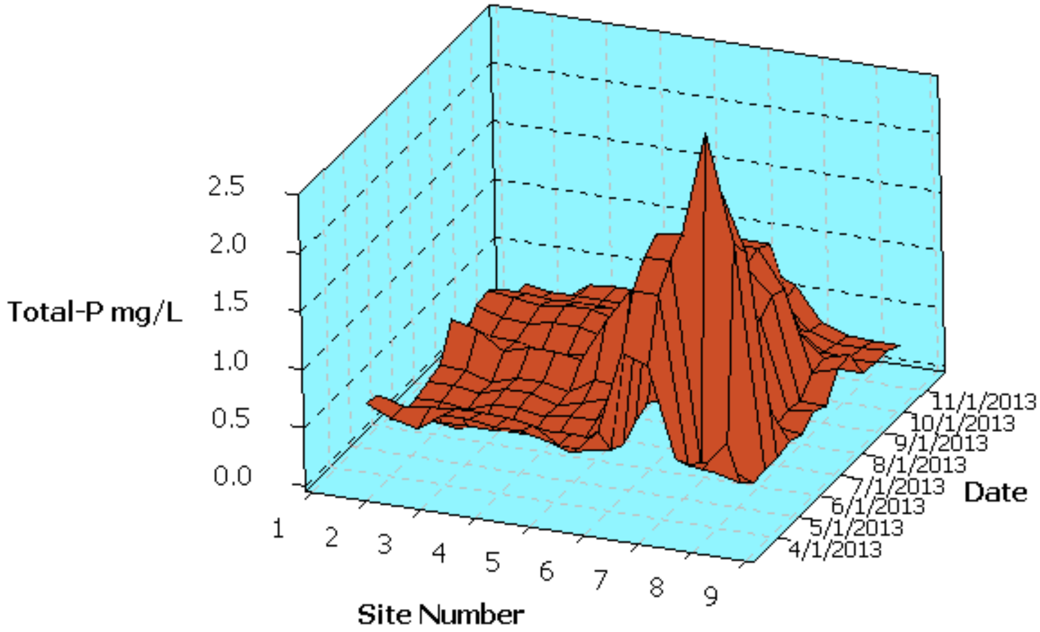
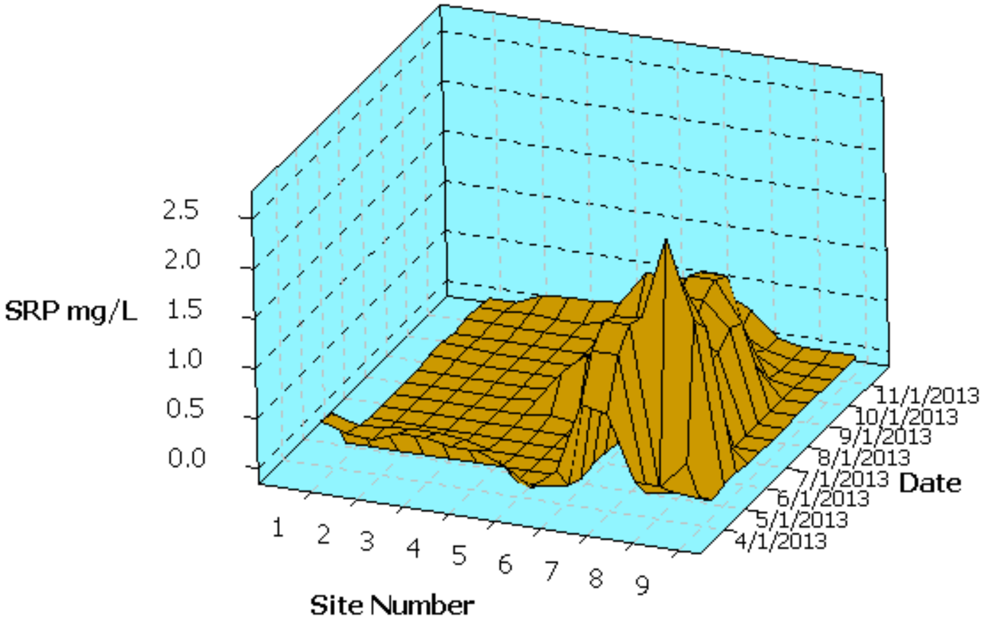
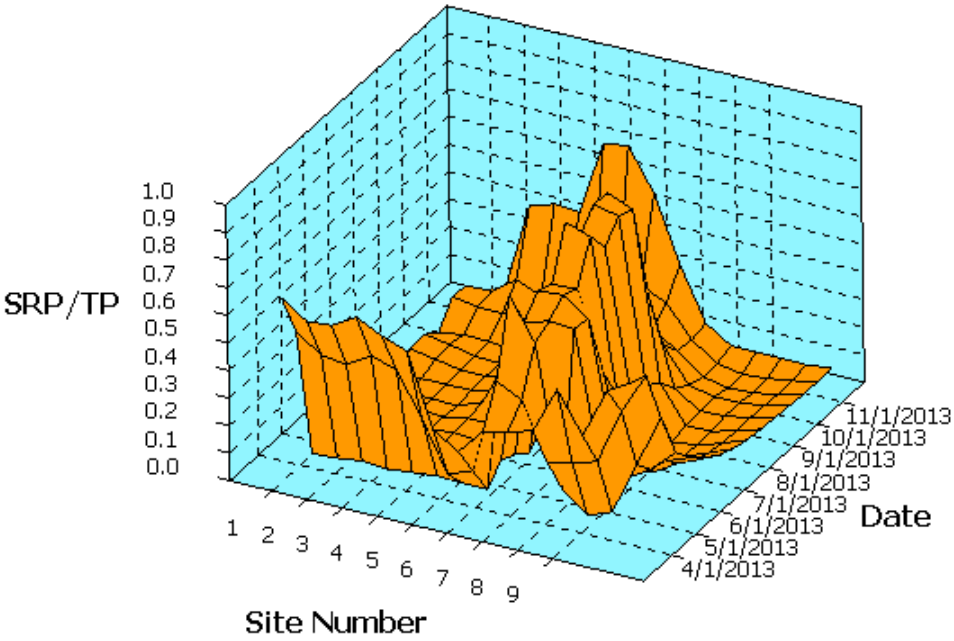


Figure 18b. Spatial and temporal pattern of soluble reactive phosphorous.



The soluble fraction of phosphorous relative to total phosphorous again followed a south to north gradient. The lowest percentage of SRP/TP at site 7 was 65.2%, while all other sites had periodic low percentages in the single digits: 1%-2% SRP/TP (Figure 19). The average percentage of SRP/TP for site 7 was 65.2%-85.8% while the range for the rest of the sites was: 1.0% to 73.3%. It is noteworthy that in March, when ice in southern half of the bay prevented access to sites 7 and 8, the average percentage of SRP/TP was 57.4%.

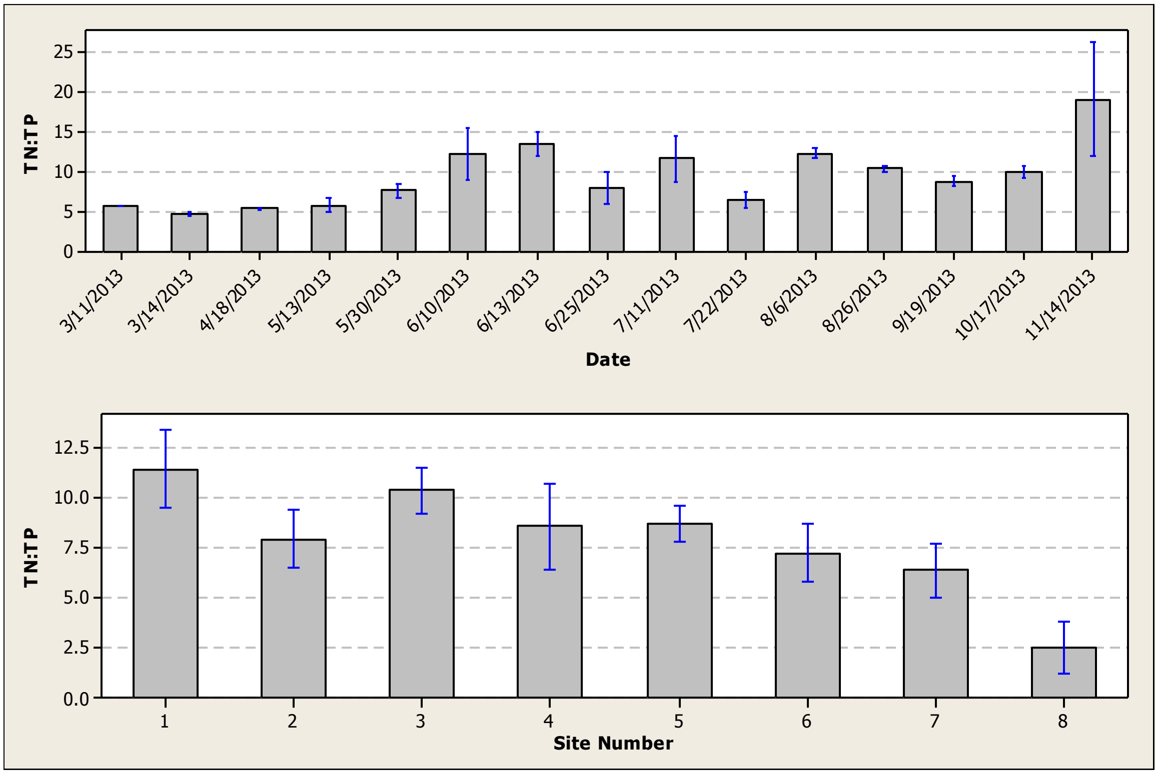
Figure 19. The SRP:TP ratio was examined over the same spatial and temporal groups as were applied to each nutrient type. SRP constituted the highest percentage of total P in the southern region of the bay, and as expected near sites 7 & 8. Early in the spring soluble P was identified in the water column throughout the bay. As algal groups began to bloom in mid-April the levels of soluble P in the northern regions of the bay declined rapidly and remained depleted until November. Site #9 also exhibited elevated percentage of SRP in the early spring.



TN:TP ratios for Farmington Bay had an average of 9.254. The low end was 3.60 and the upper limit for this ratio was 32.18 (Figure 20). This high value appeared to be anomalous and if discarded the highest ratio is 17.49. There was a temporal pattern to the TN:TP ratio in which the ratio from March until early May suggested nitrogen limitation. The ratio began to increase in mid-May with a peak average among sites of 13.16 occurring on June 13th. The increase and the peak in the ratio coincides reasonably well with the abundance of nitrogen fixing cyanobacteria in the bay; nodularin cell counts increased dramatically in

May and reached a peak abundance on May 30th. The average TN:TP ratio for the entire bay, over the remainder of the summer months, remained between 9.5 and 12.0, with two exceptions.

Figure 20. TN:TP ratios examined on a spatial and temporal basis across Farmington Bay.



Biotic Characteristics

Phytoplankton, Cyanobacteria and Cyanotoxins

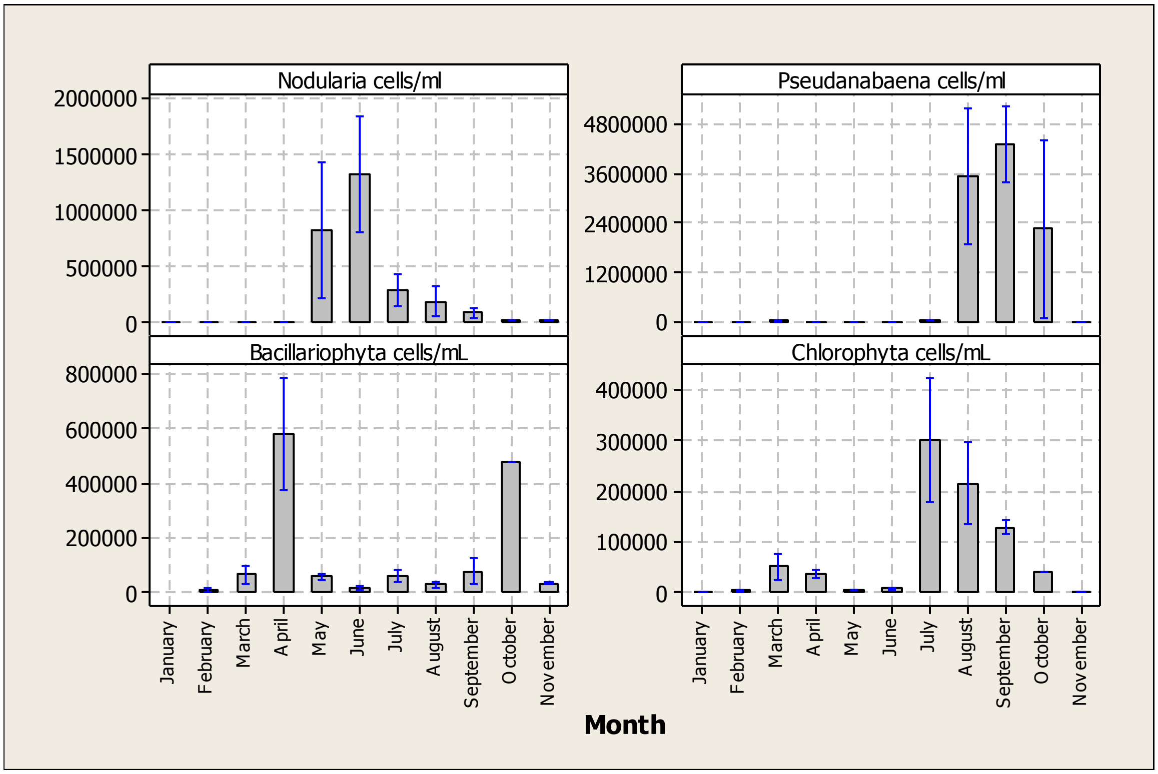
Water samples for phytoplankton, cyanobacteria and cyanotoxins were routinely collected throughout the project from 9 transect sites (or as long as water depth allowed access). In addition, multiple extra samples were collected from site #1 for cyanobacteria and cyanotoxin analyses. The samples were collected from site #1 due to its ease of access from the Antelope Island Causeway and because this gave an indication of the amount of cyanobacteria and cyanotoxin transported to Gilbert Bay. Over the course of this initial year of field research the phytoplankton community included 10 major taxonomic groups (9 identified and 1 miscellaneous), 81genera, and 52 species (Table 1). The spatial and temporal organization of phytoplankton in Farmington Bay was in continuous flux; with shifting patterns of abundance attributable to niche dominance strategies, interspecific competitive displacements, grazing depletion, exponential growth and dramatic collapse. We also observed the appearance of an asymmetric relationship between *Nodularia* abundance and nodularin toxin production indicative of a critical density dependent threshold. Microalgal assemblages in the bay exhibited a most remarkable array of diversity and shifting dynamics. Trophic regime changes were observed throughout the observation period and unique site specific as well as bay-wide patterns of algal dominance and genera specific collapse were documented. To capture the full scope of the biological diversity and the complexity of the interactions between and within trophic levels it is necessary to scrutinize site specific changes and to then evaluate those local shifts in diversity and abundance with respect to the broader developing pattern that emerges when analyzing the bay as a single limnological entity.

Table 1. Major algal groups and genera, or further classification specifics, are listed for samples collected on Farmington Bay from March to November 2013.

Major Taxonomic Groups	**Genera or Further Classification**	**Genera or Further Classification (continued)**
Bacillariophyta	Actinastrum	Mallomonas
Chlorophyta	Amphora	Melosira
Chrysophyta	Anabaena	Merismopedia
Cryptophyta	Anabaenopsis	Micratinium
Cyanobacteria	Ankistrodesmus	Microflagellate
Euglenophyta	Ankyra	Monoraphidium
Haptophyta	Aphanocapsa	Navicula
Prasinophyta	Aphanothexe	Nephroselmis
Pyrrhophyta	Aulacoseira	Nitzschia
Miscellaneous other groups	Bitrichia	*Nodularia*
	Centric Diatoms	Oocystis
	Chetoceros	Oscillatoria/Phormidium
	Chlamydomonas	Pandorina
	Chlorogonium	Pediastrum
	Chlorophyte cell pair	Pennate diatom
	Chrysochromulina	Peridinium
	Chrysococcus	Phacus
	Chrysophyte colony	Phaedactylum
	Chrysophyte flagellate	Phormidium
	Closterium	Planktothrix
	Coelastrum	*Pseudanabaena*
	Cryptophyte	Pteromonas
	Cyanodictyon	Rhoicosphenia
	Cyanophyte unicellular	Romeria
	Cymbella/Encyonema	Scenedesmus
	Dactylococcopsis	Schroederia
	Diatom unspecified	Spiruliona
	Diatoma	Stephanodiscus
	Dictyosphaerium	Stigeoclonium
	Didymocystis	Suriella
	Dinoflagellate	Synedra
	Elakatothrix/Fusola	Tetraedron
	Entomoneis	Tetraselmis
	Euglena	Tetrasturm
	Euglenophyte	Tryblionella
	Golenkinia	Unknown colony forming
	Gomphonema	Urosolenia
	Kirchneriella	Vitreochlamys.
	Koliella	
	Koliella/Monoraphidium	
	Komvophoron	
	Lepocinclis	
	Lobocystis	

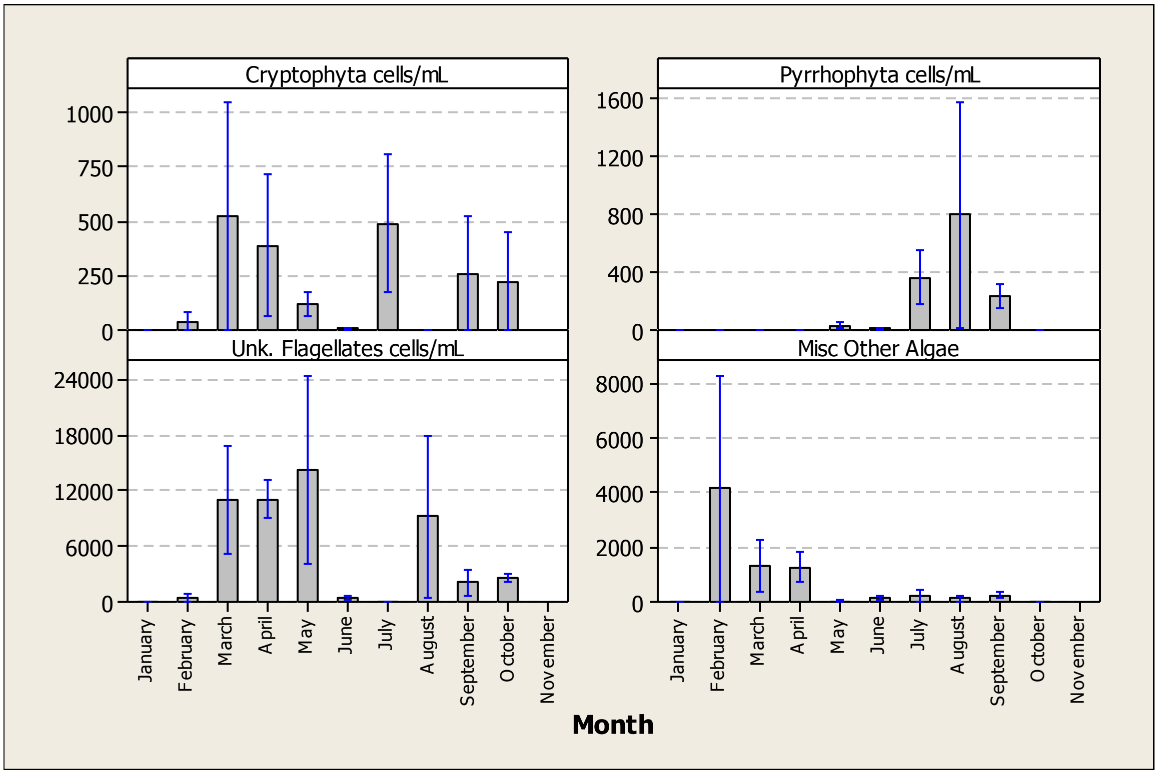
Our record of the particular pattern of algal dominance began following the melting of winter surface ice in March in which the phytoplankton population was initially dominated by a combination of diatoms and chlorophytes and a minor contribution from euglenophytes and cyanophytes (Figure 21). The relative abundance shifted dramatically in May as the cyanophytes emerged and rapidly proceeded to dominate the algal community across broad reaches of the bay. Cyanobacteria dominance developed more rapidly in late May and throughout June and July *Nodularia* was by far the most abundant algal genera across the bay. In August another cyanobacteria, *Pseudanabaena* emerged as the predominant genera, especially in the mid-northern regions of the bay. Coinciding with the decline in zooplankton grazers some of the springtime algal groups, such as diatoms and chlorophytes, returned in significant numbers in a site specific manner.

Figure 21: Major algal groups displayed patterns of dominance and collapse throughout the spring, summer and fall. Algal groups began with diatoms and chlorophytes which were later displaced as the dominant groups by the nitrogen fixing cyanobacteria Nodularia and Pseudanabaena. As water temperature declined, and the grazing pressure by zooplankton diminished, edible phytoplankton showed a resurgence.



