Eutrophication and Metal Concentrations in Three Bays of the Great Salt Lake (USA)

2009 Final Report to the

Utah Division of Water Quality, Salt Lake City, Utah

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Ten-liter containers of water collected from the three bays of the Great in June, 2006, demonstrating the high algal abundance in Farmington Bay

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Units used in study

Metric		English Equivalent
Km	kilometer	0.62 miles
m	meter	0.305 feet
µm	micrometer (one millionth of a meter)	0.305 millionths of a foot
km^2	square kilometer	0.386 square miles; 247 acres
L	liter	0.946 quarts
µg	microgram (one millionth of a gram)	15.43×10^{-6} grains
mg	milligram (one thousandth of a gram)	15.43×10^{-3} grains
°C	degree centigrade	°F = (°C + 32) * 9/5
μm^3	cubic micrometers	–

Eutrophication and Metal Concentrations in Three Bays of the Great Salt Lake (USA)

Executive Summary

The Great Salt Lake, which lies close to several major population centers in the State of Utah, has received heavy loading of various contaminants. In the past the potential impacts of these contaminants have commanded little attention, but during the last decade increasing concern has been raised about their influence over the beneficial uses of the State's largest lake. Nutrient loading, eutrophication, selenium and mercury are of particular concern, but the potential impact of other metals and contaminants is not known.

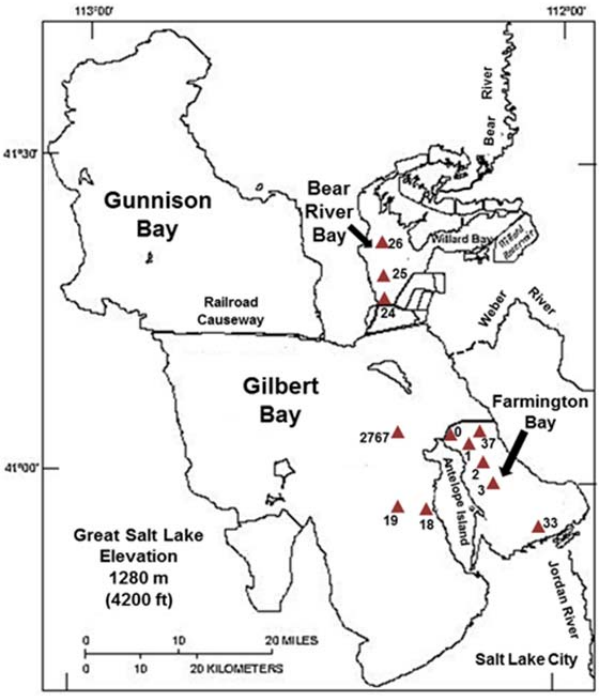

Fig. I. Map of the Great Salt Lake showing the sampling stations (Δ) used in 2009.

Causeway construction has divided the lake into four distinct bays: Farmington, Bear River, Gilbert, and Gunnison. Each bay has its own contaminant inputs, water quality, and salinities. Shallow Farmington Bay, which borders the State's major population centers, receives significant levels of nutrients and perhaps heavy metals from wastewater treatment plants and the Sewer Canal (NW Oil Drain). Approximately 50% of the water inflow to Farmington Bay is from municipal treatment plants that discharge secondary-treated wastes that are high in nutrients. Bear River Bay in the northeast is also very shallow. Moreover, it receives the largest inflow of freshwater and sediment loading. Both Farmington Bay and Bear River Bay have moderate salinities that provide habitat for waterfowl, shorebirds, and other avian species. Consequently, potential contaminant pollution in these areas is vitally important. Since Bear River Bay receives less metal and nutrient loading than Farmington Bay, it can serve as a reference site to compare against conditions in Farmington Bay. Hypersaline Gilbert Bay is the largest part of the lake and has received the most attention with regards to selenium and mercury research. High production of brine shrimp and brine flies in Gilbert Bay provides important food for many avian species, but there are concerns that the food web in the bay may facilitate biomagnification of metals and other contaminants. Finally, Gunnison Bay in the north has salinities near saturation. Consequently, it normally produces negligible amounts of invertebrate prey, and relatively few birds utilize it. It presently supports only very limited recreational use, but its waters are an important source for the mineral extraction industry.

Due to these growing concerns about the lake, we monitored plankton populations and water quality in Farmington, Bear River and Gilbert Bays during 2009 to provide information on metal and eutrophication parameters. Two or three stations in each bay were sampled at 2-3 week intervals from May-October, 2009. Additional information from previous years is also summarized in this report.

During 2009, surface water salinities in Gilbert Bay varied from 13-15%, and those in the northern end of Farmington Bay changed from approximately 1% in the spring, to 3% in the fall (seawater is 3.5%). Salinities in Bear River Bay were highly variable, ranging from freshwater during spring runoff, to 24% in mid-summer. The high mid-summer salinities were likely from discharges or seepage from the adjoining solar evaporation ponds. Farmington Bay and Gilbert Bay are salt-stratified (have deep brine layers) because of intrusions of higher-density salt water from adjoining bays. Bear River Bay also became salt stratified, likely because of contributions of high-salinity water from the solar evaporation ponds.

Measurements of eutrophication parameters indicated that Farmington Bay had extremely high concentrations of phytoplankton and was hypereutrophic, whereas Gilbert and Bear River Bays had only moderate phytoplankton biomass (measured as chlorophyll; **Fig. IIa**). Chlorophyll levels in Farmington Bay averaged 76 µg per liter in 2009, above the hypereutrophic contamination threshold of 56 µg per liter, whereas Bear River Bay and Gilbert Bay both had less than 15 µg per liter. Average water transparency (Secchi depth) was near 0.25 m (10 inches) in both Farmington and Bear River Bays, but was 2.4 m (8 feet) in Gilbert Bay (Fig. IIb). The phytoplankton biomass in Farmington Bay was high (97 μm^3/ml) and overwhelmingly dominated by very high densities of cyanobacteria (blue-green algae), particularly *Nodularia spumigena*. In contrast, respective phytoplankton biomasses in Bear River and Gilbert Bays were only 6% and 2% of those in Farmington Bay, and were dominated by diatoms, green algae, and chrysophytes. The cyanobacteria found in Gilbert Bay appeared to have been primarily washed in from Farmington Bay.

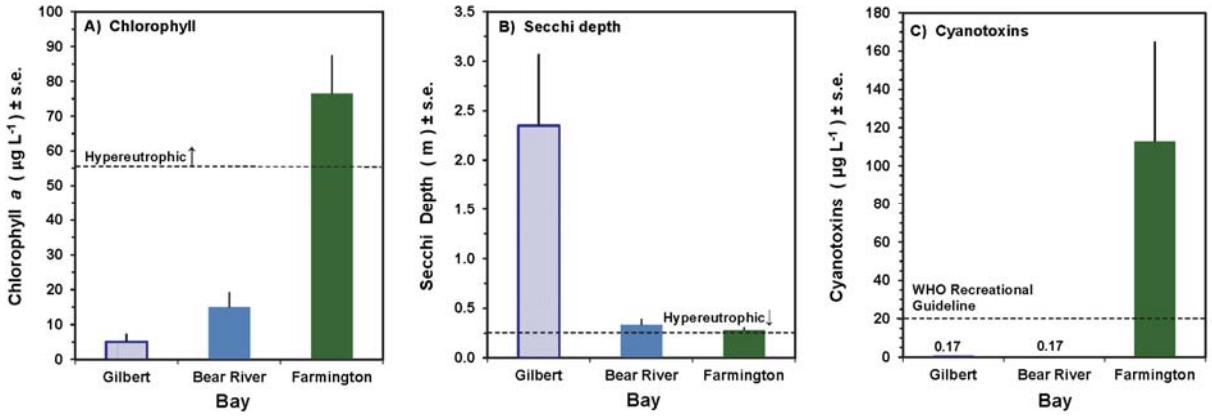

Fig. II. A. Mean chlorophyll *a* concentrations in three bays of the lake during 2009. Chlorophyll provides a good index of overall phytoplankton biomass. The dotted line shows the criteria for excessive algal abundance. **B.** Secchi disk transparencies. **C**. Cyanotoxin (as microcystin LR equivalents) in the three bays. The dotted line shows the World Health Organization's Recreational Guideline for contact recreation.

Cyanotoxin concentrations produced by cyanobacteria were negligible in Gilbert and Bear River Bays, but very high in Farmington Bay (**Fig. IIc**). Mean concentrations in Farmington Bay exceeded the World Health Organization's recommendation for contact recreation by 6-fold, and the highest concentrations exceeded the recommendation by over 20-fold. Cyanotoxin concentrations in Farmington Bay were well above those found to have caused bird mortalities in other systems.