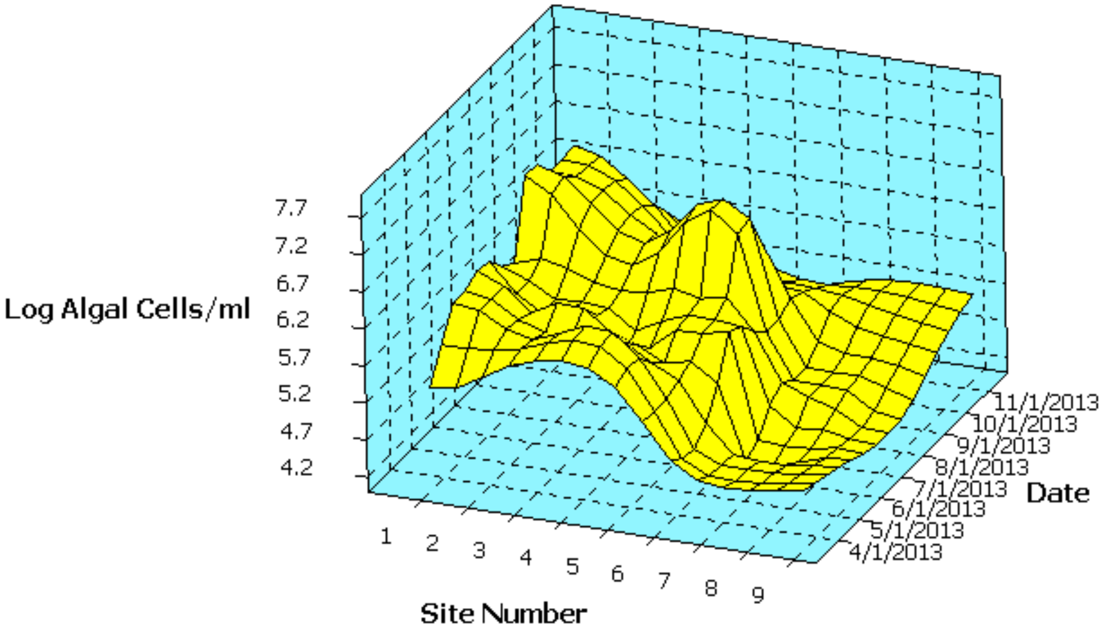
Minor contributions of cryptophytes, phyrrhophytes, flagellates and miscellaneous other algal species were observed during March, April, May and August. Notable among these other divisions was the contribution by flagellates to the total biomass during the early spring months (Figure 22).

Figure 22. The less abundant algal groups are shown according to monthly abundance. Notice that the Y-axis scales differ among the algal groups.



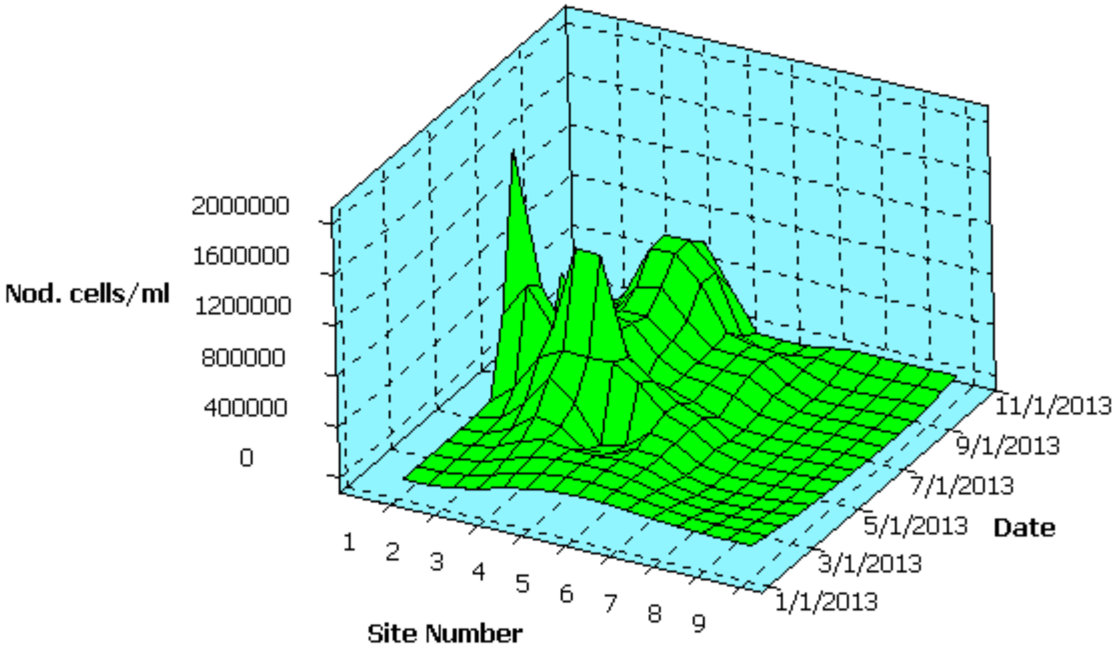
An examination of the collective number of algal cells and their distribution across Farmington Bay provides a generalized pattern of abundance. The pattern that emerges is one of substantial algal growth in the middle to northern regions of the bay with those sites in the southern area having substantially lower total algal biomass. Centrally located sites and northern sites exhibited peak abundance in late July and August. Cyanobacteria were clearly the dominant algal group in terms of abundance with *Nodularia* and *Pseudanabaena* numbers dwarfing the total counts for other algal groups. Although this generalized pattern of phytoplankton growth and abundance is of interest to understand the biological dynamics of Farmington Bay, especially in terms of the spatial relationships of phytoplankton growth and development, the genera or group specific responses reveal more relevant information about how the phytoplankton are exploiting critical niche resources such as nutrients and available light, or the manner in which selective grazing pressure may be constraining or liberating the proliferation of different algal groups.

Figure 23. The total growth response of phytoplankton across Farmington Bay from April to November. Some of the mid-bay sites, such as sites 3 and 5 exhibited tremendous growth and dominant total algal cell counts in comparison to other sites. The sites located proximal to key nutrient inflow sources were usually the lowest in total cell counts.



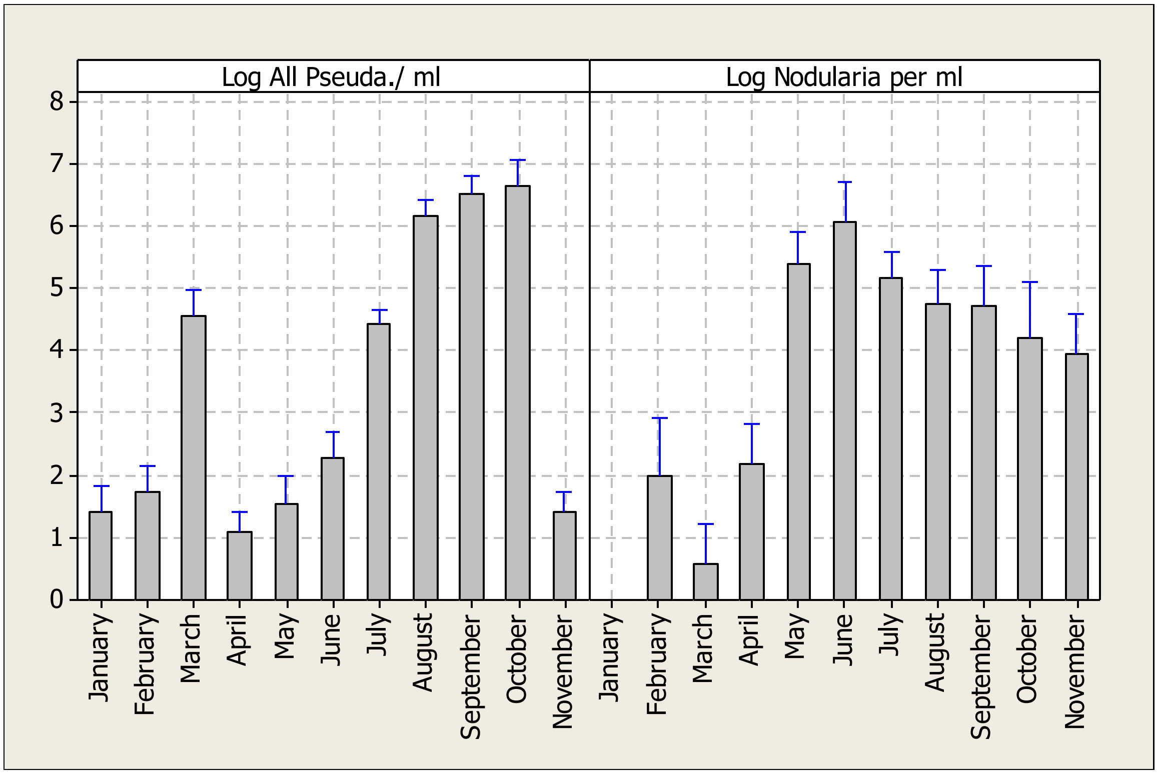
Of particular interest for the current study is the size and distribution of the cyanobacteria population in the bay. Cyanobacteria blooms have been at the forefront of concern for the ecological health of Farmington Bay. The potential effects of cyanobacteria and cyanotoxins on the biota of the bay and the surrounding environs have been the source of multiple scientific investigations and speculation and are a primary area of concern for the USEPA and the State of Utah Department of Water Quality. The overarching question is whether the cyanobacteria blooms adversely impact the beneficial uses of Farmington Bay. *Nodularia* has been the key cyanobacteria genera cited with respect to potential adverse effects on the biota of Farmington Bay. This focus on *Nodularia* is due to its well-established capacity to grow exponentially in the bay and to produce vast accumulations of dense floating algal mats. The presence of these *Nodularia* blooms in the bay are not uniformly or randomly distributed; instead there is somewhat of a south to north gradient in the algal mats with the highest abundance being located from approximately mid-bay to the northern extension near the Antelope Island causeway (Figure 24).

Figure 24. Robust accumulations of Nodularia occurred primarily in the mid- to northern regions of Farmington Bay. Although Nodularia was present throughout the study period its period of dominant growth began in earnest in May and continued into October and November. The spatial dominance of Nodularia appeared to be influenced by a critical distance from the southern areas of the bay suggesting that nutrient concentrations were suboptimal for Nodularia growth in closer proximity to the primary nutrient sources.



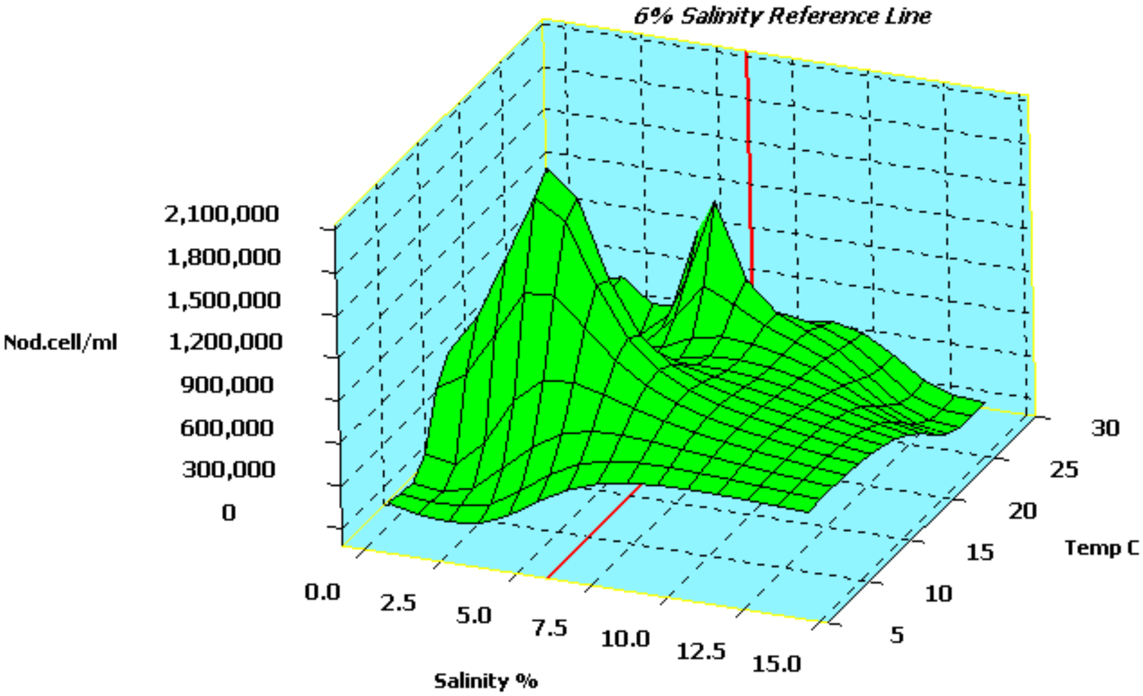
Cyanobacteria blooms documented during this current study were essentially in two phases: a *Nodularia* bloom and a *Pseudanabaena* bloom. The *Nodularia* bloom preceded the *Pseudanabaena* bloom; *Nodularia* growth occurred in earnest in late May and continued through October while the *Pseudanabaena* bloom began in late June, peaked in August, and continued into October (Figure 25). A single sample taken from site #1 in March showed a moderately high value for *Pseudanabaena* (37,128 cells/ml), while sample results immediately preceding and following this time period showed substantially lower values.

Figure 25. The dominant growth of cyanobacteria in Farmington Bay begins with Nodularia in May followed by robust growth of Pseudanabaena in July which continues to competitively displace Nodularia as the dominant algal group into October.



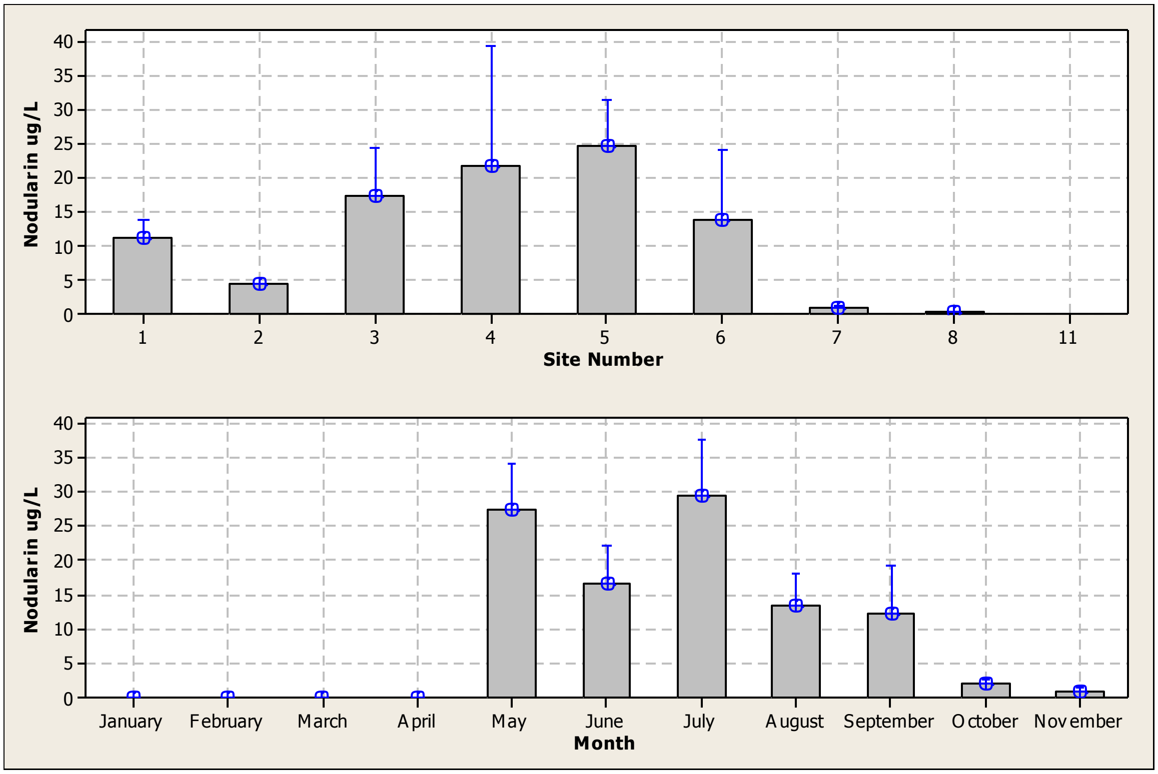
The causes and consequences of these cyanobacteria blooms are indeed challenging to define. Contributors to the causes of the algal bloom are abiotic factors such as temperature and salinity in which there are ranges that are tolerable or even favorable for cyanobacteria to enjoy exponential growth. In the current study there appeared to be a salinity limitation for *Nodularia*; at a salinity of 6% and higher the prevalence and competitive dominance of *Nodularia* diminished (Figure 26).

Figure 26. The response of Nodularia to different salinities and temperatures is depicted. Nodularia had robust growth in Farmington Bay below 6% salinity and over a range of temperatures from 15C to 30C. The growth appeared to be constrained by the higher salinity range while it flourished between 0% and 5% salinity.



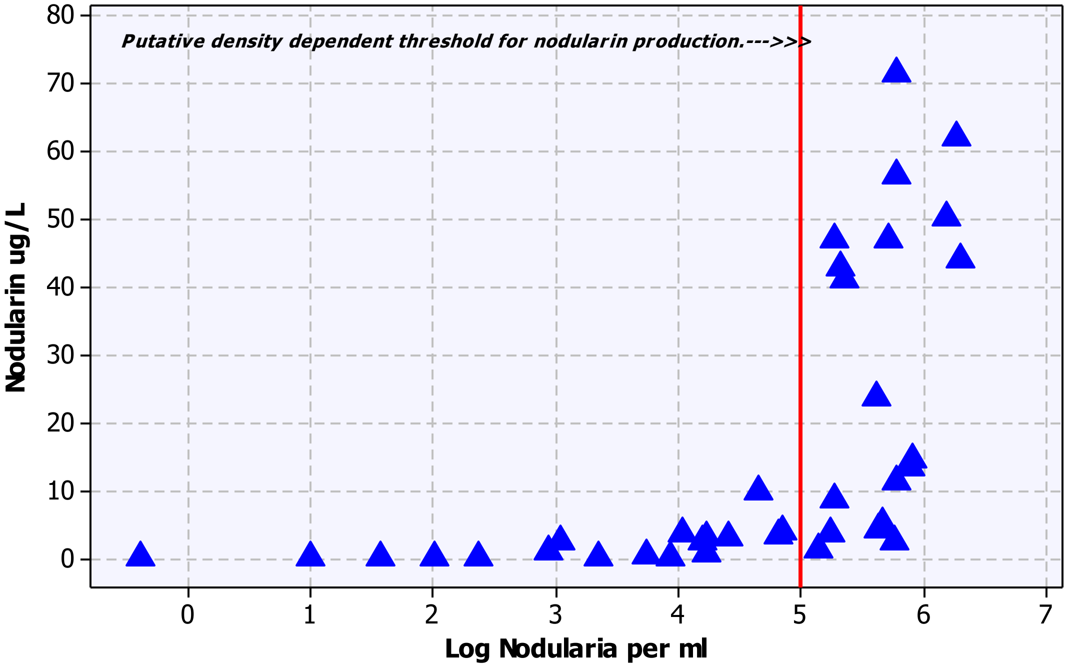
The cyanotoxin nodularin was identified in water samples from Farmington Bay. The concentration of nodularin had a maximum level of 88 ug/L with a mean value of 13.39 ug/L. The lowest concentration observed was at the limit of detection for the toxin (0.03 ug/L). The presence of the toxin in water samples was neither uniformly nor randomly distributed but followed a spatial pattern in which central site locations (i.e., sites 3-6) demonstrated higher nodularin values than sites located in the northern or southern regions of the bay (Figure 27).

Figure 27. The concentration of nodularin in Farmington Bay water samples is indicated by monthly average as well as the site specific average over the course of the study period. The overall average of 13.39 ug/L is below the conservative WHO recommended limit for water quality.



The spatial distribution of nodularin roughly tracked the spatial pattern for large accumulations of *Nodularia*. However, there appeared to be a density-dependent relationship between nodularin and *Nodularia* in which nodularin concentrations greatly increased when the number of *Nodularia* cells reached or exceeded 10,000 cells per ml (Figure 28). This non-linear, and possibly threshold dependent, relationship of the toxin to the abundance of cells may be attributable to release of the toxin in response to cellular crowding, intercellular signaling, environmental stressors and their actions on the cyanobacteria cells, or it may be the consequence of released vacuolar contents coinciding with increased membrane permeability and cellular destruction during the cyclical bloom and decline of *Nodularia*. Laboratory studies tracking density dependent production would be a beneficial complementary undertaking to further examine this relationship. It is worth noting that the nodularin concentration was below the WHO highly protective value of 20 ug/L when *Nodularia* cells were less than 10,000 per ml.

Figure 28. The concentration of nodularin in Farmington Bay water samples is a non-linear relationship with the number of Nodularia cells per ml. There appears to be a density dependent production of nodularin occurring when Nodularia is in excess of 10,000 cells per ml.



Relative and absolute algal abundances were highly diverse and dynamic across the entire bay and also within each sample location. As an example of the within-site temporal dynamics of algal population growth and development the characteristics of site #1 are shown in Figure 29 at different time intervals. Absolute cell numbers per ml as well as the unit of measure (i.e., single cell, cell cluster, filament, etc.) per ml are portrayed in terms of percent of total for each site and each measure. These daily comparisons provide an understanding the rapidly changing conditions and features of Farmington Bay and they further illustrate the need for frequent collections of data in order to discern meaningful patterns of biological activity in the bay. The results further support the observation that cyanobacteria become the dominant algal group beginning throughout most of the summer and into the fall months. But the fine detail at the site level provides a glimpse into the shifts that can occur within the broader framework of a dominant trend. For example on July 11th, in the midst of a regime change from diatoms to cyanobacteria, unicellular chlorophytes had a transient resurgence in abundance, only to be followed by complete dominance in cyanobacteria abundance again.

Figure 29. The relative composition of algal groups located at site #1 are shown for specific days in the months of March, April, May, June, July and August to provide an impression of the local shifts in algal abundance that can occur. It can be seen that the relative abundance of a single day can differ substantially from the monthly average.

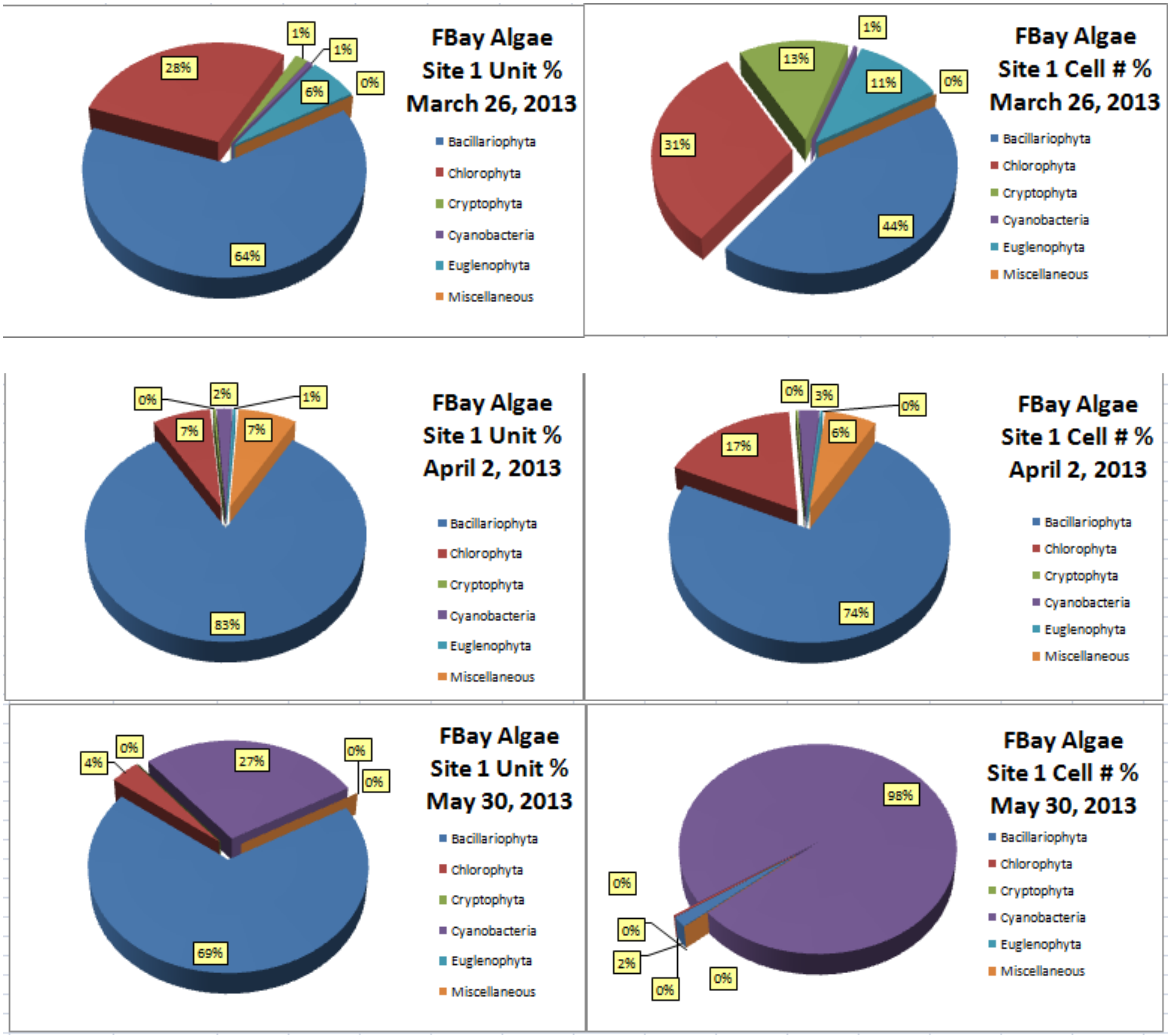
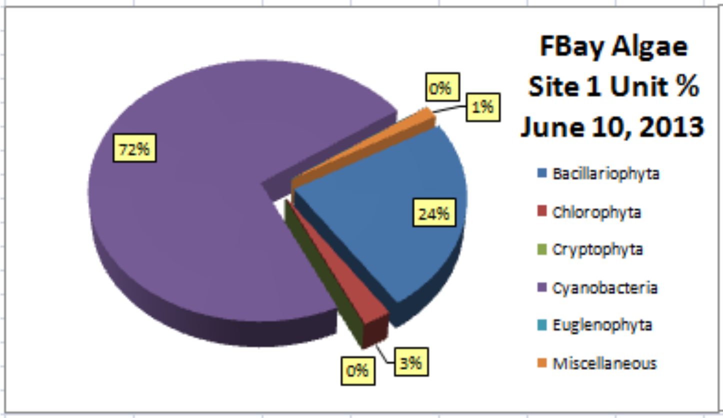
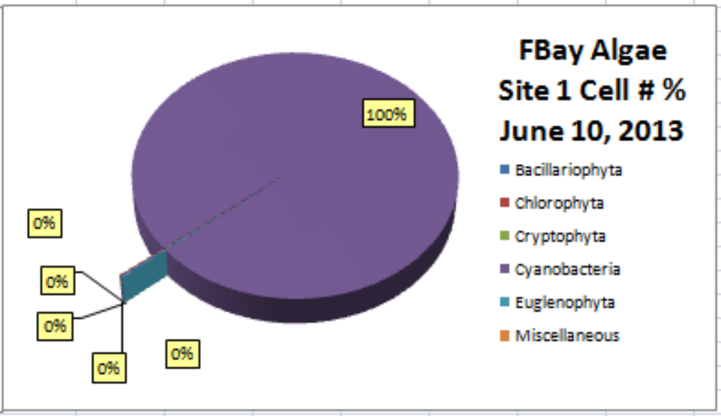
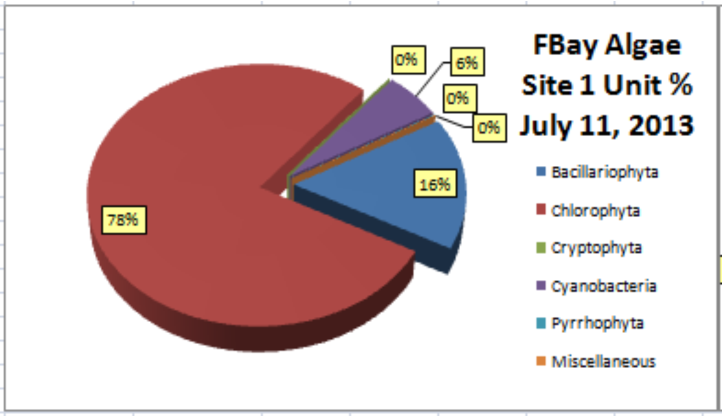
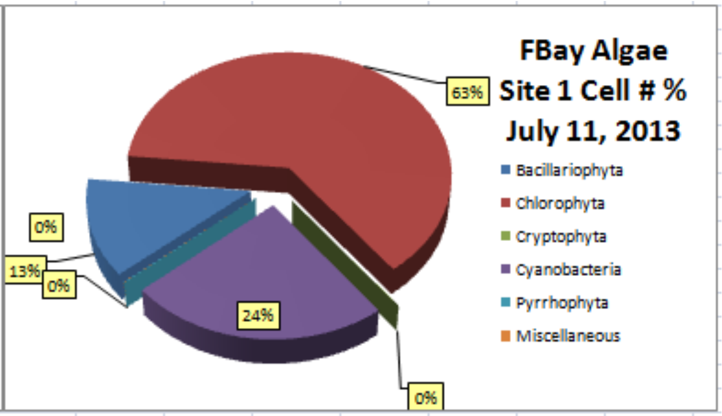


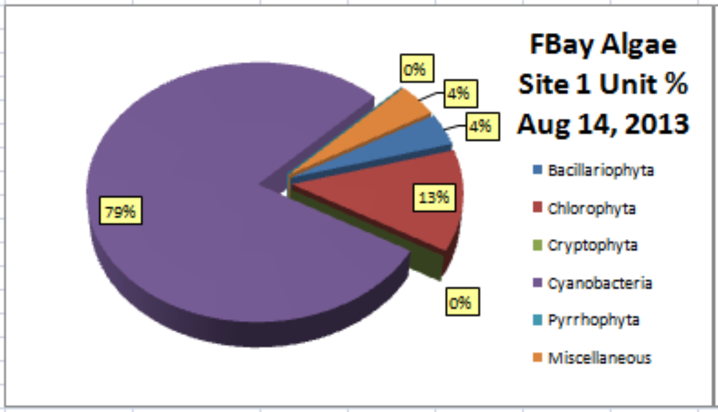
Figure 29 (continued).

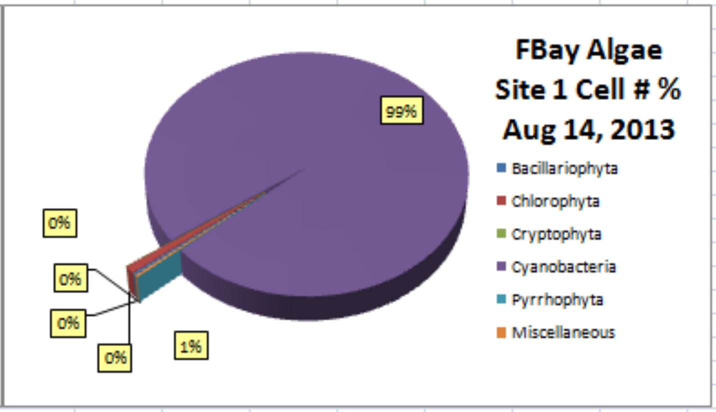

FBay Algae
Site 1 Unit %
June 10, 2013
Bacillariophyta
Chlorophyta
Cryptophyta
Cyanobacteria
Euglenophyta
Miscellaneous
72%
0%
1%
24%
0%
3%


FBay Algae
Site 1 Cell # %
June 10, 2013
Bacillariophyta
Chlorophyta
Cryptophyta
Cyanobacteria
Euglenophyta
Miscellaneous
100%
0%
0%
0%
0%
0%


FBay Algae
Site 1 Unit %
July 11, 2013
Bacillariophyta
Chlorophyta
Cryptophyta
Cyanobacteria
Pyrrhophyta
Miscellaneous
0%
6%
0%
0%
16%
78%


FBay Algae
Site 1 Cell # %
July 11, 2013
Bacillariophyta
Chlorophyta
Cryptophyta
Cyanobacteria
Pyrrhophyta
Miscellaneous
63%
0%
13%
0%
24%
0%


FBay Algae
Site 1 Unit %
Aug 14, 2013
Bacillariophyta
Chlorophyta
Cryptophyta
Cyanobacteria
Pyrrhophyta
Miscellaneous
0%
4%
4%
13%
79%
0%


FBay Algae
Site 1 Cell # %
Aug 14, 2013
Bacillariophyta
Chlorophyta
Cryptophyta
Cyanobacteria
Pyrrhophyta
Miscellaneous
99%
0%
0%
0%
0%
1%

Zooplankton

A sizeable diversity and remarkable abundance of zooplankton were identified in Farmington Bay. Eight major groups of zooplankton were observed and included: Cladocera, Copepoda, Branchiopoda, Ostracoda, Rotifera, Insecta (Diptera and Hemiptera) and Annelida (Oligocheata). Within these taxonomic groups 17 species of zooplankton were found and four unidentified species were consistently observed. All populations of zooplankton on Farmington Bay exhibited growth and decline patterns throughout the study period. Additionally, there were spatial differences among the zooplankton likely attributable to salinity tolerance differences, competition, food availability, predation and other abiotic and biotic factors that exert a pronounced effect on the distribution of a particular zooplankton species. Within each zooplankton group the key species in terms of numbers and biomass were: Rotifera—*Brachionus plicatilis*; Cladocera—*Moina macrocarpa*; Copepoda (Harpacticoid)—*Cletocamptus sp.*; Branchiopoda—*Artemia franciscana*; Insecta (Hemiptera)—*Trichocorixa verticalis*.

Although previous research (Taylor, 2004) has shown the need to use mesh size of less than 100 microns to collect most microzooplankton it is possible that other microzooplankton, and picozooplankton, such as protozoans, were not adequately collected nor identified due to the mesh size of the plankton net used for the current study; the mesh size was 60 microns and the sieve size used to capture the net contents was a 38 micron mesh. Due to these mesh sizes some of the smallest micro- and picoplankton may have been lost in the sample collection. Additionally, at times of the year when *Nodularia* blooms were in abundance the collection and separation of zooplankton from algae became increasingly difficult (selective filtration required multiple hours per sample) and some loss of the microzooplankton such as rotifers could have occurred.

Zooplankton taxa observed during the study are shown in Table 2. Rotifers and copepods were the most abundant of the zooplankton observed. Rotifers (*Brachionus*) exhibited three peak abundances: April, June and November. The maximum number observed was in June with 1,761 individuals per liter. The copepods had a maximum abundance of almost twice this level with 3,376 individuals per liter in June. Among the Rotifera the only species identified in large numbers of substantial biological relevance was *Brachionus plicatilis.* One other species (*Notholca acuminate)* was identified in November 2013 but was insignificant in abundance (0.13 per liter maximum count). No other species of rotifers were identified in the bay.

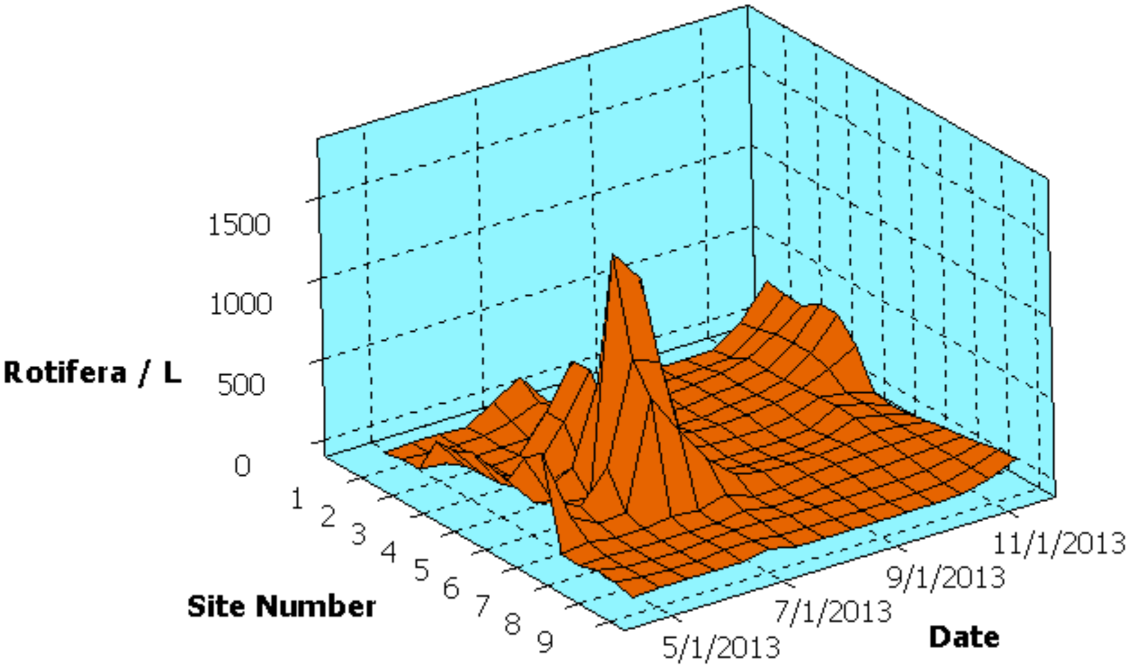
Table 2. All major zooplankton taxa observed in Farmington Bay. Zooplankton were collected from the water column while benthic invertebrates were not separately collected. Bottom dwelling invertebrates may therefore be underrepresented in the assessment of zooplankton species living within Farmington Bay. Substantial species diversity and abundance were observed during the study period. The list also includes zooplankton from one sample site on the Gilbert Bay side of the Antelope Island causeway. Species diversity and richness was substantially higher among the Farmington Bay samples compared to those observed in the single sample from Gilbert Bay. The key species, in terms of abundance, for each group is identified in bold text.

NUMBER	Major Group	Family or Order	Species
1	Crustacea / Cladocera	Daphniidae	*Daphnia dentifera (Sars)*
2	Crustacea / Cladocera	Daphniidae	*Daphnia pulex Leydig*
3	Crustacea / Cladocera	Daphniidae	*Simocephalus vetulus (O.F.M.)*
4	Crustacea / Cladocera	Daphniidae	*Ceriodaphnia quadrangular (O.F.M.)*
5	**Crustacea / Cladocera**	**Moinidae**	***Moina macrocarpa Straus***
6	Crustacea / Cladocera	Chydoridae	*Pleuroxus striatus Schoedler*
7	Crustacea / Cladocera	Chydoridae	*Pleuroxus sp.*
8	Crustacea / Cladocera	Chydoridae	*Chydorus sphaericus (O.F.M.)*
9	Crustacea / Cladocera	Chydoridae	*Alona sp.*
10	Crustacea / Copepoda	Cyclopidae	*Eucyclops agilis (Koch)*
11	Crustacea / Copepoda	Diaptomidae	*Leptodiaptomus connexus Light*
12	**Crustacea / Copepoda**	**Harpacticoid**	***Cletocamptus sp.***
13	**Crustacea / Branchiopoda**	**Artemiidae**	***Artemia franciscana Kellogg***
14	Crustacea / Ostracoda	Undetermined	*Undetermined*
15	**Phylum Rotifera**	**Brachionidae**	***Brachionus plicatilis (O.F.M.)***
16	Phylum Rotifera	Brachionidae	*Notholoca acuminate Ehrenberg*
17	Insecta: Diptera	Chironomidae	*Various sp.*
18	Insecta: Diptera	Ephydridae	*Undetermined*
19	**Insecta: Hemiptera**	**Corixidae**	***Trichocorixa verticalis (Fieber)***
20	Insecta: Hemiptera	Corixidae	*Corisella decolor (Uhler)*
21	Annelida: Oligochaeta	Naididae	*Undetermined*

The numbers of *Brachionus* were quite substantial in the spring and later declined, coinciding with the increase in the number of corixids and to a lesser extent copepods in the water column. Rotifers have a short generation time, rapid development, and high fecundity rates due to their ability to reproduce parthenogenetically. With these capacities, and in temperate zone lakes, in which dietary items such as bacteria, ciliates, and phytoplankton are abundant, rotifers are usually multivoltine. Given the conditions on Farmington Bay one would expect multigeneration production by rotifers throughout the summer months. However, their presence in the bay was abruptly diminished in July while there remained suitable environmental conditions and adequate dietary items for further reproductive output. This abbreviation in reproduction suggests a “top-down” control by a dominant predator or from multiple predators.

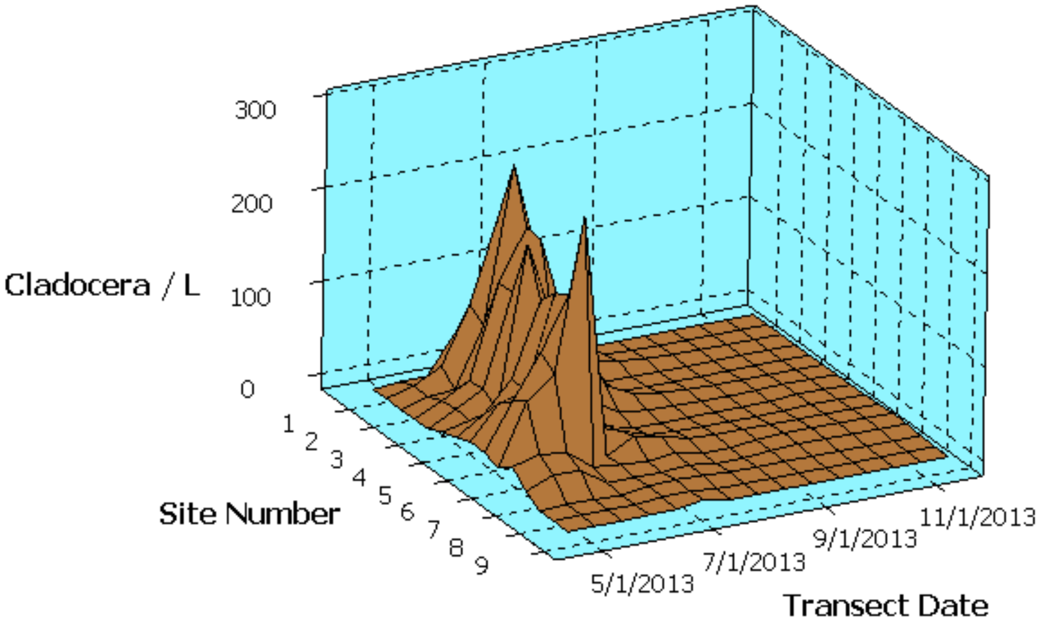
Among the zooplankton, the rotifers were the only taxa that showed a rebound of population numbers in the late summer and early fall (Figure 30). This rebound in rotifer numbers may reflect renewed favorable conditions in the bay, hatching of viable and non-resting eggs, or it may be indicative of diminished predation pressure thus allowing the rotifers to survive and replenish the population. The return of rotifers in the water column occurred once Corixidae numbers were in substantial decline.

Figure 30. Rotifers were observed in Farmington Bay in abundance in the spring and early summer, declined to very low numbers from July until October and demonstrated a limited recovery in population numbers in November. The presence of rotifers in the bay seemed to bracket the presence of corixids—as corixid numbers climbed in July the rotifers were essentially absent from the samples and when corixid numbers declined in September and October the rotifers were again observed in the bay. Although this is only a rough correlation it does not confirm predation by corixids as the sole factor controlling the rotifer population.



Other zooplankton that were found in substantial abundance included the Cladocerans (water fleas): Daphniidae, Chydoriodae and Moinidae. Total numbers of cladocerans reached 277 per liter with an average abundance of 31 individuals per liter. Among the cladocerans, the Moinidae *(Moina macrocarpa Straus)* were by far the most abundant with the maximum number of individuals showing up in May (238 individuals per liter) and June (243 individuals per liter). Cladocerans are known to have a life span of 1-3 months (Kalff, 2002) and to produce many offspring of either haploid or diploid numbers depending on environmental conditions. It has also been observed that under inhospitable conditions, or significant predation, the eggs will be produced in a resting state, ephipia, and deposited in the sediments until favorable conditions are encountered. The presence of the cladocerans roughly followed this pattern of being observed for approximately three months (April, May and June) followed by a notable absence of the cladocerans in the water column. The spatial-temporal pattern of cladocerans in Farmington Bay is graphically depicted in Figure 31.

Figure 31. The pattern of Cladoceran distribution and abundance in Farmington Bay. Among the cladocerans (water fleas) Moina was the most abundant genus found in Farmington Bay and is largely responsible for the pattern observed. Cladocerans were found in substantial numbers in the spring and early summer, however from July through the remainder of the study the average count per liter was less than one individual.



Among the Copepoda, the Harpacticoida showed the greatest abundance followed by Diaptomidae and Cyclopidae. There was a peak abundance of 2,668 harpacticoid copepods per liter while maximum numbers of adults of the diaptomids and cyclopids were 201 and 47 per liter respectively. The most commonly identified genus among the copepods was the harpacticoid copepod *Cletocamptus.* The other two species of copepods identified were *Eucyuclops agilis* (Cyclopidae) and *Leptodiaptomus connexus Light* (Diaptomidae), though their numbers were a fraction of the harpacticoid copepods. Table 3 shows the mean, median and maximum numbers for each of the major Copepoda groups.