Farmington Bay's high phyto-plankton production led to super-saturated oxygen concentrations during the day, but very low oxygen concentrations at night as a result of respiration and phytoplankton decomposition (**Fig. III**). Day-night temperature variations were also large. In Gilbert Bay, oxygen levels were near saturation and varied little over 24 hours. Additionally, the bottom waters of approximately 50% of the area of both Farmington and Gilbert Bays were devoid of oxygen, contained high concentrations of toxic hydrogen sulfide and consequently could not support aquatic invertebrate life. These "dead zones" (*sensu* Rabalais et al. 2002; Conroy et al. 2011) are due to the combined effect of the stable salt-stratification caused by diking, and the phytoplankton that fall into these lower layers and decompose.

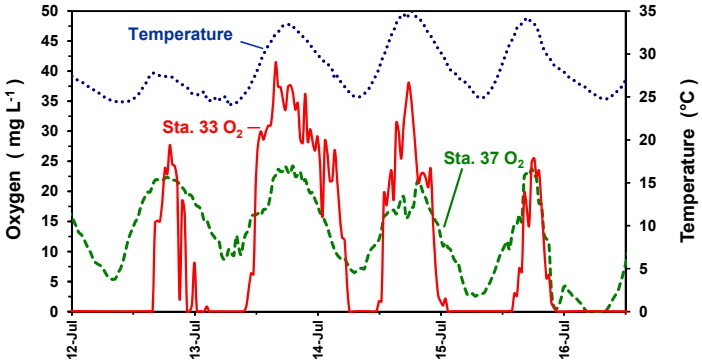

Fig. III. An example of the extreme day-night changes in oxygen and temperature in the shallow hypereutrophic waters of Farmington Bay measured with a recording sonde (July 2007).

An odor survey of citizens residing or working in close proximity to different parts of the Great Salt Lake was conducted that indicated that most objectionable odors originated in Farmington Bay. Of 505 responses obtained during the five-month survey, all odors rated as "strong" or "unbearable" were from locations near Farmington Bay, whereas the odors in locations associated with Bear River and Gilbert Bays were rated between "none" and "moderate".

Invertebrate biomass (zooplankton) in the water column was high in both Gilbert Bay and Farmington Bay, but low in Bear River Bay (**Fig. IV**). In Gilbert Bay the zooplankton was composed entirely of brine shrimp (*Artemia franciscana)*, whereas in Farmington Bay it was a mixture of small water fleas (cladocera), copepods, *Artemia* and predacious water boatmen (corixids). The zooplankton in Bear River Bay was dominated by corixids and had a low biomass. The low biomass there may be due to fish predation. The

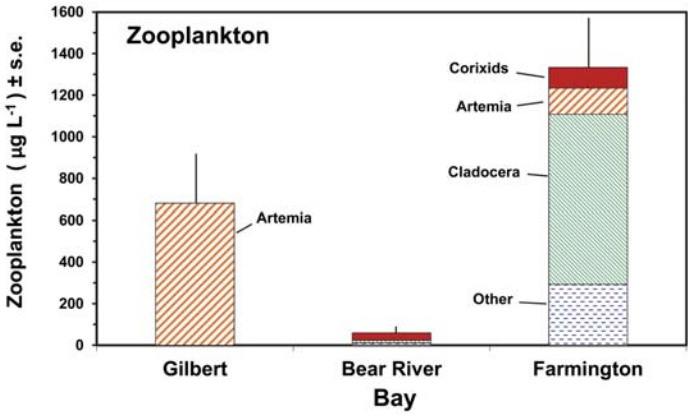

Fig. IV. Mean zooplankton biomasses in three bays of the Great Salt Lake from May-October 2009.

calculated grazing rates of zooplankton feeding on phytoplankton were very high in both Farmington and Gilbert Bays (87% and 43% of water grazed per day, respectively), and low in Bear River Bay (<1% per day). The high grazing rate by *Artemia* in Gilbert Bay explains its low phytoplankton biovolume and chlorophyll levels, as these parameters climb to high values when *Artemia* disappear from the water column during winter. In Farmington Bay, by contrast, the extreme nutrient loading appears to maintain very high algal concentrations despite the elevated grazing pressure there.