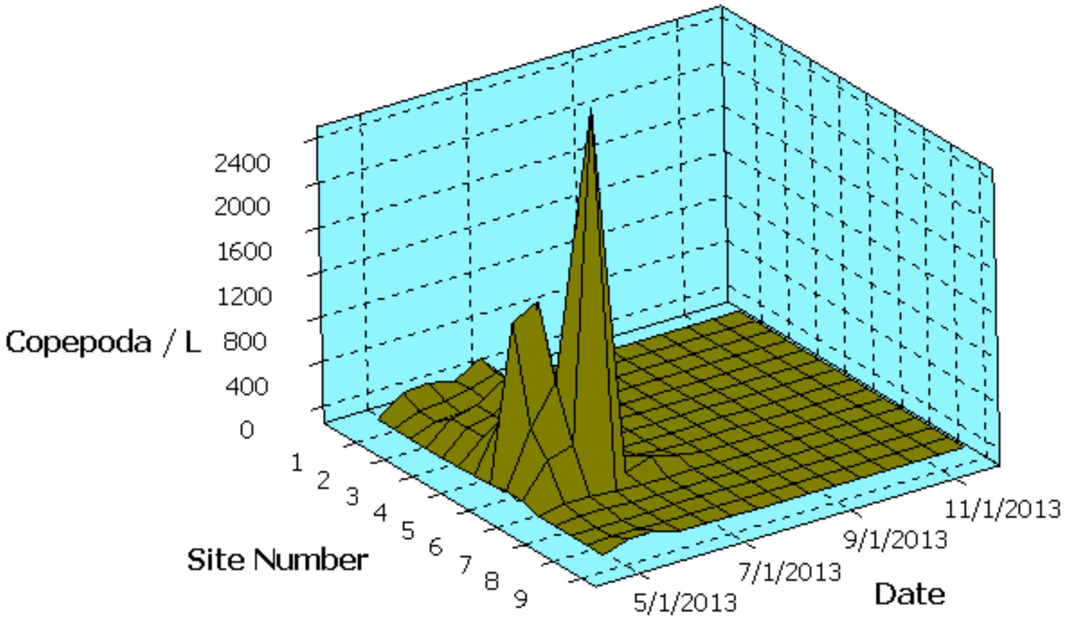
Table 3. Major Copepoda genera observed in Farmington Bay. Values are given for mean, median and maximum abundance for each of the genera identified and are on a per liter basis. Values are provided for total numbers and for adults only. The harpacticoid copepods were by far the most abundantly observed of the copepods.

Family or Order	**Genus and Species**	**Age Class**	**Mean**	**Median**	**Maximum**
Harpacticoida	*Cletocamptus sp.*	Total	97.2	0.6	2910.1
Harpacticoida	*Cletocamptus sp.*	Adult	89.0	0.5	2668.7
Diaptomidae	*Leptodiaptomus connexus Light*	Total	30.5	0.3	466.5
Diaptomidae	*Leptodiaptomus connexus Light*	Adult	16.3	0.2	201.7
Cyclopidae	*Eucyclops agilis (Koch)*	Total	1.9	0.0	64.2
Cyclopidae	*Eucyclops agilis (Koch)*	Adult	1.4	0.0	46.9

Copepods reproduce sexually and rely more on longevity and survival rates to maintain and replenish the population (Kalff, 2002), thus differing from the high reproductive output and shorter generation time of the Rotifera. Given that the life history strategy of copepods is longevity and that it is anticipated that they will survive as long as food availability and environmental conditions allow, it is somewhat surprising that their presence in Farmington Bay dropped off so precipitously in July—the maximum number in July was 14.5 individuals per liter versus 2669 individuals per liter in May and 344 individuals per liter in June. Harpacticoid copepods are often characterized as benthic feeders, yet they are able to exploit both benthic or water column food resources and have been shown to preferentially consume diatoms among the available phytoplankton (Decho, 1988). It is possible then that diatoms, which were only observed in significant quantities in the spring, were a limiting factor for copepods, but the more likely regulating factors were predation or environmental factors such as dissolved oxygen that may have constrained population growth and development.

The spatial-temporal pattern of Copepod presence in Farmington Bay is shown graphically in Figure 32. In this figure the spatially distinct location of copepods in the bay can be seen; copepods were highest in the mid-region of the bay near sites 4 & 5. Copepods were essentially absent from plankton net hauls after the beginning of July and remained absent or in very low numbers (i.e., < 1 per liter) from the site samples for the remainder of the summer and fall.

Figure 32. Copepod abundance counts are presented by sample date and site number. There was a distinct spatial and temporal pattern to the presence and abundance of copepods in Farmington Bay. Peak abundance occurred in June followed by a substantial and nearly permanent collapse of the copepods. Copepods seemed to prefer the sites in mid-bay as evidenced by the substantial numbers observed and collected at these sites.



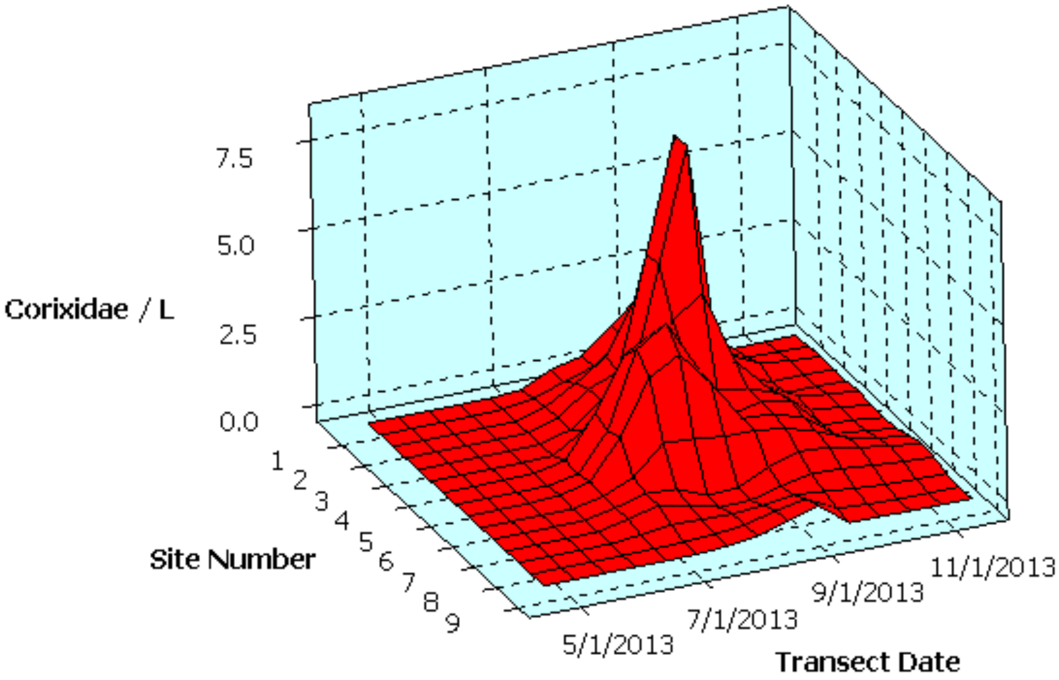
The Artemiidae were obviously a consistent and important zooplankton group in the northern regions of the bay and especially at site #9, which was located on the Gilbert Bay side of the Antelope Island causeway and therefore was a site in which salinity remained well above the tolerance level for most of the other zooplankton (i.e., >11%). The maximum number of adult *Artemia* found in the sample locations essentially followed a north to south pattern of declining abundance Table 4. This pattern of abundance is in alignment with the salinity tolerances and optima for brine shrimp. Salinity gradients are driven by relative elevations of the two water bodies and wind driven bulk water movement between Gilbert and Farmington Bays. Periodic seiche events, caused by prolonged winds from the north, northwest, or northeast, may explain the presence of *Artemia* as far south in Farmington Bay as sites #5 and #6.

Table 4. Artemiidae abundance according to sample location in Farmington Bay. Sample sites listed by site number are shown in a descending order from north to south along Farmington Bay. Peak abundances are shown for each sample location and are reported on a per liter basis.

Site	Max Adult Male *Artemia* /L	Max Adult Female *Artemia* /L	Max Immature *Artemia* / L
9	13.6	16.3	270.3
1	3.5	3.5	13.7
2	0.8	1.4	8.8
3	1.8	2.4	23.6
4	1.0	1.5	14.1
5	6.6	2.4	8.7
6	0.1	0.1	1.5
7	0.0	0.0	0.2
8	0.0	0.0	0.0

Corixidae began to appear in the water column in June and reached peak abundance in August followed by a steady decline in September and October (Figure 33). Peak adult abundance reached 8.1 individuals per liter in August while the average number in the water in June was just 0.1 individuals per liter. In July this mean value increased over one adult per liter and remained high throughout August with an average number of corixids of 2.0 per liter.

Figure 33. Corixid densities began to increase in Farmington Bay in June and peaked in August. This increase in corixids coincided with a pronounced decline in other zooplankton groups; most notably the cladocerans and copepods.



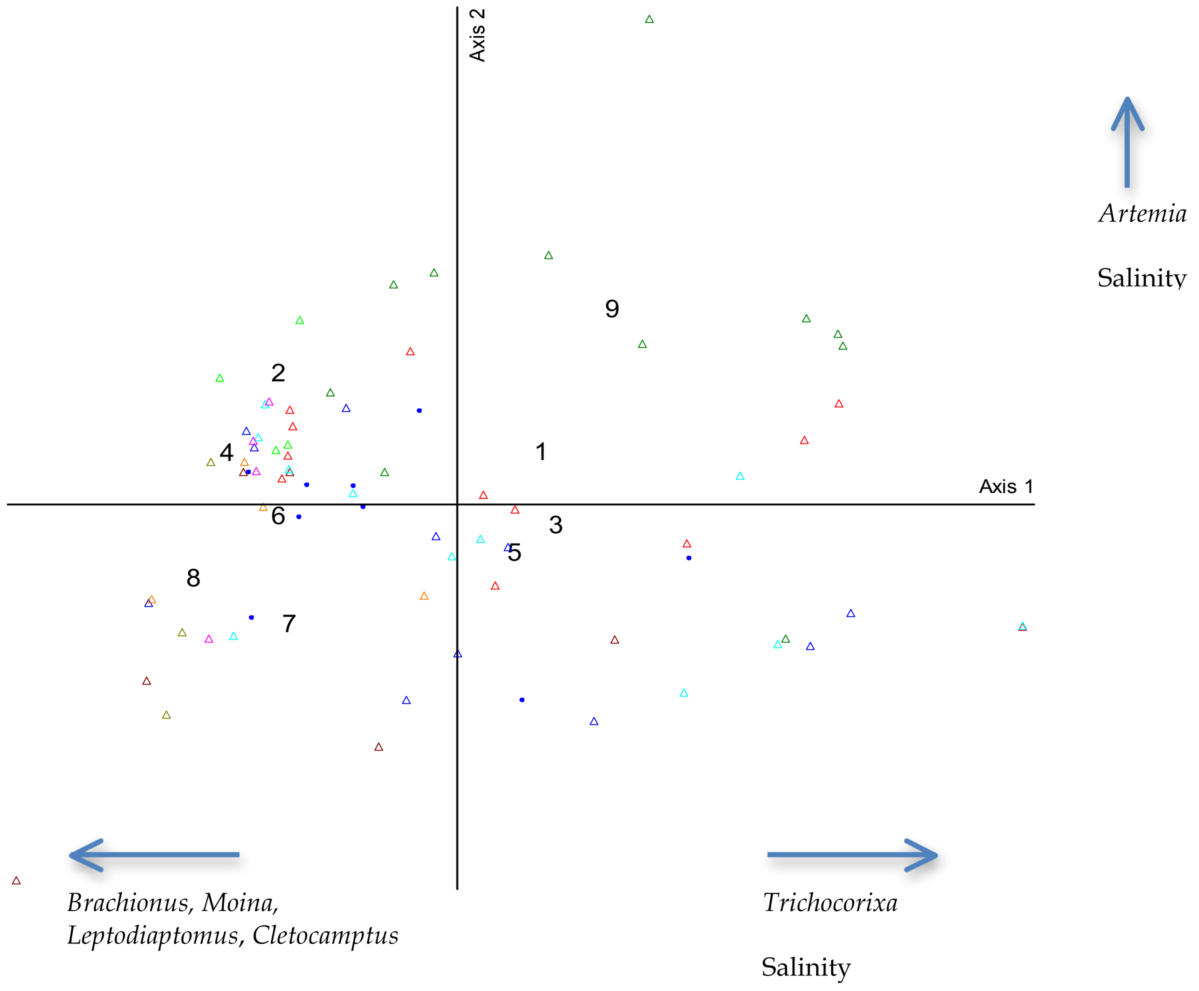
The spatial and temporal heterogeneity of zooplankton in Farmington Bay illustrates the pronounced need for frequent sampling and for a sampling program that includes multiple sites across the bay. The fact that there is often a north-south salinity gradient, and that salinity is well established to be a driving factor in the distribution of phytoplankton and zooplankton, is just one clear reason for the need to have multiple sample sites that capture the status of biota within representative hydrological/hydrochemical zones of the bay. Furthermore, identifying and assessing such trophic relationships with small-scale physical and chemical constraints taken into consideration would enhance evaluating interactions among the biota of the bay. This same approach applies to evaluating local abundances versus bay-wide averages; average abundances are less useful in terms of documenting and interpreting the dynamics of phytoplankton and zooplankton in Farmington Bay. Of greater interest are the spatially discrete counts of individuals and the dynamics of the zooplankton at sites where peak abundance occurs.

Whereas the current study of Farmington Bay was just the first year in a multi-year effort to understand the ecological dynamics of the bay with respect to nutrient loads and cyanobacteria blooms, the zooplankton results provide some valuable insight into the very important role that the substantial abundance and diversity of zooplankton play in the GSL ecosystem. The magnitude of the zooplankton biomass coupled with the diversity serves to provide predatory avifauna with multiple prey choices in the spring and early summer, and fewer options in mid-summer and fall. The biological basis for this shift in diversity and abundance may be attributable to the influence of top-down effects via invertebrate predation and perhaps in combination with other environmental factors that constrain or limit zooplankton population growth.

Spatial relationships of Farmington Bay macroinvertebrates

NMS analyses resulted in an excellent three dimensional ordination (Figure 34, final stress = 8.0%), which explained 94 % of the variability in the distance matrix (axis 1 $R^2 = 0.68$, axis 2 $R^2 = 0.15$, and axis 3 $R^2 = 0.11$). The dissimilarities of the macroinvertebrate assemblages were well defined by site and date. Several of the taxa contributed to define Axis 1; primarly *Brachionus plicatillis*, *Moina macrocarpa*, *Leptodiaptomus connexus*, and *Cletocamptus* sp.(left side of Axis 1) and *Trichocorixa verticalis* (right side of Axis 1). Axis 2 was primarily defined by *Artemia franciscana*. Because the final stress of the NMS ordination was < 10%, interpretation of assemblage relationships is straightforward with little chance of misinterpretation (McCune and Grace 2002). Salinity was greater moving towards the right of Axis 1 and to the top of Axis 2.

Figure 34. Spatial relations of FB macroinvertebrate assemblages: NMS axes 1 and 2. Sites are labeled 1 through 9.

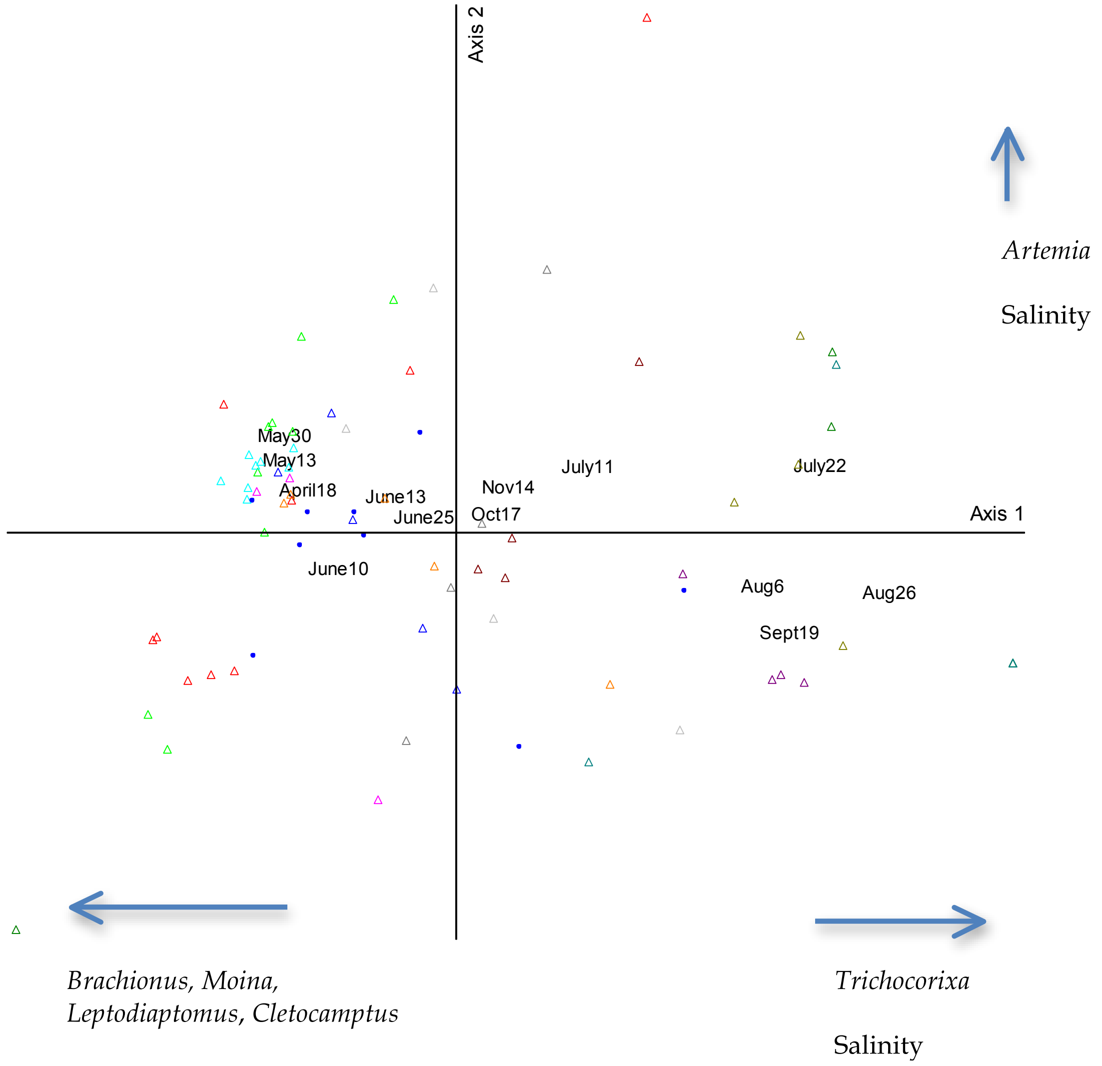


Macroinvertebrate assemblages in Site 9 grouped separately from the other sites. Assemblages in Sites 7 and 8 were similar to each other, which reflects their close spatial proximity in FB. Sites 2, 4, and 6 clustered together as did sites 1, 3, and 5. The reason sites 2, 4 and 6 were different than 1, 3, and 5 was the dates samples were collected and the strong temporal effect on assemblages. The macroinvertebrate assemblage at site 1 was most similar (closest in ordination space) to the site 9 assemblage, which was also physically closest to site 9 (Figure 34).

In general, macroinvertebrate assemblages tended to group into three (or four) clusters based on their spatial arrangement in FB: a) 7 and 8 closest to b) 2, 4, 6; c) 1, 3, and 5, located mid FB and; d) site 9, outer FB. Graphs of each of the nine taxa’s relative proportion biomass (log generalized) per sample in ordination space (axis 1 and axis 2) are in Appendix 6.

Macroinvertebrate assemblages followed a seasonal pattern from left to right in Figure 35. However, October and November assemblages were more similar to early season samples probably because both early and late season biomasses were much lower than mid season.

Figure 35. Temporal relations of FB macroinvertebrate assemblages: NMS axes 1 and 2.



FB Macroinvertebrate Assemblage Relationships to Site and Date

Macroinvertebrate assemblages were highly significantly ($p < 0.001$) affected by site and date. The *A* chance-corrected within-group agreement statistic for site was 0.12 and for date was 0.36.

Food web analysis

Structural Equation Models (SEMs)

Although we were able to create a valid Structural Equation Model (SEM) of a basic food web, we only consider it useful at this time as an illustration of how our future models will be developed after more data is collected. We do not consider this SEM to be a completely reliable or final product model, however the chi square test of fit showed that the model fit the data quite well (chi square = 5.28 and Prob < chi square = 0.26) and some intuitive relationships were supported. These include: a strong negative relationship between SRP and PTox cells; a potentially significant top-down and bottom-up relationship between zooplankton on non-cyano cells; a positive effect of non-cyano cells on zooplankton; and a strong negative effect of corixids on zooplankton (Figure 36, Table 5). These relationships are symbolized by the red ovals in Figure 36. No significant relationship was observed between PTox cells and zooplankton or the corixids.

Figure 36. Generalized SEM . E_a = error; connect line values = SEM coefficients; values n lower right of boxes = model constant; values in upper right = mean coef.