Bird densities in the open waters of Farmington Bay were much lower than in Gilbert Bay (**Fig. V**). In five surveys conducted from March-December in the two bays, respective eared grebe and phalarope densities in Farmington Bay were only 19% and 4% of those in Gilbert Bay. Likewise, low numbers of Franklin's gulls and other gull species were found in Farmington Bay relative to Gilbert Bay. The generally low densities of birds in the open water of Farmington Bay contrasts with its high abundance of shorebirds (Paul and Manning 2008). Potential reasons for the low densities of birds in the open water of Farmington Bay include: 1) lower densities of large prey compared to Gilbert Bay, where *Artemia* and brine flies are abundant; 2) absence of benthic (bottom-dwelling) invertebrates in the dead zone; 3) poor visibility for underwater feeding; 4) toxic algae. However, more work is needed to understand why the open waters of the Farmington Bay do not have greater bird abundance.

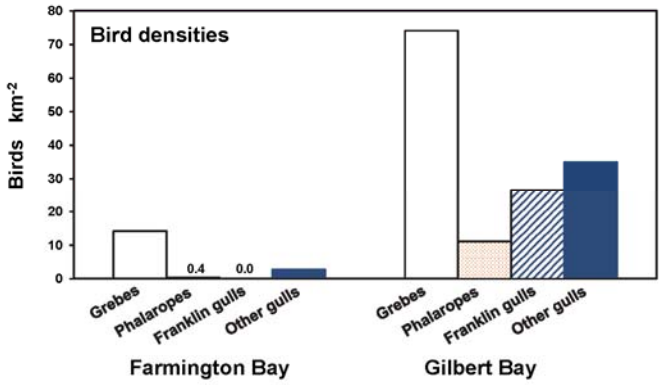

Fig. V. Bird densities estimated in the open water areas of Farmington and Gilbert Bays on five dates between March and December (2002-2003).

Concentrations of six different metals in the zooplankton exceeded concentrations that could harm birds (threshold effects concentrations) on some dates. However, when average concentrations over the sampling period were considered, only mercury in Gilbert Bay, and selenium in all three bays exceeded the guidelines for protecting aquatic wildlife (**Fig. VI**). Geometric mean mercury concentrations in *Artemia* in Gilbert Bay were 0.65 μg g^{-1}, which is 75% above the threshold effects level. Selenium concentrations in Farmington and Gilbert Bay zooplankton were approximately 150% above the threshold effects level. Mean concentrations of arsenic, cadmium, lead, and zinc in zooplankton were generally below 60% of the threshold effects levels.

In summary, Farmington Bay was hypereutrophic as a consequence of heavy nutrient loading from greater metropolitan Salt Lake City. Dense cyanobacterial blooms and very high cyanotoxin levels in the bay present problems for contact recreation and may threaten birds and other wildlife. The zooplankton community in Farmington Bay was dominated by relatively small cladocera and copepods, and may not provide optimal feeding opportunities for birds. Nighttime anoxia occurs in most of the water column, and an anoxic dead zone underlies a large portion of the bay which is incapable of producing invertebrate food. Most metal concentrations in the zooplankton of Farmington Bay were below threshold effects levels, but the metalloid selenium was well above the level of concern. Since bird use

of the open waters of Farmington Bay was limited, the transference of metals from zooplankton to bird populations through zooplankton consumption may be limited. However, extensive populations of shorebirds do use Farmington Bay, and thus benthic invertebrate and biofilm food in the shallowest areas may be important vectors in the transfere of metals into birds.

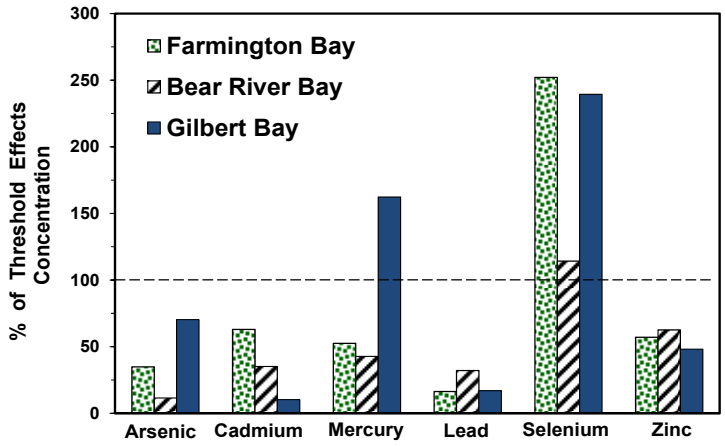

Fig. VI. Geometric average concentrations of metals and metalloids in zooplankton in three bays of the Great Salt Lake sampled on 5-8 dates during 2009. On one or more sampling dates each of these metals exceeded threshold effects concentrations determined by the US Fish and Wildlife Service or other literature sources. The mean concentrations shown here are expressed as percentages of these thresholds. The theshold effects concentrations in µg L^{-1} were: Arsenic – 30; cadmium – 3.3; mercury – 0.4; lead – 5; selenium – 3; zinc – 178.

In contrast to Farmington Bay, Bear River Bay, which does not have high nutrient loading from metropolitan areas, had far less phytoplankton and negligible amounts of cyanobacteria and cyanotoxins. Concentrations of selenium in the zooplankton exceeded threshold effects levels slightly, but other metals were well below levels of concern. Although water quality in Bear River Bay is reasonably good, it is frequently desiccated in the summer due to irrigation withdrawals from the Bear River. This desiccation, in conjunction with salt addition from solar ponds, drives salinity levels well above those tolerated by fish and macroinvertebrates.

Gilbert Bay was mesotrophic and did not have abundant cyanobacteria or cyanotoxins. Heavy grazing pressure by *Artemia* on the phytoplankton maintains the summer algal populations at low levels. Although eutrophication is not presently a problem there, the population in the area is expected to more than double in the next 50 years, thus increasing nutrient loading and phytoplankton production. Because a railway causeway changes the hydrology and salinity of the lake, approximately half of the Gilbert Bay is underlain by an anoxic dead zone (deep brine layer) where macroinvertebrates cannot survive and where toxic methyl mercury concentrations magnify. Finally, both mercury and selenium concentrations in the *Artemia* of Gilbert Bay were well above threshold effects levels and may present problems for migratory birds that consume them.

Introduction

The Great Salt Lake, bordered by several major population centers in the State of Utah, has received heavy loading of various pollutants that until recently have received little attention. However, during the last decade management agencies and environmental groups have become concerned that these contaminants might limit the beneficial uses of the lake. Recent work by the Utah Department of Environmental Quality, The Utah Division of Forestry, Fire and State Lands, universities, and federal agencies have focused on how selenium, mercury, eutrophication and salinity may influence recreational use of the lake and the migratory bird populations that rely on the lake for feeding and nesting.

The causeways that divide Great Salt Lake restrict circulation between the bays, effectively concentrating pollutants and affecting and salt concentrations. Farmington and Bear River Bays are shallow and receive substantial river inflows that dilute salts to near freshwater levels during spring runoff. However, as those flows subside, evaporation and intrusion of salts from adjoining bays and/or salt ponds increase their salinity levels. Farmington Bay can reach salinities of up to 9%, which is 2½ times saltier than the ocean (3.5%). Salinities in Bear River Bay can be even higher. Currently, the salinity of Gilbert Bay is near 14% (although during flooding in 1984-85, Gilbert Bay's salinity decreased to 5%). Both Gilbert Bay and Farmington Bay are salt-stratified with anoxic deep brine layers that do not support macroinvertebrate life. Finally, Gunnison Bay is recharged primarily from Gilbert Bay and evaporation results in salt concentrations exceeding saturation with salts precipitating out and accumulating on the bottom. Each bay has its own particular salinity regime and biological and pollution characteristics although the designated beneficial uses are similar (**Table 1**).

Table 1. Beneficial use classification for the open waters of three bays of the Great Salt Lake. Rule R317-2 Standards of quality for waters of the state. (http://www.rules.utah.gov/ publicat/code/r317/r317-002.htm#T8).

Bay	Beneficial Uses for Open Waters
Gilbert (5A)	Protected for frequent primary and secondary contact recreation, waterfowl, shore birds and other water-oriented wildlife including their necessary food chain.
Bear River (5C)	Protected for infrequent primary and secondary contact recreation, waterfowl, shore birds and other water-oriented wildlife including their necessary food chain.
Farmington (5D)	Protected for infrequent primary and secondary contact recreation, waterfowl, shore birds and other water-oriented wildlife including their necessary food chain.