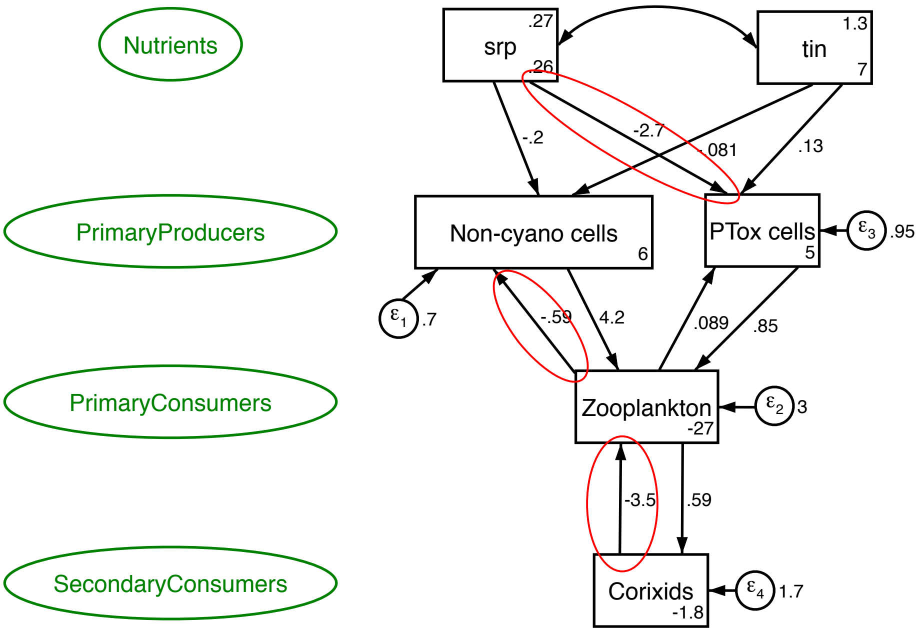
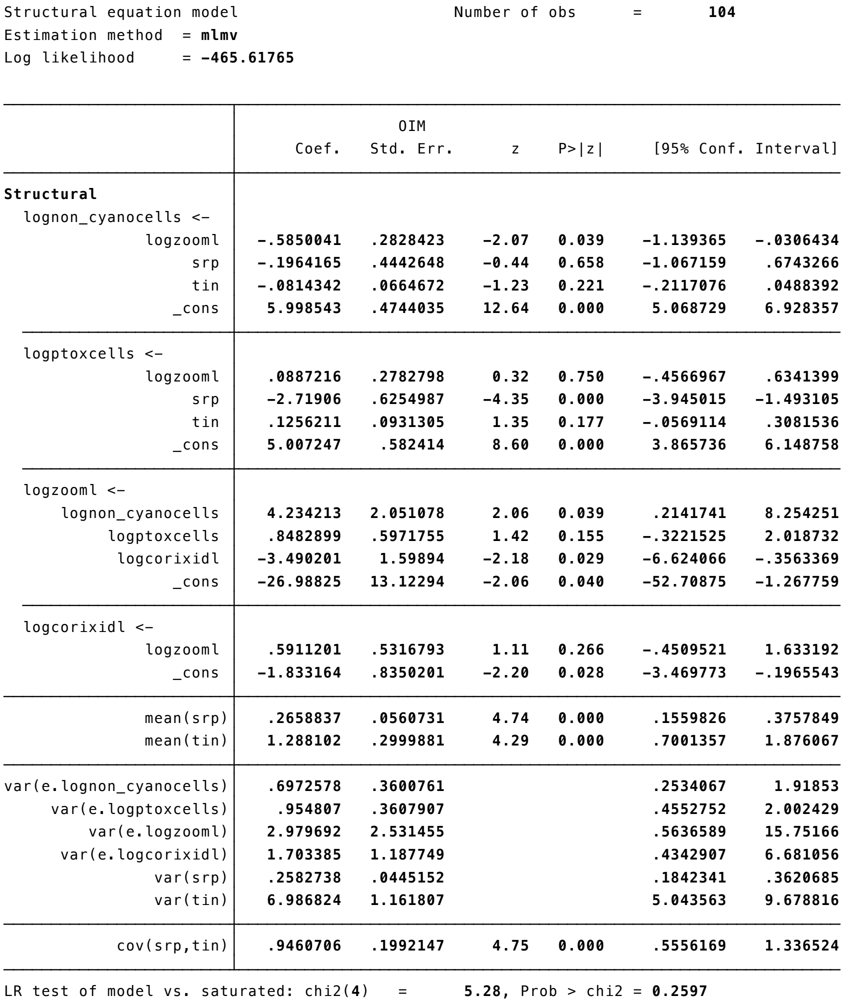


Table 5. SEM for food web model results including a determination if perceived connections between variables were significant.



```
Structural equation model                       Number of obs      =        104
Estimation method  = mlmv
Log likelihood     = -465.61765

------------------------------------------------------------------------------------------
                        |                 OIM
                        |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
------------------------+-----------------------------------------------------------------
Structural              |
  lognon_cyanocells <-  |
               logzooml |  -.5850041   .2828423    -2.07   0.039    -1.139365   -.0306434
                    srp |  -.1964165   .4442648    -0.44   0.658    -1.067159    .6743266
                    tin |  -.0814342   .0664672    -1.23   0.221    -.2117076    .0488392
                  _cons |   5.998543   .4744035    12.64   0.000     5.068729    6.928357
  ----------------------+-----------------------------------------------------------------
  logptoxcells <-       |
               logzooml |   .0887216   .2782798     0.32   0.750    -.4566967    .6341399
                    srp |   -2.71906   .6254987    -4.35   0.000    -3.945015   -1.493105
                    tin |   .1256211   .0931305     1.35   0.177    -.0569114    .3081536
                  _cons |   5.007247    .582414     8.60   0.000     3.865736    6.148758
  ----------------------+-----------------------------------------------------------------
  logzooml <-           |
      lognon_cyanocells |   4.234213   2.051078     2.06   0.039     .2141741    8.254251
           logptoxcells |   .8482899   .5971755     1.42   0.155    -.3221525    2.018732
            logcorixidl |  -3.490201    1.59894    -2.18   0.029    -6.624066   -.3563369
                  _cons |  -26.98825   13.12294    -2.06   0.040    -52.70875   -1.267759
  ----------------------+-----------------------------------------------------------------
  logcorixidl <-        |
               logzooml |   .5911201   .5316793     1.11   0.266    -.4509521    1.633192
                  _cons |  -1.833164   .8350201    -2.20   0.028    -3.469773   -.1965543
------------------------+-----------------------------------------------------------------
              mean(srp) |   .2658837   .0560731     4.74   0.000     .1559826    .3757849
              mean(tin) |   1.288102   .2999881     4.29   0.000     .7001357    1.876067
------------------------+-----------------------------------------------------------------
var(e.lognon_cyanocells)|   .6972578   .3600761                      .2534067     1.91853
   var(e.logptoxcells)  |    .954807   .3607907                      .4552752    2.002429
       var(e.logzooml)  |   2.979692   2.531455                      .5636589    15.75166
    var(e.logcorixidl)  |   1.703385   1.187749                      .4342907    6.681056
               var(srp) |   .2582738   .0445152                      .1842341    .3620685
               var(tin) |   6.986824   1.161807                      5.043563    9.678816
------------------------+-----------------------------------------------------------------
           cov(srp,tin) |   .9460706   .1992147     4.75   0.000     .5556169    1.336524
------------------------------------------------------------------------------------------
LR test of model vs. saturated: chi2(4)   =      5.28, Prob > chi2 = 0.2597
```

This model is an important first step in developing more comprehensive and realistic food web models and it also serves to confirm some of our theories on how the components of the food web interact. Our next step will be to incorporate more data into the models and add more complexity, including latent variables that synthesize other variables.

Zooplankton Interactions

We used SEM to examine the interactions between Corixidae and seven zooplankton taxa (Figure 37). We used maximum likelihood with missing values with a maximum of 200 iterations using the SEM package in STATA 13 (StataCorp 2014). In our first model all zooplankton taxa were correlated with each other. SEM results showed that only Cladocera, Copepoda, and Artemiidae were significantly correlated, therefore we conducted a second model with only these correlations. We also created an SEM with only top-down effects of Corixidae on zooplankton taxa but this resulted in a poor fit of the model to the data.

SEM Results

The second model (i.e., zooplankton interactions) fit the data quite well (chi2 = 14.69; Prob > chi2 = 0.548) and is a good representation of the interactions between Corixidae and zooplankton taxa (Figure 37). Although no zooplankton taxa appeared to have a bottom up effect on Corixidae, it was necessary to include the bottom up effects in the final model. The significant (negative) interaction effects of Corixidae on zooplankton taxa include the following taxa: Copepoda, Rotifera, Artemiidae, and possibly Cladocera (Table 6).

Figure 37. SEM diagram of interactions between Corixidae and seven zooplankton taxa.
SEM . E_a = error; connect line values = SEM coefficients; values n lower right of boxes = model constant; values in upper right = mean coef. See Table below for SEM results including if connections between variables were significant.

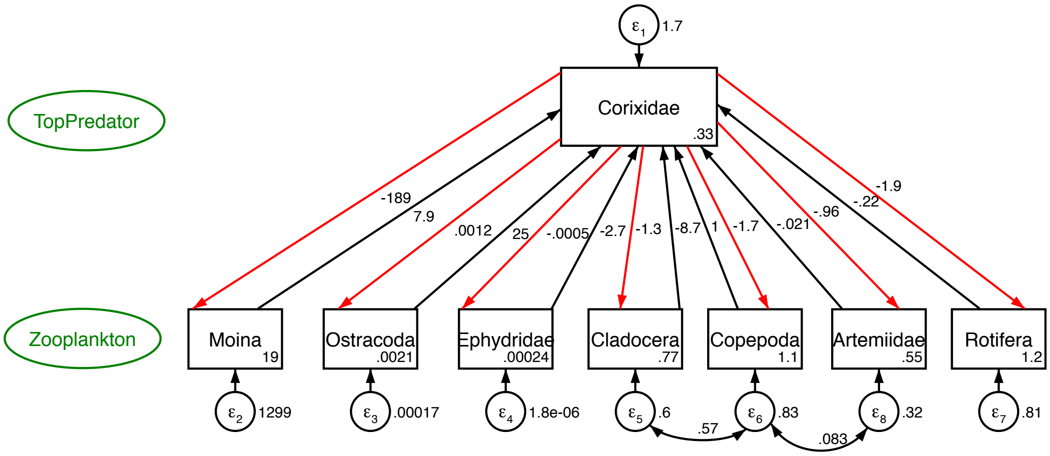


Table 6. SEM results interactions between Corixidae and seven zooplankton taxa.

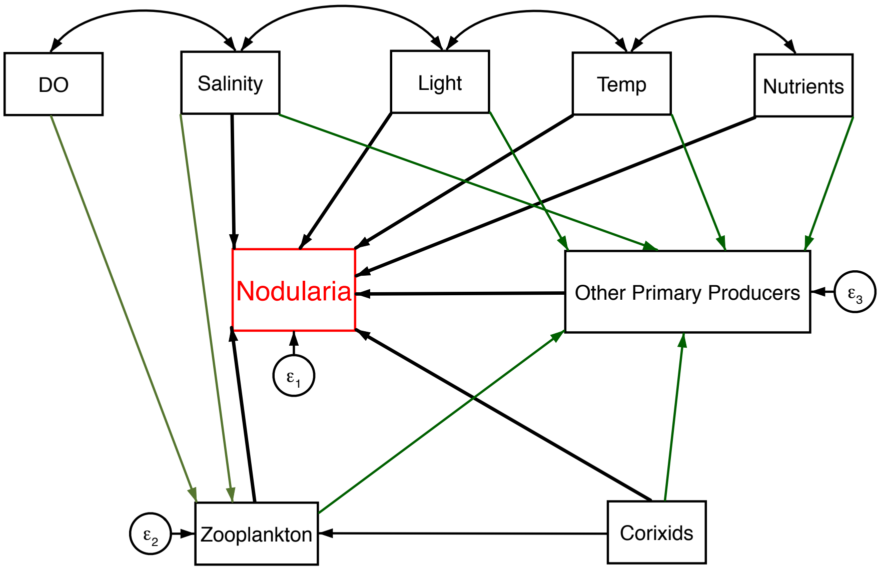
```
Structural equation model                       Number of obs      =        68
Estimation method  = ml
Log likelihood     =  318.32662

------------------------------------------------------------------------------------------------
                              |                 OIM
                              |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
------------------------------+-----------------------------------------------------------------
Structural                    |
  corixidael <-               |
           moinamacrocarpal   |   7.861774   7.756897     1.01   0.311    -7.341465    23.06501
                 ostracodal   |   24.54211   28.20226     0.87   0.384     -30.7333    79.81753
                ephydridael   |  -2.687426   118.8129    -0.02   0.982    -235.5565    230.1817
                 cladoceral   |  -8.719566    8.59675    -1.01   0.310    -25.56889    8.129753
                  copepodal   |   1.041487   1.095374     0.95   0.342    -1.105407    3.188381
                  rotiferal   |  -.2225821   .2319815    -0.96   0.337    -.6772574    .2320932
                artemiidael   |  -.0213622   .2983128    -0.07   0.943    -.6060444    .5633201
                      _cons   |   .3286921   .2943853     1.12   0.264    -.2482925    .9056766
  ----------------------------+-----------------------------------------------------------------
  moinamacrocarpal <-         |
                 corixidael   |  -189.2091    1219.76    -0.16   0.877    -2579.895    2201.477
                      _cons   |   18.88316   118.1206     0.16   0.873     -212.629    250.3953
  ----------------------------+-----------------------------------------------------------------
  ostracodal <-               |
                 corixidael   |   .0012399   .0081709     0.15   0.879    -.0147749    .0172546
                      _cons   |   .0021485   .0017526     1.23   0.220    -.0012866    .0055836
  ----------------------------+-----------------------------------------------------------------
  ephydridael <-              |
                 corixidael   |  -.0004983   .0008435    -0.59   0.555    -.0021515    .0011549
                      _cons   |   .0002413   .0001812     1.33   0.183    -.0001138    .0005964
  ----------------------------+-----------------------------------------------------------------
  cladoceral <-               |
                 corixidael   |  -1.344779    .740605    -1.82   0.069    -2.796338    .1067802
                      _cons   |   .7685267   .1182391     6.50   0.000     .5367824    1.000271
  ----------------------------+-----------------------------------------------------------------
  copepodal <-                |
                 corixidael   |  -1.727666    .759213    -2.28   0.023    -3.215696   -.2396355
                      _cons   |   1.130393   .1327823     8.51   0.000     .8701448    1.390642
  ----------------------------+-----------------------------------------------------------------
  rotiferal <-                |
                 corixidael   |  -1.900357   .5707889    -3.33   0.001    -3.019083   -.7816318
                      _cons   |   1.162018   .1225342     9.48   0.000     .9218552     1.40218
  ----------------------------+-----------------------------------------------------------------
  artemiidael <-              |
                 corixidael   |  -.9615433   .3551444    -2.71   0.007    -1.657614    -.265473
                      _cons   |   .5453623   .0762622     7.15   0.000     .3958911    .6948336
------------------------------+-----------------------------------------------------------------
           var(e.corixidael)  |   1.657738    3.28198                       .0342225     80.3008
     var(e.moinamacrocarpal)  |   1298.882    16849.1                       1.18e-08    1.43e+14
           var(e.ostracodal)  |   .0001664   .0000285                       .0001189    .0002328
          var(e.ephydridael)  |   1.78e-06   3.05e-07                       1.27e-06    2.49e-06
           var(e.cladoceral)  |   .6013801   .1032408                       .4295568    .8419329
            var(e.copepodal)  |    .831852   .1390859                       .5994113    1.154429
            var(e.rotiferal)  |   .8135192   .1395175                       .5812834    1.138539
          var(e.artemiidael)  |   .3151627     .05405                        .225193    .4410773
------------------------------------------------------------------------------------------------
```

chi2 = 14.69; Prob > chi2 = 0.548

Cyanobacteria Food Web Model

A conceptual food web model for Nodularia growth in Farmington Bay is shown in Figure 38. Although SEM analysis was developed, such a food web model would greatly benefit from, and be more statistically robust, with additional data. Therefore this refined model is presented at this point to illustrate the linkages to be examined and to assist in the identification of data gaps that need to be filled with more extensive investigations.

Figure 38. Conceptual food web model of Nodularia and the primary factors influencing its growth and expansion on Farmington Bay. This conceptual model is a useful tool for identifying data gaps and prioritizing research needs for subsequent investigations.



DISCUSSION

Zooplankton: Predator-prey relationships, trophic interactions: top-down and bottom-up effects.

Zooplankton abundance and diversity of the zooplankton assemblages were observed and recorded. There were clear spatial and temporal changes in the zooplankton abundance. Although salt-tolerant *Artemia* were recorded in the northern portion of the bay near the Antelope Island causeway, meso-haline-adapted invertebrates dominate the remainder of the bay. Rotifers were the dominant zooplankter in June and then again in November. Their population decline was followed by an increase in cladocerans, which yielded dominance to copepods in some locations—primarily in the north-central region of the bay; the region that often had the highest cyanobacteria counts. The temporal and spatial pattern observed in this study corresponded to previous studies on zooplankton on Farmington Bay in which cladocerans (primarily *Moina* sp. and *Daphnia* sp.) were found in substantial concentrations in May, but showed a diminished presence in the bay thereafter (Wurtsbaugh et al., 2010). These authors also recorded depletion in zooplankton abundance during mid-summer once the number of corixid adults started increasing and eventually reached densities of 0.5 per liter or higher. Corixid eggs are known to hatch between 20-36C (Kelts, 1979) and this may indicate why the emergence of Corixids as a dominant zooplankter began in June when water temperature was sustained at or above 20C. Corixid adults appeared in meaningful densities in mid-June and remained until the end of September. Corixids have four advantages over other zooplankton: 1) they are air-breathers and are therefore not harmed by anoxic or hypoxic events; 2) they are predators of most other zooplankton; 3) they are omnivorous and can exploit a variety of food sources; and 4) they have piercing mouth parts that can be used to pierce filamentous algae, that are too large for most other zooplankton to consume, and ingest the contents (Cheng, 1976). It is not surprising then that throughout the time period of corixid abundance other zooplankton were found in low numbers.

Other invertebrates such as the Chironomids were occasionally identified but were quite patchy in their distribution and were found in substantially lower abundance numbers. Their presence nevertheless represents an additional and potentially important alternative food source for shorebirds and waterbirds. For example, Miller, Hoven and Cavitt (2009) found that corixids and midges (Chironomidae) were the main prey items identified in the stomach contents of shorebirds such as American avocets and black-necked stilts. Clearly the diversity of invertebrates found in Farmington Bay is a highly important element included in the beneficial use of “support for waterfowl and shorebirds and the aquatic life in their food chain”.

The early (i.e., pre-Corixid time period) dynamics of cladocerans and copepods may be a function of their selective or generalist grazing habits. Cladocerans, especially the large-bodied ones like *Daphnia* are generalist feeders and may encounter foraging stress sooner in the presence of filamentous algal blooms, whereas many of the copepods are selective grazers and have been shown to have a greater capacity to exploit alternative phytoplankton, or protists, during times of cyanobacteria dominance (Ger, Hansson and Lurling, 2014). Other investigators such as Fulton and Paerl, (1988) and Hansson et al. (2007) have observed shifts in zooplankton population composition as a result of adaptations among the zooplankters. In particular, the copepods exhibit selective feeding capabilities that allow them to forage for alternative food sources in the midst of a cyanobacteria bloom. These authors additionally commented that cyanobacteria blooms did not favor dominance by rotifers—an observation somewhat consistent with rotifer population dynamics in Farmington Bay during our study in which peak rotifer abundance occurred prior to and after peak cyanobacteria blooms.

In the present study, cladocerans, such as *Moina*, were disproportionately abundant relative to other species, which may be a function of their tolerance of cyanobacteria. *Moina* population size remained relative stable throughout May and June--months over which *Nodularia* densities were at their peak. In contrast, the larger-bodied, and generally more sensitive species, *Daphnia dentifera* was identified in plankton net hauls in notable numbers (0.2 to 38.7 individuals per liter) only during April and May. They declined in number well in advance of the presence of corixids, but consistent with the progression of cyanobacteria blooms in May, thereby suggesting vulnerability to conditions dominated by filamentous algae. In contrast, *Moina* abundance was in the range of 17 to 243 individuals per liter throughout May and June in spite of tremendous growth of the cyanobacteria population. Numbers of *Moina* did not coincidentally decline with the emergence of cyanobacteria dominance, but instead appeared to be more influenced by corixid predation. Other authors such as Gustafsson support this relative tolerance of cyanobacteria by Moina compared to Daphnia and Hansson (2004) and Guo and Xie (2006) who found that the smaller cladocerans like *Moina* and *Ceriodaphnia* develop tolerance to cyanobacteria better than the larger bodied *Daphnia*.

Depletion of algal species, such as diatoms, coinciding with increases in known phytoplanktivorous species suggests important predator-prey or grazing relationships that shape the temporal and spatial abundance and population structure of phytoplankton. Evidence of grazing pressure caused by the zooplankters was indicated by the phytoplankton population fluctuations and responses. Zooplankton grazers such as the cladocerans and *Artemia* have the capacity to graze near 100% of the water column per day according to studies conducted by Wurtsbaugh (2012). In the current study the results were consistent with "top-down" control of algal dominance in the presence of substantial grazing pressure: when algal grazers such as the cladocerans and *Artemia* were present the densities of "edible" algae were held in check. However, once the grazing pressure of these zooplankters diminished, for example during July, the densities of "edible" phytoplankton, such as the chlorophytes, showed signs of resurgence in abundance.

Predation of other zooplankton by corixids was anticipated based on observations of previous investigations (Wurtsbaugh, 1992; Tanner, Glen and Moore, 1999; Cheng, 1976; Reynolds, 1975) and from our own laboratory studies demonstrating predator-prey relationships between corixids and *Artemia*. Of particular importance are the observations of Simonis (2013a) that all instars of *Trichocorixa verticalis* preferentially prey on *Moina* in food preference studies and that prey by corixids creates a top-down cascade releasing phytoplankton from grazing pressure. Additionally Wurtsbaugh and Berry (1989) reported that *Trichocorixa verticalis* invaded the pelagic region of the GSL when the salinity dropped from around 100 g/L to 50 g/L and as a result initiated a cascading trophic shift in the food web structure by depleting the phytoplanktivore *Artemia*. In an investigation of rock-pool communities Simonis (2013b) found that *Moina* population density is the primary factor influencing emigration of *Trichocorixa verticalis*—at certain low abundances of *Moina* the corixids will leave their current ponds and exploit other ponds with greater abundance of *Moina*. They further found that *T. verticalis* are "voracious predators" of *Moina macrocapa*. In our study there was definitive progression of depletion of cladocerans, copepods, rotifers, and *Artemia* when corixids were in an adult abundance of more than 1 mature adult/L. This progression of population decline was observed both temporally, beginning in June, and spatially, with corixids reaching maturity first in the southern region of the bay and then over time moving in a south-northward expansion of dominance in zooplankton assemblage. Although the evidence indicates pronounced top-down control by corixids, the decline in the abundance and diversity of zooplankton may not be solely attributed to corixid predation as it may be a combined function of predation coupled with intra- and interspecific competition, normal life-cycle sequences of development, growth and mortality, food limitation, temperature tolerances, dissolved oxygen levels or the presence of cyanotoxins. Yet the combination of controlled laboratory experiments that documented corixid predation rates, coupled with the correlation between corixid presence and the decline of other zooplankton, followed by recovery of other zooplankton once corixid numbers were in decline, all strongly support top-down control mechanism of zooplankton abundance in Farmington Bay by corixids. This top-down control appears to be a more significant factor regulating zooplankton population size and diversity than direct adverse impacts of cyanobacteria blooms on the zooplankton.

The trophic transfer of energy, nutrients, carbon and other essential elements and compounds is most certainly influenced by phytoplanktivory rates among the various zooplankton species. It is well established in the scientific literature that the type of algae available exerts an influence on grazing rates and digestibility of consumed food by zooplankton (Gibor, 1956). While there are substantial differences in grazing rates and digestibility among the various divisions of algae—for example cyanobacteria (division Cyanophyta) compared to diatoms (division Chrysophyta) and green algae (division Chlorophyta)—there are even differences within the families or genera of phytoplankton (Tanner et al., 1999). For example, Gibor (1956) found that differences existed even within the same genera of green algae: he observed that *Dunaliella viridis* was superior over *D. salina when grazed by Artemia*. He also found that *Artemia* could selectively graze one type of green algae in preference to other less desirable and less digestible species. In his study the *Artemia* grazed selectively on *D. viridis* over *Stichococcus*. Gibor also reported that *Stichococcus* cells that passed through the digestive system of the *Artemia* remained viable. In similar studies Tanner et.al. (1999) observed that equivalent populations of *Artemia* in salt ponds had very different impacts on the abundance of algae; they found that *Artemia* grazed diatoms down to low densities (only 1,250 cells per mL), whereas when the cyanobacteria *Synechococcus* was present more than 4.2 million cells per mL remained in spite of the same density of adult *Artemia*. They also found that when *Artemia* were not present the salt ponds contained high numbers of diatoms, thereby supporting the hypothesis that selective algal grazing by *Artemia* can determine the algal species composition of salt ponds. These and other studies illustrate the importance of food quality on zooplankton and the pressure that they exert on competition, growth and survival among the invertebrate grazers. In Farmington Bay this has particular relevance because phytoplankton of presumed high quality, such as diatoms and green algae, are displaced by filamentous cyanobacteria resulting in suboptimal forage for a diversity of zooplankters.

Artemia were found primarily in the central to northern regions of Farmington Bay and their distribution was influenced by salinity. It is well known that *Artemia* are classic extremeophiles (Hengherr, Schill and Clegg, 2007) that exhibit a remarkable capacity to withstand hypoxia and a vast range of salinities, ranging from marine water to saturated brines. It is in this capacity that they derive a competitive advantage over other zooplankters. They are known to demonstrate selective feeding capacities and can survive given a wide range of phytoplankton options as long as the size of algal cells is sufficiently small (i.e., 4-8 microns for metanauplii and <20 microns for adults) to pass their feeding apparatus (Makridis, P., & Vadstein, O., 1999). In our study there were periodic periods of high abundance in the northern regions of the bay (20.6/L to 27.9/L) while peak abundance in sites 6, 7& 8 (southernmost sites in our study) the *Artemia* only achieved a maximal value of 1.73, 0.18, and 0.00/L respectively. The low salinity of this region of Farmington Bay did not support *Artemia* growth and development likely due to interspecific competition and predation pressure. In contrast, at site #9, just on the north side of the Antelope Island causeway breach, the peak value for total number of *Artemia* reached 300.1/L. Within the northern section of Farmington Bay (defined as sites 1, 2, & 3) the mean salinity ranged from 2.4% to 4.1% and the highest observed at site #1 was 8.2%. These are well below values for site #9 where the average salinity was 11.1% and the high was 14.0%. Clearly the salinity of site #9 conferred some advantage for *Artemia* over other zooplankton as well as relieving the *Artemia* from the predation pressure of corixids—the average number of corixids per liter at this site was a mere 0.09/L and the maximum value was 0.69/L. In previous work on Farmington Bay by Wurtsbaugh and Marcarelli (2004) they found that corixid abundance of just 0.28/L was sufficient to control *Artemia* population size, whereas the lower corixid abundance they observed in 2003 (0.06/L) did not control the *Artemia* population size.

Artemia abundance in sites 1- 5 were comparable to reports in the literature of *Artemia* abundance in Farmington and Gilbert Bay. In our study *Artemia* mean values for these sites were between 1.84 and 6.64 individuals/L with a peak abundance range of 8.81 to 27.91/L. These peak values are more than were reported by Stephens and Gillespie (1976) for Gilbert Bay in which they found that 12-15 individuals per liter was the upper limit for *Artemia*. Wurtsbaugh and Gliwicz (2001) present a mean value for adult *Artemia* in Gilbert Bay of 3.1/L and compare this to a more productive Mono Lake that boasts 6-8/L. These values, and the average abundance we observed for site #9 in our study (4.62/L) are well above the mean values for *Artemia* abundance even in the northern zone of Farmington Bay (0.75/L to 0.85/L). Collectively this indicates that a variety of conditions in Farmington Bay such as competition, predation, and food availability maintain the *Artemia* population below more productive levels observed when salinity is higher and *Artemia* have an ecological advantage, such as in Gilbert Bay.

Phytoplankton and Chlorophyll-a

There was a remarkable diversity of algal taxa observed in the current study: 10 major taxa, 81 genera and more than 50 species of algae were collected and identified. This is greater diversity than some of the previously reported values for Farmington Bay (Wurtsbaugh, Marcarelli, and Boyer, 2012) and may be a result of the thoroughness and frequency of the sampling program and area of the bay that was sampled. It is also greater diversity than was found in the other more saline bays of the GSL. The decrease in diversity of species observed in the other bays of the GSL is an expected outcome of the diminishing effect that increases in salinity has on algal and zooplankton species diversity (but not necessarily on the bacterial populations). One of the factors that favored species richness during the course of our study was the low level of the GSL (elevation between 4194 and 4197 and approaching the lowest level ever recorded—4191 feet above sea level). This low elevation of Gilbert Bay results in most of Farmington Bay being in the lower range of salinity (i.e., 0%-6%). Previous studies of Farmington Bay that reported less diversity also recorded higher salinity across the bay—with salinities ranging from 4% to 10% (Wurtsbaugh and Marcarelli, 2006), 1% to 9% (Wurtsbaugh, Marcarelli, and Boyer, 2012). The low elevation and therefore low salinity of Farmington Bay during 2013 favored the growth of cyanobacteria.

Farmington Bay is a highly dynamic water body characterized by constant production, movement, mixing, grazing, and ultimately decline of algal species. In the midst of this perpetual change there are patterns that emerge and that can be identified and characterized. Clearly the most apparent pattern is the emergence and dominance of the cyanobacteria bloom that begins in May and results in pronounced dominance of the algal assemblage that continues well into September. This is consistent with a variety of earlier studies that are reviewed in great detail in Wurtsbaugh, Marcarelli, and Boyer (2012). In this publication they cite multiple earlier investigations of Farmington Bay that also recorded cyanobacteria blooms starting in May and extending into the fall. One difference in our study from some of the previously reports is that while *Nodularia* was the early and dominant cyanobacteria it was displaced in dominance by *Pseudanabaena* in August. In most of the studies reported by Wurtsbaugh this dramatic increase in *Pseudanabaena* is not reported, yet *Aphanothece* does show up in some of the studies at high abundances. In a thorough investigation of Farmington Bay by Wurtsbaugh in 2009 (cited in Wurtsbaugh et al., 2012) *Nodularia* represented 91% of the total cyanobacteria and 86% of the total algae in Farmington Bay. In this same publication Wurtsbaugh et al., had similar results to our study in which the southern locations in the bay, with salinities in the range of 1% to 3%, did not support cyanobacteria blooms. Their interpretation of the cause is consistent with ours: exclusion of cyanobacteria from this region of the bay is due to available nitrogen from input sources (mainly discharges by POTWs) that create an environment which favors other algal groups and not nitrogen fixing filamentous algae. Another consistent finding is that there is a salinity threshold for *Nodularia*: both in our study and in a summary of findings from 2002, 2003, 2005 and 2009: the upper threshold limit for *Nodularia* at approximately 6% salinity (Wurtsbaugh et al., 2012). Roney (2009) also reported on the exclusion of specific cyanobacteria species as a result of salinity.

As a point of clarification, the generally accepted definition of the term "algal bloom" indicates the emergence of a particular algal group that represents >50% of the total algal population. Throughout this report the term "bloom" is used to reference the rapid appearance of a particular algal group, and of a magnitude approaching or exceeding 50% of all represented algae. Among the algal groups that were documented during this study only the cyanobacteria and diatoms demonstrated "large algal blooms" that resulted in dominance of a particular group of more than 50%. Hence these two taxa are the predominant algal groups in Farmington Bay during the course of our study. Chlorophytes never achieved this degree of dominance, but they did show a pattern of pronounced resurgence once grazing pressure was diminished in July through September.

In the early spring the bay supports the growth and development of edible and desirable algal groups for zooplankton grazers. Among these are the diatoms and chlorophytes. Other algal groups such as the cryptophytes, chrysophytes, pyrrhophytes, and flagellates that periodically make notable appearances in the bay, albeit at far lower abundance, than the three main algal groups: cyanophytes, bacillariophytes, and chlorophytes. Close scrutiny of the dynamics of each of the algal groups provides some insight into the relationship between nutrients, algae and zooplankton grazers and the patterns of abundance. There is evidence that grazing pressure coupled with nutrient availability, salinity, and temperature all interact to select patterns of algal dominance. Tanner et al. (1999) found *Artemia* to selectively graze chlorophytes and diatoms in preference to cyanobacteria. The conditions that favor cyanobacteria are readily available phosphorous, nitrogen limitation, salinity below 6%, water temperature over 20C, and a reduction in grazing pressure by zooplankton. In a separate experiment, Wurtsbaugh and Marcarelli (2004) did controlled studies of nitrogen-fixing bacteria growth under differing conditions of nutrients and salinity. They found that growth of nitrogen-fixing algae occurs below 7% salinity. Our field research does not provide a definitive range of factors that favor the presence of diatoms or green algae over the nitrogen fixing algae, but some general observations are that nitrogen availability (and in particular the bioavailable forms of nitrate or nitrite and ammonia), salinity of 6%or greater, and reductions in grazing pressure, lend some support to the growth of these algal divisions. Additionally, reductions in the shading effects caused by the extensive cyanobacteria blooms—an event which happens when the blue-green algae "scums" settle to the bottom of the bay—also confer some advantage to other algal groups.

The sheer magnitude and persistence of the *Nodularia* bloom that occurred in late May and extended into late fall, and the subsequent *Pseudanabaena* bloom in August-September, are indicative of a trophic barrier to the transfer of nutrients and carbon through the food web (Ger, Hansson and Lurling, 2014). In this capacity it represents a significant "bottleneck" to the potential capability of Farmington Bay to transfer nutrients and energy up trophic levels and to support the growth and development of higher level grazers and predators. It is therefore a stark limiting factor to the potential secondary and tertiary productivity of the bay.

Farmington Bay is quite different from Gilbert Bay and the wetlands that border the eastern, northern and southern margins of the GSL. In this study of the phytoplankton flora of GSL wetlands Rushforth and Rushforth (2004) found the order of importance was pinnate diatoms>centric diatoms>chlorophytes>cyanophytes. In their study of ten different wetlands these authors attributed 83% of the summed index of importance to diatoms. It is noteworthy when making comparisons among regions of the bay to include temporal effects; in the Rushforth study the wetlands were only sampled in October and November—months in which the cyanobacteria were already in their decline in Farmington Bay. In our study clearly the dominance pattern differed from the surrounding wetlands and was cyanophytes>diatoms>chlorophytes.

Algal assemblages differ in very profound ways in Farmington Bay compared to the other bays of the GSL. For example, during 1972 and 1973 Stephens and Gillespie found that the algal flora of Gilbert Bay was essentially limited to just two species: *Dunaliella viridis* and an unidentified green algae. In a 1998 paper Stephens reports only 6 species of algae in Gunnison Bay and 15 species of algae in Gilbert Bay. This low level of diversity in Gilbert Bay during times of high salinity reveals one of the very important aspects of Farmington Bay—its diversity and the role that said diversity of algae and zooplankton serve in terms of beneficial uses. A broad variety of conditions that supports an array of zooplankton in turn provides much greater diversity of prey choices for the tens-of-thousands of waterbirds and shorebirds that utilize Farmington Bay and its surrounding environs.

Chlorophyll-a levels reached exceedingly high values at various times and locations during this study. The mean chlorophyll for the entire study was114.6 ug/L and the highest value recorded was 506.0 ug/L. This is quite similar to previous studies in which the mean chlorophyll level from 2002 to 2009 was 141 ug/L (Wurtsbaugh et al., 2012). Throughout our study the chlorophyll levels were above the generally accepted value for hypereutrophic conditions of 56 ug/L (Carlson and Simpson, 1996). An exception to this occurred at sites 7 and 8 where peak values were 45.4 and 32.7 ug/L respectively. The mean values at these locations were: 29.8 and 32.4 ug/L. These are well below the mean values for sites 1-6 that had mean values of 131 to 291 ug/L and maximum values that were between 373.8 and 506.0 ug/L. These are extremely high values for chlorophyll and are associated with robust primary production and in particular cyanobacteria blooms.

Cyanotoxins

Cyanotoxins are a huge concern in association with cyanobacteria blooms. The presence of cyanotoxins is well known to accompany blue-green algae blooms; for example, Antoniou, de la Cruz and Dionysiou (2005) state that up to 50% of all recorded cyanobacteria blooms contain cyanotoxins. Cyanotoxins are known to harm resident biota, contaminate ground water, and can be toxic to humans via dermal or ingestion exposure (Funari and Testai, 2008). The two main modes of toxicity of cyanotoxins are either via neurological or hepatic disruption. In our study, the hepatotoxin nodularin was observed in substantial concentrations when *Nodularia* abundance exceeded 10,000 cells per ml. We also analyzed for the neurotoxin Anatoxin-a, but did not record elevated levels. Nodularin, on the other hand, was first observed in May and later reached a maximum value of 88.0 ug/L in early June. Over the entire study the mean concentration was 13.4 ug/L and according to the distribution of blue-green algae across the bay nodularin was highest in the mid to northern regions of the bay and quite low among the southern sites. Nodularin continued to be found in water samples until November. Concentrations recorded during 2013 were lower than some of the previous reported values. In 2009 Wurtsbaugh et al. documented a bay-wide average of 41 ug/L and they report an astonishing, and questionable, value of 600 ug/L at one site. Over a 3 year period (including 2006, 2007 and 2009), and for the time period May to August, they reported mean values of 20, 24, and 104 ug/L respectively. In contrast to our threshold model for nodularin these authors documented a linear relationship between microcystins and *Nodularia*. It should be noted that an investigation by Goel (2007) did not arrive at the same conclusions regarding cyanotoxins in Farmington Bay as were reported by Wurtsbaugh et al. While direct impacts of nodularin on the biota of Farmington Bay was not evident from our field study, controlled laboratory studies of nodularin impacts on the zooplankton that utilize Farmington Bay should be undertaken.

The presence of cyanotoxins in the water of Farmington Bay raises some concerns with regard to direct harm to the biota as a result of exposure to the toxins. Various studies have demonstrated adverse impacts on zooplankton such as *Artemia* as a result of cyanotoxin exposure (Lee, Chen, and Chen 1999; Kiviranta et al., 1991). In the study by Kiviranta eta al., (1999), exposure of *Artemia* to 29 toxic bloom samples, they found that only 4 out of the 29 were nontoxic to *Artemia*. In an investigation of detoxication mechanisms of *Artemia* Beattie et al. (2003) found that *Artemia* have phase II conjugation enzyme systems (i.e., glutathione S-transferase) that afford the *Artemia* some limited capacity to withstand nodularin exposure. Although Anatoxin-a was not found in substantial concentrations in our study, it is a neurotoxin of potential concern. It is produced by Anabaena flos-aquae strain NRC 525-17 and has a LD50 of a mere 20-50 ug/kg body weight in mice; and at this level of toxicity is included in the class of potent toxins (Patocka, Gupta and Kuca, 2011). It exerts its toxic potential via the inhibition of cholinesterase which includes it alongside some of the well known neurotoxins, such as Sarin gas, used in chemical warfare. However, Anatoxin-a apparently does not cross the blood-brain barrier and is unable to disrupt central nervous system neurons. It causes its harm to the individual through impairment in peripheral nervous system tissues and neuromuscular junctions. Because of its extreme toxicity it is prudent to continue to monitor Farmington Bay for elevated levels of Anatoxin-a. As described above, we could not find any significant relationship between Nodularia densities and changes in the zooplankton community. However, this is the first study that provides sufficient frequency and ecological detail that can address the potential for this linkage. Additional monitoring and research should be conducted to elucidate the potential for toxicity due to cyanobacteria blooms in Farmington Bay.

Dissolved oxygen and Salinity

Depletion of oxygen is one of the concerns often expressed with regard to eutrophication of water bodies. In our study all mean daily values for the bay were above 2 mg/L. There were isolated cases of hypoxia or anoxia in which the oxygen levels dropped below 1 mg/L. Because all of our measurements of dissolved oxygen took place during the day the perception of impairment is lessened and anoxic events could have taken place during the night but were unrecorded. When comparing zooplankton abundance with oxygen levels during the day there is no clear evidence of harm to the biota. Yet, declines in oxygen during the night remains a concern though, especially when one considers the observations of Wurtsbaugh et al. (2012) who found that oxygen levels in the daytime could reach as high as 40 mg/L but would decline to 0 ug/L at night. In our study oxygen levels peaked at 17.3 mg/L while the lowest values were between 0.09 to 0.39 mg/L. The lowest levels coincided with the development and collapse of cyanobacteria blooms in May through July.

Observations of the abiotic factors of Farmington Bay included a well defined spatial salinity gradient extending from the northern end of the bay near the Antelope Island causeway to the southern regions of the bay near the various hunting club preserves and the recently exposed former lake bed. Salinity in the northern region of the bay near sites 1-3 was typically in the range of 1% to 6%. Sites 4, 5, and 6 exhibited some influence of salt influx from Gilbert Bay and showed salinity in the range of 0.5% to 3%. Sites 6, 7 and 8 were essentially fresh water sites. These salinity levels are consistent with previous investigations that also documented consistent north-south gradient across the bay (Wurtsbaugh and Marcarelli 2004; Wurtsbaugh et al., 2012). Salinity has a strong influence on the diversity of biota found in a given water body and as salinity increases diversity decreases. Williams (1998) found that although salinity is an important factor in the structure of biological communities it is less influential as a determinant of community structure that is often thought, yet Williams does support the observation that increasing salinity coincides with a decrease in species richness. Salinity becomes a major influence at high levels but at lower levels the various salinity tolerances of zooplankton and phytoplankton and the predator/prey relationships that emerge serve a similarly important role in determining the overall biotic structure. In Farmington Bay perhaps the most relevant expression of salinity tolerance is that held by cyanobacteria; and it appears that it has an upper limit of 6% to 7%. In the combined salinity and nutrient enrichment experiments conducted by Marcarelli, Wurtsbaugh, and Griset (2006) these investigators found that when the salinity was 70g/L nitrogen fixation ceased. Under such conditions nitrogen can become limited rather than phosphorous. In their policy forum paper Conley et al., (2009) commented that significant planktonic nitrogen fixation is not observed at salinities in excess of 8% even in circumstances of severe nitrogen limitation. These experiments illustrate that when considering nutrient effects on a waterbody salinity must also be taken into account as a controlling factor.

This awareness of the upper threshold of cyanobacteria can potentially be used as an effective tool to restrain the magnitude of cyanobacteria blooms in Farmington Bay rather than focusing on reductions in nutrient input as the sole remedy for reducing harmful algal blooms. In fact, engineering solutions that enhance the exchange of water between Gilbert Bay and Farmington Bay may be a more ecologically prudent approach to reducing cyanobacteria blooms in the bay. It would serve a dual function of reducing cyanobacteria blooms but also increasing the movement of nutrients into Gilbert Bay, thereby providing for enhanced growth in the resident algal population and as a beneficial consequence it could support a larger and more productive *Artemia* population. Wurtsbaugh et al. (2012) expressed concern about the impact that the Antelope Island causeway has had on Farmington Bay and they supported the idea that greater exchange between Farmington Bay and Gilbert Bay would have multiple beneficial outcomes. They state that the causeway has increased residence time in the bay thereby capturing and containing the high nutrient loads and preventing them from entering Gilbert Bay. The reduced exchange between bays has clearly lowered the salinity in Farmington Bay into a range that favors cyanobacteria blooms. The additional benefit of improving the exchange between the bays would be increased primary productivity in Gilbert Bay and as a result would be greater production of foraging items for birds, hence an improvement in the beneficial uses of the lake. It is worth noting that Herbst (2006) found that evaporation ponds of intermediate salinity (112 g/L) produced the best combination of zooplankton diversity and nutritional quality in terms of foraging opportunities for shorebirds. He observed greater usage of these ponds by birds and found that the lower salinity (98 g/L) and higher salinity ponds (173 g/L) were suboptimal in terms of food quality and quantity for birds. The undesirable excessive predation by corixids on zooplankton could also be mitigated by increases in salinity (Van De Neutter, Trekels, Green and Stoks, 2010). It is worth noting however, that Miller, Hoven and Cavitt (2009) found corixids to be a dominant prey item in shorebirds feeding in Farmington Bay and other GSL wetlands. This generally points out the opportunistic nature of shorebird feeding behavior. Nevertheless, general increases in salinity will be favorable in that such feeding is restricted to the shoreline of the bay, allowing greater zooplankton abundance and diversity in deeper pelagic portions of the bay. Similarly, greater salinity would generally be restricted to open water regions because of the innumerable tributary flows (emitting from impoundments, drains, POTW discharges and streams) and natural springs, maintaining substantial brackish to freshwater zones that would remain optimal to corixid and midge production. This concept of addressing the problem of cyanobacteria blooms in Farmington Bay via increased salinity has been given some thought in earlier studies but warrants more serious consideration as a prudent approach to solve the ecological concerns in Farmington Bay.