Both toxic compounds and nutrients are of concern because of the population, industry, and mining located in the Great Salt Lake's watershed. In 1889, the first sewer system in Salt Lake City began discharging raw sewage into the Jordan River, but by 1911 conditions in the river were so bad that a Sewer Canal was constructed to bypass the Jordan River and discharge sewage directly to Farmington Bay (Hooton no date). In 1922, the Northwest Oil Drain was connected to the Sewer Canal to discharge industrial wastes from refineries and other industries in the NE part of Salt Lake City. Gwynn (2002) provides a history of raw and treated sewage discharge into Farmington Bay and reviews the earlier studies. Today, the domestic wastewater of approximately 2.3 million people are discharged into the Great Salt Lake or its tributaries resulting in increased loadings of nitrogen and phosphorus. A recent paleolimnological study (Leavitt et al. 2012) indicated that increased nutrient loading and eutrophication to Farmington and Gilbert Bays began in the lake in the early 1900s, and is continuing to increase, at least in Farmington Bay. Previous analyses of eutrophication have indicated that Farmington Bay is hypereutrophic with large blooms of toxic

cyanobacteria (e.g. Hayes 1971, Wurtsbaugh and Marcarelli 2006). The eutrophication problem has been recognized for decades. Van der Meide and Nicholes (1972) described a "sewage delta" at the mouth of the Sewer Canal, and Coburn and Eckhoff (1972) warned that the "disregard for the... water quality of Farmington Bay might lead to...a tremendously large mismanaged waste lagoon upwind from metropolitan Salt Lake City." Gilbert Bay also has high algal densities in the winter, but grazing by brine shrimp reduces summer standing stocks (Wurtsbaugh and Gliwicz 2001, Belovsky et al. 2012). Little is known, however, about nutrient loading and eutrophication in Bear River and Gunnison Bays.

Until pollution controls were enacted in the 1960s and 1970, industrial wastes were freely discharged into Farmington Bay via the NW Oil Drain and City Canal. Additionally, mining for heavy metals began in the late 1800s in the Wasatch and Ochre Mountain Ranges that lie to the east and south of the lake. Gold, silver, lead, and zinc were initially exploited, but copper extraction from the Kennecott Copper Corporation mine in the Oquirrh Mountains has dominated Utah mining in recent decades (Utah Geological Survey 2011). In the first half of the twentieth century, several smelters in the Salt Lake Valley processed ores from throughout the intermountain west. Only the Kennecott facility remains and it is located on the south shore of the Great Salt Lake. Several mining and smelting sites have become EPA Superfund sites. Despite improvements in emissions from smelters there is nevertheless concern that previously-deposited metals may continue to cycle within the lake and that continued discharges from mining, other industrial activities, and long-distance atmospheric deposition (Naftz et al. 2008) may influence the lake's biota (Waddell et al. 1999). Paleolimnological analyses of Gilbert and Farmington Bay's sediments have indicated that most metal contamination peaked in the mid-1950s and has now declined due to stricter emission control standards for smelters. However, selenium concentrations are stable or increasing in the sediments (Wurtsbaugh 2012). Mercury contamination in the lake is of particular concern because the deep brine layer in Gilbert Bay has some of the highest reported methyl mercury concentrations reported in United States waters (>30 ηg L^{-1}; Naftz et al. 2009, Wurtsbaugh and Jones 2012) and mercury levels are high in many birds that utilize the lake (Gardberg et al. In Prep.).

The existing and potential problems noted for the Great Salt Lake indicates that monitoring of water quality is needed in order for the State to determine if standards are adequate to protect the designated Beneficial Uses for the Great Salt Lake. Although previous work on metals contamination has focused on Gilbert Bay, and eutrophication studies have been primarily conducted in Farmington Bay, the work described here assessed contamination problems in all three of the bays that are used extensively by bird populations and by recreationists (Gilbert, Farmington, and Bear River Bays). A comparison of water quality in Farmington Bay and Bear River Bay is particularly useful because the latter receives considerably less effluents, and thus it can serve as a reference site for the more heavily impacted Farmington Bay.