Nutrients: sources, gradients, and evidence of limitation.

The nutrients that were thoroughly documented during the study included various molecular forms of nitrogen (N) and phosphorous (P). Other nutrients or essential elements were not evaluated. The results show evidence of site-specific loading of nutrients into Farmington Bay. The primary source location is the Northwest Oil Drain that transports the Salt Lake City POTW effluent to a discharge point located near sample site #7. Both phosphorous and nitrogen were elevated in this area well above most other sites. All assessments of nutrients varied temporally and spatially across the bay. TN:TP ratios were low (overall mean value was 9.25) and were consistent with ratios expected from eutrophic systems and are indicative of N limitation rather than P limitation. The ratio was, however, higher than the values provided in the Wurtsbaugh et al. (2012) paper in which they found that all bays of the GSL had TN:TP ratios of 25 or higher—indicating that in all bays of the GSL nitrogen would be adequate while phosphorous would in fact be the limiting nutrient. This observation is counter to almost all systematic studies of nutrient limitation in the GSL, including Wurtsbaugh's own studies, in which nitrogen is shown to be the rate limiting nutrient and P is in abundance.

The TN:TP ratio in our study finally increased over 16:1 in November (20.73) when algae growth had slowed substantially due to low angle incidence of the sun and colder temperatures. There was also a notable increase in the ratio of TN:TP in early June that continued to be maintained until fall. This increase likely resulted from nitrogen fixing capacities of cyanobacteria blooms that began in May but that reached their peak in June and July. The TN:TP ratio generally followed a south to north gradient with the lowest ratio usually found along the southern margin of the bay and increasing ratios as the samples were progressively collected from a northerly direction. An explanation for this observation is multi-faceted but essentially involves substantial inputs of nitrogen and phosphorous from the Northwest Oil Drain outlet near sites 7 & 8 followed by rapid uptake of bioavailable forms of N (nitrate, nitrite, and ammonia) and P (SRP) by algae and "downstream" of this nitrogen uptake and depletion cyanobacteria gain a competitive advantage and grow in earnest—increasing the TN:TP ratio and contributing nitrogen to the system.

The bioavailable forms of P and N were readily assimilated at points close to the source canal. The lack of cyanobacteria growth relative to other forms of algae in close proximity to site #7 supports the hypothesis that nitrogen availability diminishes the competitive advantage of cyanobacteria over other nitrogen dependent species. The TN:TP ratio then increases in a consistent manner with the production and distribution of cyanobacteria in the bay; grouping sites by region (7-8; 6-4; and 3-1) gives the following average ratios: 4.4; 8.12; and 10.0 respectively. The explanation for the spatial pattern (cyanobacteria production reflects nitrogen fixation and the generation of nitrogen for biological growth) is supported by the temporal pattern in which there are increases in TN over time and consistent with cyanobacteria growth.

The mean concentration of bioavailable forms of N and P near site #7 were higher than other sites by almost an order of magnitude: SRP at sites #7 and #8 had an average of 0.98 to 1.29 to mg/L and a maximum value of 1.64 to 2.61 mg/L. In contrast the other sites had mean values between 0.02 to 0.14 mg/L and maximum values of 0.04 to 1.14 mg/L. Similarly ammonia near site #7 had a mean value of 3.95 while all other sites were between 0.22 to 0.54 mg/L. Nitrate and nitrite also showed the same type of pattern: the mean value at site #7 was 3.77 compared to a range of 0.03 to 0.28 mg/L. Consistently this was the case near site #7. Based on these results it is quite evident that this source is one the major contributors to nutrient input into Farmington Bay. It should also be pointed out that two additional POTWs discharge to Farmington Bay, the Central Davis and North Davis Sewer Districts' discharges. However, under such low lake elevations (as during the last several years), the Central Davis discharge evaporates before it reaches the open water of the bay. The North Davis discharge occurs approximately 500 meters from the Antelope Island causeway. While it is a substantial flow (approximately 30 cfs), our sampling, even at site 1, did not identify any chemical, nutrient or biological differences that could be associated with this discharge. It likely flows parallel to the causeway until it reaches the breach where it is immediately discharged to Gilbert Bay.

There is a wealth of information in the scientific literature evaluating the roles of N and P in eutrophication of water bodies. Classic long term, lake-scale, studies done by Schindler et al., (2008) found that P was the dominant nutrient controlling eutrophication in lakes. This, and other studies, ushered in the "Phosphorous Paradigm" in which it was recognized that implementation of P controls could effectively reduce deleterious impacts of eutrophication on fresh water lakes and streams. Success stories, such as was encountered in Lake Washington, following P controls bolstered the awareness of the value of P controls for improving water quality of lakes and streams. However, there has also been much debate about the applicability of this approach to other water bodies, especially marine or estuary systems (Smith and Schindler, 2009; Genkai-Kato and Carpenter, 2005; Lewis and Wurtsbaugh, 2008; Sondergaard, Jensen and Jeppesen, 2003; Sondergaard, Jensen and Jeppesen, 2001; Schindler et al., 2008; Sterner, 2008; Lewis, Wurtsbaugh and Paerl, 2011). A synthesis of the minutiae of all of these investigations is beyond the scope of this paper, but a distillation of ideas and observations suggests that in Farmington Bay initial reductions in P coupled with unchanged N inputs may reduce the dominance advantage of cyanobacteria over other algal species. However, one should recognize that changes in either N or P or the combination of them causes a shift in the pattern or status of limitation and may also introduce unintended consequences. Furthermore, it is known from a variety of studies (Sondergaard, Jensen and Jeppesen, 2003) that years of nutrient loading into lakes, internal cycling of nutrients, and other biogeochemical processes can continue to supply biota with nutrients for years even with dramatic reductions in loading of nutrients. The processes of remineralization, nitrogen fixation or denitrification all contribute to either depletion or liberation of nutrients for assimilation into biological systems.

Field observations can only provide a glimpse into the relative limitation, or co-limitation, of nutrients in the bay. It is absolutely necessary to conduct laboratory and mesocosm studies of algal responses to enrichment in order to understand the spectrum of likely outcomes of either P or N or N&P limitation on the ecological processes in Farmington Bay. Other essential considerations of proposed reductions in nutrient input into Farmington Bay must take into account the possible implications on other bays of the GSL and their resident biota. Nutrient dynamics and goals of ecological conditions in the bay need to accurately understand the broader implications of changes in nutrient input and connectivity between bays. It is possible that dramatic reductions in nutrient input into Farmington Bay could result in diminished primary and secondary productivity of Gilbert and Gunnison Bays. An unintended consequence of this could be reduced food available for of avian predators that rely upon sizeable zooplankton populations. Such a change would violate the primary beneficial use of bays of the GSL.

Eutrophication of Farmington Bay is undeniably of concern, but changes in nutrient input into the bay must take into account a wide array of potential consequences and need to be based on rigorous science that couples field observations with carefully designed and executed laboratory studies that can simulate the variety of possible outcomes from changing nutrient input into the bay. Management of the bay needs to be an iterative, systematic process that judiciously takes into account both short and long term goals and outcomes and that understands the interconnectivity of Farmington Bay with the rest of the GSL.

SOME INITIAL RECOMMENDATIONS FOR FURTHER RESEARCH ON FARMINGTON BAY

Nutrient Enrichment Studies

- Conduct both laboratory and mesocosm experiments. Laboratory studies have the advantage of being able to control many of the variables.
- Mesocosms have perhaps more practical applied relevancy, but they are prone to disruption by the vicissitudes of the weather or demonic interventions.
- Conduct experiments on both Farmington Bay and Gilbert Bay water sources collected at various times of the year.
- Add N, P, N&P
- Combine salinity modifications and nutrient enrichment tests

Toxicity Testing of Cyanotoxins on Relevant Zooplankton from Farmington Bay

- Test the impacts of nodularin on *Daphnia* and *Artemia* collected from Farmington Bay
- Test nodularin on other cladocerans, rotifers, or copepods
- When using *Artemia* do hatching, growth, development and survival tests

Nutrient Balance Study

- Conduct detailed studies of the input sources and then fate and effects of nutrients that enter Farmington Bay.
- Devote particular attention to the role that the Salt Lake City POTW drain imposes on Farmington Bay

Economic Feasibility Study of Enhanced Exchange Between Farmington Bay and Gilbert Bay

- Conduct a feasibility study to determine the costs and potential benefits associated with increasing the exchange between Gilbert Bay and Farmington Bay.

Ecological Studies of Farmington Bay

- Continue with monthly or bi-monthly investigations of the biota and abiotic characteristics of Farmington Bay (essentially continue the baseline ecological work that has already been underway for two years)
- Increase monitoring intensity of waterfowl and shorebirds that use Farmington for resting and feeding. The use of drone-mounted cameras is a potential cost effective technique that should be tested.

Corixid Top-Down (Predation Effects) Food Web Study

This research would employ novel techniques in DNA genetic barcoding. Genetic barcoding is essentially a process of specifically identifying, usually to the genera or species level, the DNA of collected biological samples. One of the distinct advantages of DNA barcoding is the ability to derive very specific and precise information on the organism from which DNA in the analyzed sample originates. This can be used to ascertain the dietary choices of predatory invertebrates and their prey, as well as the food choices of filter feeding phytoplanktivorous zooplankton. In essence it can be used to track the trophic transfer of DNA and the associated biological molecules through the food web.

The goal of future work using DNA barcoding should include, but not be limited to:

1. Put together phytoplankton and zooplankton taxonomy list from data file
    See if their DNA barcodes are ready to be downloaded
    Determine which taxonomic level of specificity is available (e.g., genera or species)

2. Collect corixid sample weekly or biweekly at several sites throughout 2015
    20 individuals at each instar/size class: combine individuals
    Group according to age-class (immature or adult) or size classification within age categories .

3. Use DNA genetics/barcoding to identify the taxonomy and relative abundance of each taxonomic fraction.

4. Verify with several samples collected in the same location; genetics vs. taxonomy

5. Collect water samples and perform DNA barcoding; compare with corixid diets and see if there is evidence of selective food preferences and/or ontogenetic shifts.

Dynamic Food Web Models

Verify our simple SEM model and other results from this report and then refine and build more complex, stochastic models using well known, highly regarded, and modifiable food web modeling programs such as EcoPath/EcoSim/EcoSpace (or similar models) and improved SEMs. EcoPath may provide us with a static, mass-balanced snapshot of the system; EcoSim is a time dynamic simulation module that can be used for policy and management exploration and decision making; and EcoSpace is a spatial and temporal dynamic module (http://www.ecopath.org).

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APPENDICES

Appendix 1. Log generalized transformations

A log transformation is often useful when there is a high degree of variation within attributes or when there is a high degree of variation among attributes within a sample. **Log generalized transformation** is best if the data contain zeros and the smallest positive value is not close to 1 (for example, smallest x = 0.02 or smallest x = 200). The formula for the generalized log transform is:

$$b = \log(x+xmin) - \log(xmin)$$

where xmin is the smallest positive value in the data set or individual variable. If data are count data with the smallest positive value = 1, the results will be the same as choosing log(x + 1).

Appendix 2. Pearson(r and r-sq) and Kendall (tau) correlations with ordination axes (N= 68 samples)

Taxon	r	r-sq	tau	r	r-sq	tau	r	r-sq	tau
Bracplic	0.509	0.259	0.296	0.029	0.001	0.057	-0.452	0.204	-0.303
Daphdent	0.443	0.197	0.407	-0.116	0.013	-0.135	0.251	0.063	0.236
Moinmacr	0.71	0.504	0.517	0.085	0.007	0.039	0.14	0.02	0.118
Artefran	0.192	0.037	0.063	-0.842	0.709	-0.686	0.074	0.005	0.042
Leptconn	0.651	0.424	0.489	-0.165	0.027	-0.147	0.296	0.088	0.245
Cletocam	0.471	0.222	0.332	-0.184	0.034	-0.178	0.642	0.412	0.477
Eucyagil	0.416	0.173	0.369	0.436	0.19	0.32	-0.37	0.137	-0.228
Tricvert	-0.827	0.683	-0.673	0.333	0.111	0.266	0.162	0.026	0.105
Chironom	-0.053	0.003	-0.086	0.285	0.081	0.25	0.342	0.117	0.28
Salinity	0.497	0.247	0.434	0.497	0.247	0.321	0.218	0.048	0.123

Appendix 3. NMS axes coordinates by sample

FB1-4/18	-0.146	-0.53022	0.71926
FB2-4/18	-0.72668	-0.43778	0.60937
FB3-4/18	-0.68501	0.41247	0.64775
FB4-4/18	-0.75984	0.42298	0.61336
FB5-4/18	-0.94568	0.31227	0.45477
FB6-4/18	-0.93595	0.2987	0.47083
FB7-4/18	-0.5133	-0.13246	0.82405
FB8-4/18	-0.85625	0.38692	0.87259
FB9-4/18	0.57943	-1.60852	0.27648
FB1-5/13	-0.51213	-0.30298	-0.33241
FB2-5/13	-0.48425	-0.59592	-0.50856
FB3-5/13	-0.58853	-0.31899	-0.4005
FB4-5/13	-0.57605	-0.33116	-0.35042
FB5-5/13	-0.62185	-0.17852	-0.34664
FB6-5/13	-0.59644	0.01113	-0.15085
FB7-5/13	-0.95222	0.58573	-0.28031
FB8-5/13	-0.8931	0.70073	-0.40724
FB9-5/13	-0.19656	-0.72476	-0.09723
FB1-5/30	-0.50555	-0.25355	-0.16197
FB2-5/30	-0.52046	-0.1941	-0.15308
FB3-5/30	-0.61151	-0.21344	-0.27774
FB4-5/30	-0.62672	-0.20114	-0.27111
FB5-5/30	-0.64759	-0.23529	-0.28529
FB6-5/30	-0.65163	-0.1289	-0.35154
FB7-5/30	-0.65626	-0.08384	-0.59654
FB8-5/30	-0.74578	-0.14328	-1.03342
FB1-6/10	-0.51859	-0.15822	-0.1952
FB4-6/10	-0.61898	-0.10646	-0.17334
FB7-6/10	-0.24084	0.83098	-0.52105
FB2-6/13	-0.55551	-0.1763	-0.14982
FB3-6/13	-0.32137	-0.03296	-0.15142
FB5-6/13	-0.00056	0.48533	0.08811
FB6-6/13	-0.10433	0.2999	-0.0488
FB9-6/13	-0.38938	-0.37128	-0.00822
FB1-6/25	-0.53809	-0.08516	0.00194
FB3-6/25	-0.51612	-0.11784	0.03217
FB5-6/25	-0.06799	0.10352	0.03895
FB7-6/25	0.47879	0.46553	-0.82794
FB9-6/25	-0.22376	-0.10621	-0.03254
FB1-7/11	0.17371	0.0318	-0.51847
FB3-7/11	0.06814	0.12241	-0.29032
FB5-7/11	0.15427	0.15701	-0.45483
FB9-7/11	0.56438	-0.52546	-0.28758
FB1-7/22	1.06057	-0.20967	-0.19936

FB3-7/22	0.86391	-0.0826	-0.45717
FB5-7/22	1.20088	0.36943	-0.4435
FB9-7/22	1.06556	-0.61979	0.00385
FB1-8/6	1.16644	-0.33562	-0.01711
FB3-8/6	1.72989	0.40525	-0.11238
FB5-8/6	1.73015	0.40441	-0.11003
FB7-8/6	-1.34975	1.23313	0.44482
FB9-8/6	1.16531	-0.56879	0.09957
FB1-8/26	1.72996	0.405	-0.11193
FB3-8/26	1.72968	0.4064	-0.11042
FB5-8/26	0.41571	0.72984	-0.58334
FB9-8/26	1.17987	-0.53197	0.08167
FB1-9/19	0.70162	0.12095	0.21656
FB3-9/19	0.98098	0.43844	0.62966
FB5-9/19	1.08188	0.44902	0.45084
FB9-9/19	1.00721	0.42172	0.59602
FB1-1017	0.07806	-0.05076	0.56658
FB3-1017	-0.0177	0.16874	0.03996
FB5-1017	-0.15669	0.62792	0.49768
FB9-1017	0.27716	-0.85119	0.84377
FB1-1114	0.11578	0.25526	0.31693
FB3-1114	0.6927	0.60037	0.48749
FB5-1114	-0.34387	-0.33106	0.3058
FB9-1114	-0.07318	-0.78711	0.57879

Appendix 4. NMS axes coordinates by taxon

	Axis 1	Axis 2	Axis 3
Bracplic	-0.28972	0.00336	0.13699
Daphdent	-0.63918	-0.10074	-0.20446
Moinmacr	-0.48744	0.04114	-0.05384
Artefran	-0.11694	-0.31063	-0.04447
Leptconn	-0.46323	-0.0603	-0.12573
Cletocam	-0.32093	-0.05677	-0.25029
Eucyagil	-0.63153	0.36361	0.33346
Tricvert	0.70842	0.17767	-0.06463
Chironom	0.1953	0.6681	-0.65211