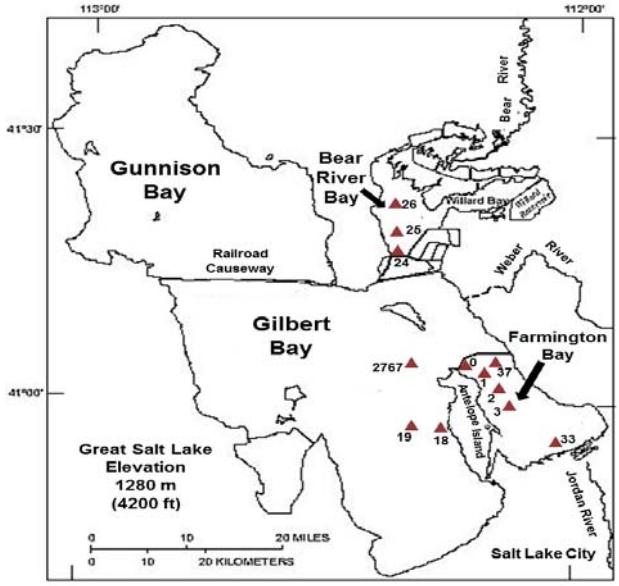

Fig. 1. Map of the Great Salt Lake showing the sampling stations (Δ) used in 2009. Identical or similar stations were sampled in other years. The lake parameter is shown at an elevation 1280 m, which is the mean lake elevation. During our study the lake elevation was lower, varying from 1279.5 m (4197.9 ft.) in 2002, to 1278.6 m

Materials and Methods

Study site

The Great Salt Lake (**Fig. 1**) is a 5200 km^2 system located in an endorheic basin in Utah, USA (41.04 N, 112.28 W). The lake has been divided by transportation causeways that separate it into four distinct bays that function somewhat independently. The two bays on the eastern side of the lake receive freshwater inflows from the mountains to the east, and can be characterized as estuaries with salinities that vary from freshwater to hypersaline conditions, both spatially and seasonally. Farmington Bay (~310 km^2) in the SE is shallow, with a mean depth of only 1.1 m at mean lake elevation (Gwynn 1986). It receives inflow from the Jordan River, which passes through Salt Lake City and wetland areas before reaching the lake, from smaller creeks on the eastern side of the bay, and from discharges of wastewater treatment plants. At the southern end of Farmington Bay, where the water is fresher, emergent and submerged macrophytes, as well as filamentous periphyton, are abundant. Fish are present in the southern end of the bay (personal observation) but have not been studied. A salt wedge intrudes from the saltier main lake (Gilbert Bay) so that the northern half of Farmington Bay is underlain with an anoxic, hydrogen-sulfide rich deep brine layer (dead zone, *sensu* Rabalais et al. 2002; Conroy et al. 2011) below a depth of ~1 m (Wurtsbaugh and Marcarelli 2004). Bear River Bay in the NE has an area of 212 km^2 and a mean depth of only 0.6 m at mean lake elevation (Gwynn 1986). Since Bear River Bay receives inflows from the lake's largest tributary, the Bear River (59% of inflows; Arnow 1980), it has fresh water during spring runoff. However, salinities can climb to over 25% after diversions for agricultural and wetland support dewater the system (Wurtsbaugh 2011). Extensive submerged macrophytes and benthic filamentous algae communities cover much of Bear River Bay when the water is fresh (**Fig. 2**). Fish are present in the freshwater areas (Moore 2012).

The main body of the Great Salt Lake was divided in two by the construction of a solid-fill railway causeway in 1959. Culverts and a breach allow the exchange of water and salts between these two bays. However, salinity in the northern bay, Gunnison Bay (2520 km^2), is normally at saturation (~28%). Consequently, Gunnison Bay was not sampled during the study because of its current limited importance for birds and recreation in most years. The southern arm of the lake, Gilbert Bay, covers approximately 2400 km^2, but lake area, depth, volume, and salinity vary greatly with precipitation cycles. At the

Fig. 2. Shallow waters of Bear River Bay showing large masses of benthic filamentous algae. Photo by W. Wurtsbaugh, 8 July 2010. Access to these shallow sites was gained by airboat.

mean lake elevation of 1280 m, the respective mean and maximum depths of Gilbert Bay are 4.4 and 10.1 m (Baskin 2005). Surface water salinities in Gilbert Bay at the time of the study varied from 13-16%. However, approximately 50% of Gilbert Bay is underlain by a deep brine layer (monimolimnion) due to density-driven return flows through the causeway from Gunnison Bay (Gwynn 2002, Wurtsbaugh and Jones 2012). This layer is anoxic and has high concentrations of toxic hydrogen sulfide (Wurtsbaugh and Marcarelli 2004), and consequently is a dead zone that does not support algae or invertebrates (Collins 1980). Although there are no macrophytes in the bay, much of the margin of the lake is covered by stromatolites with abundant cyanobacterial growth (Wurtsbaugh et al. 2011). Gilbert Bay receives water flows from the Weber River (20% of surface inflows), and from the outflows of Bear River Bay and Farmington Bay. Stephens (1990) and Belovsky et al. (2011) provide additional limnological information about Gilbert Bay, and Wurtsbaugh et al. (2008) provide information on hydrological and nutrient fluxes between the bays of the lake.