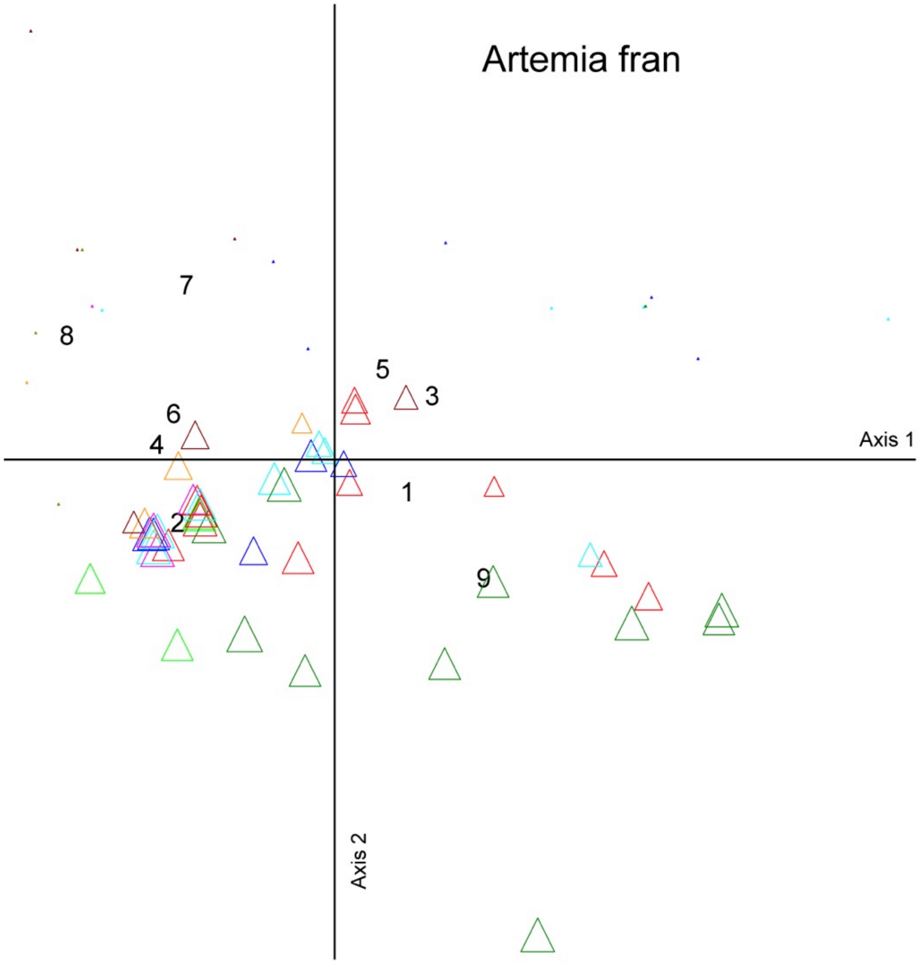
Appendix 5. MRPP results

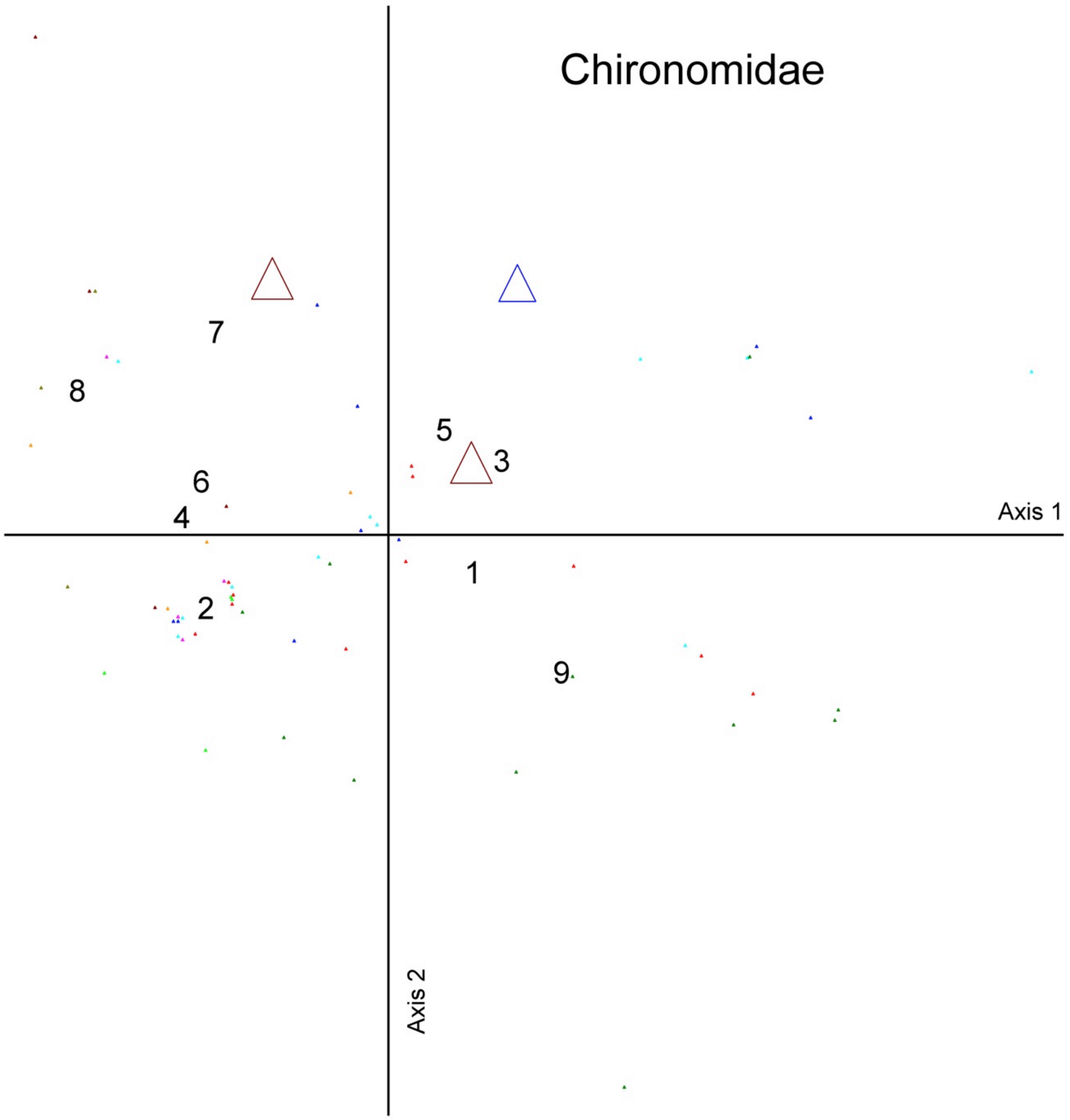
MRPP by Site

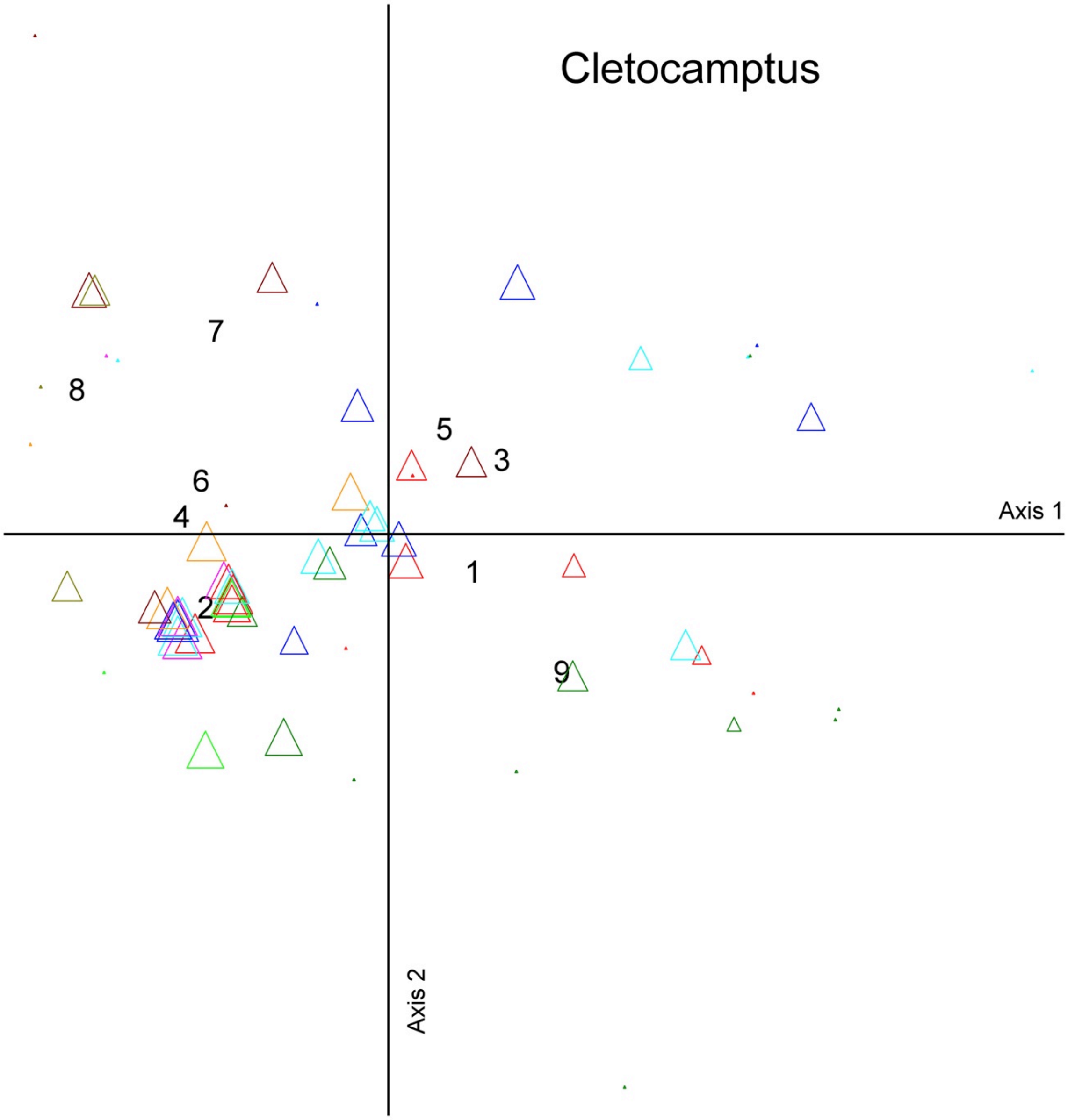
Test statistic: T = -5.0982280
Observed delta = 0.50222494
Expected delta = 0.57017162
Variance of delta = 0.17762249E-03

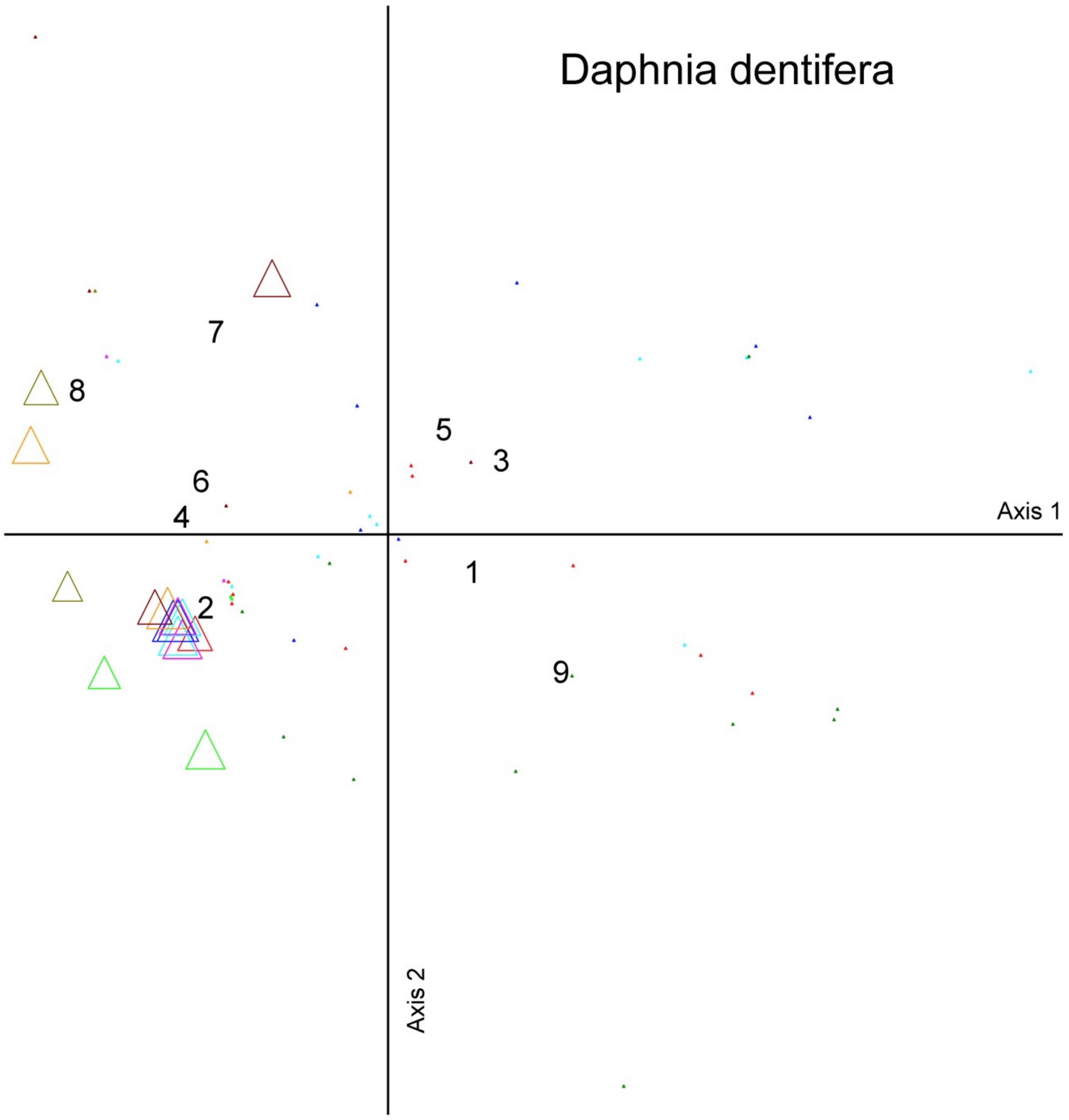
```
    Skewness of delta =    -0.52854208

    Chance-corrected within-group agreement, A =   0.11916882
     A = 1 - (observed delta/expected delta)
     Amax = 1 when all items are identical within groups (delta=0)
     A = 0 when heterogeneity within groups equals expectation by chance
     A < 0 with more heterogeneity within groups than expected by chance

    Probability of a smaller or equal delta, p =   0.00006092



MRPP by Date
  Test statistic: T =    -12.439390
       Observed delta =    0.36351597
       Expected delta =    0.57017162
    Variance of delta =    0.27599193E-03
    Skewness of delta =    -0.41672720

    Chance-corrected within-group agreement, A =   0.36244464
     A = 1 - (observed delta/expected delta)
     Amax = 1 when all items are identical within groups (delta=0)
     A = 0 when heterogeneity within groups equals expectation by chance
     A < 0 with more heterogeneity within groups than expected by chance

    Probability of a smaller or equal delta, p =   0.00000000
```

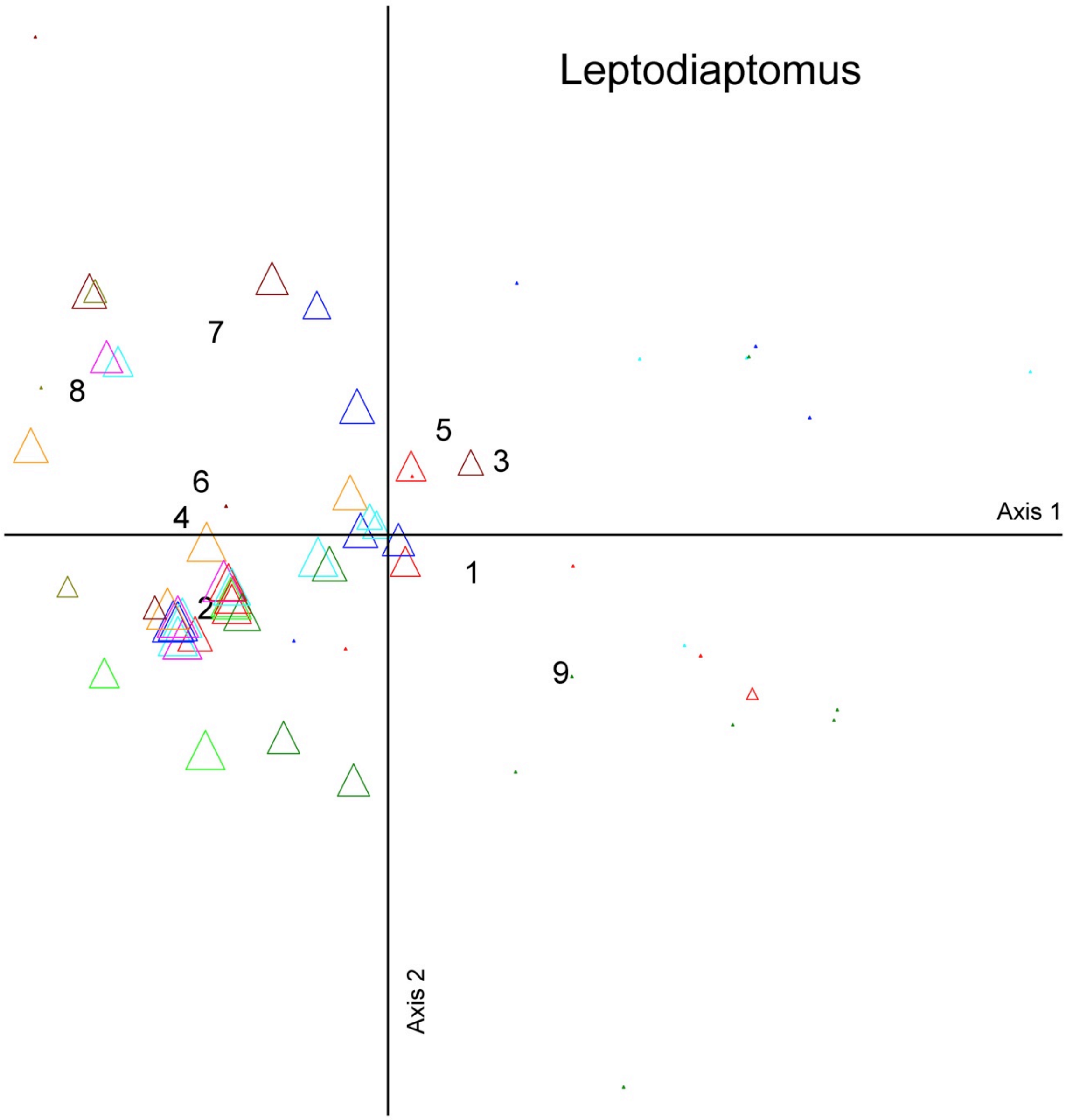
Appendix 6. Relative abundances of nine most common macroinvertebrate taxa used in NMS based on axis 1 and axis 2. Size of triangles equates to relative biomass (log generalized). Larger triangles equal greater biomass. Note: NMS axis 2 is reversed from NMS ordination figures 1 and 2.

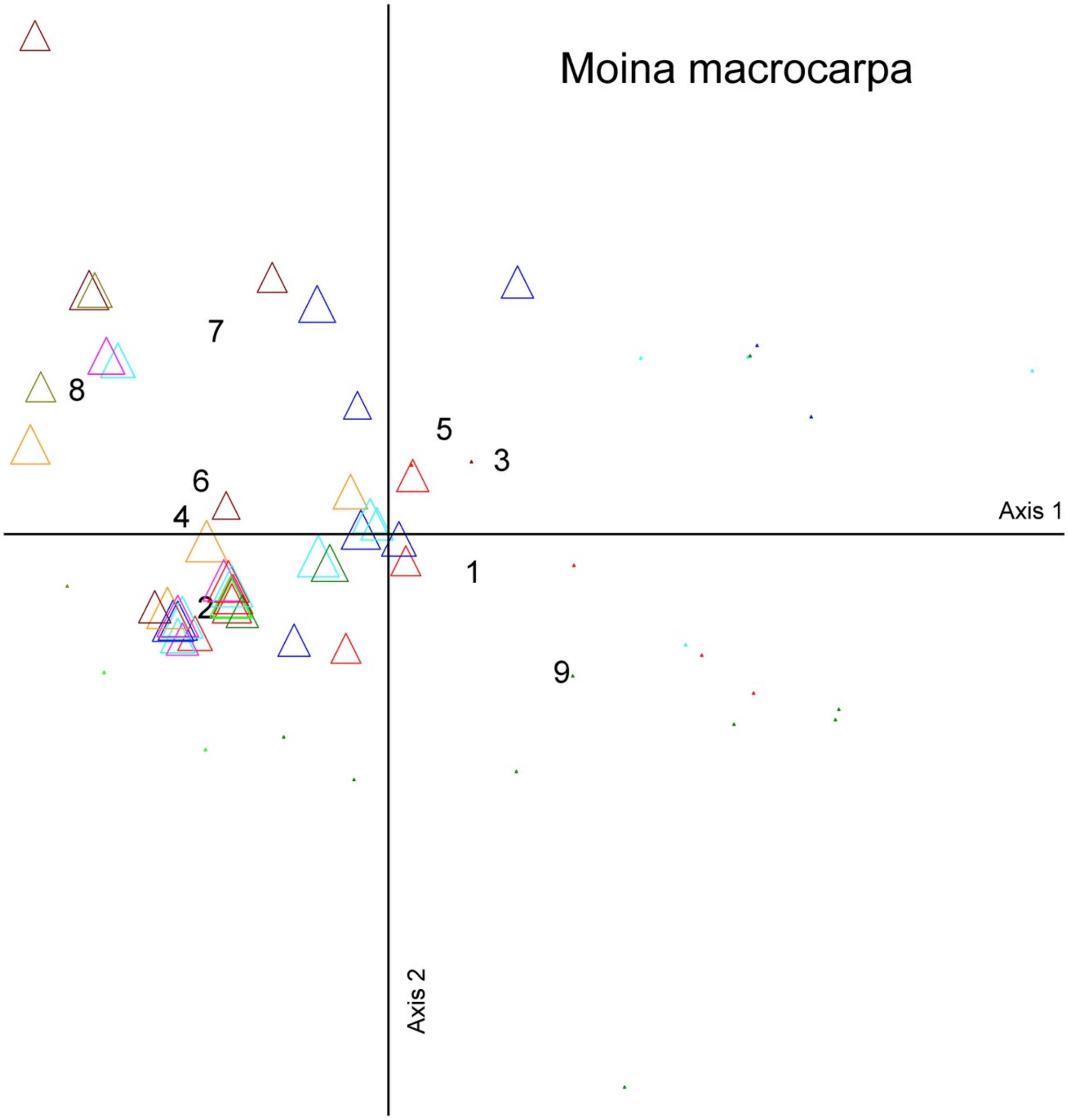


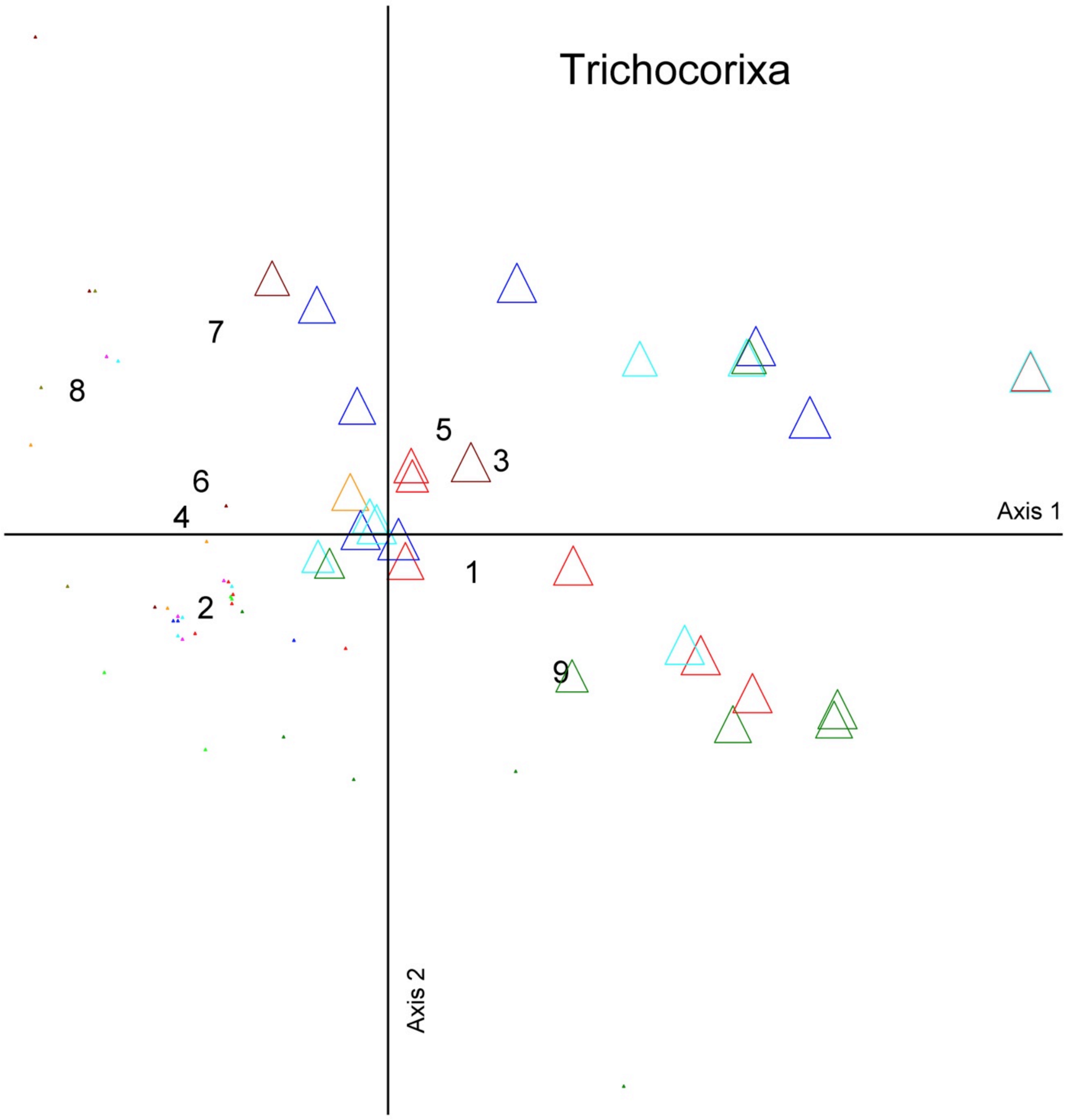

Chironomidae
7
8
5
3
6
4
Axis 1
1
2
9
Axis 2


Cletocamptus
Axis 1
Axis 2
1
2
3
4
5
6
7
8
9


Daphnia dentifera
Axis 1
Axis 2
1
2
3
4
5
6
7
8
9


Leptodiaptomus
Axis 1
Axis 2
1
2
3
4
5
6
7
8
9


Moina macrocarpa
Axis 1
Axis 2
1
2
3
4
5
6
7
8
9


Trichocorixa
Axis 1
Axis 2
1
2
3
4
5
6
7
8
9

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