Nutrient and metal loading to the lake are increased substantially above background levels, because 82% of Utah's population of 2.8 million lives within the Great Salt Lake watershed. Secondary-treated wastewaters from approximately 1.8 million people (2010 census; Wikipedia 2012) flow into Farmington Bay, although some of the flow is diverted to Gilbert Bay during spring runoff. Direct discharges to Farmington Bay occur from the Sewer Canal serving much of Salt Lake City, and from three wastewater treatment plants in Davis County on the eastern shore of the bay. Wastewater loading to Bear River Bay is considerably less, with only 0.16 million residents in the watershed, but non-point loading is appreciable. Gilbert Bay receives wastewaters from 0.24 million residents in the Weber River and from the outflows of Farmington Bay and Bear River Bay (Wurtsbaugh et al. 2008). A considerable portion of the flow from all three major rivers passes through wetlands before reaching the open waters of the lake, and consequently, some nutrients and other contaminants are removed and stored in these areas.

Metal contamination of the Great Salt Lake is driven by industrial and mining activity in the basin. The Northwest Oil Drain is connected to the Sewer Canal to discharge industrial wastes from refineries and other industries in the NE part of Salt Lake City. Because of the metals and other contaminants that have accumulated in the NW Oil Drain, it is now an EPA Superfund Cleanup Site (The Forrester Group 2001). In addition to the industrial activities in metropolitan Salt Lake City, mining activities in the immediate region have contributed to high metals loading into the lake. Numerous smelters processed lead, zinc, copper, silver, gold ores since the late 1800s (Varley et al. 1921), and the large Kennecott Copper mine operated by Rio Tinto continues to process ores that produce a variety of metal contaminants (Wurtsbaugh 2012).

Sampling stations in the three bays are shown in **Fig. 1** and coordinates and depths are shown in **Table 2**. The sites sampled varied somewhat over the decade depending on specific objectives for a study year. However, 2-4 sites in the northern half of Farmington Bay were normally sampled on each date. These sites were located in the deeper portion of the bay that could be accessed without an airboat or hovercraft. In addition to the routine sampling, a longitudinal transect at 11 sites was sampled in 2009 along the salinity gradient from the southern to northern end of the bay. In 2007, data

recording sondes were placed at shallow sites (0.28 m deep) in Farmington Bay (Stations 33 and 37) to help describe the habitat utilized by shorebirds. Sites in Gilbert Bay were located 1-5 km off the west coast of Antelope Island.

Table 2. Locations and depths of sampling stations in three bays of the Great Salt Lake. The depths for all stations except 33 and 37 are for June, 2009. Those for stations 33 and 37 are for July 2007.

Bay	USU Station #	Latitude	Longitude	Depth (m)	Description
Farmington	0	41.0663	-112.2296	0.2	Farmington Bay Bridge (SE side), collection from shore
Farmington	1	41.0498	-112.1887	1.3	N End Farmington Bay, 3.9 km ESE from causeway bridge
Farmington	2	41.0304	-112.1591	1.4	N End Farmington Bay, 7.2 km SE from bridge
Farmington	3	40.9967	-112.1406	0.6	Center Farmington Bay, 10.7 km SE from bridge
Farmington	33	40.9185	-112.0452	0.3	Southern end of Farmington Bay, near Sewer Canal discharge
Farmington	37	41.0648	-112.1749	0.3	NE area of Farmington Bay
Gilbert	18	40.9559	-112.2652	2.5	West side of Antelope I. midway, 6.8 km S of northern end
Gilbert	19	40.9643	-112.3293	7.8	Midway down Island, 6.3 km offshore
Gilbert	2767	41.0703	-112.3333	3.4	USGS site 6.7 km WNW of Antelope Island
Bear River	24	41.2728	-112.3544	1.3	Bear River Bay, 250 m NNE of GSL Minerals bridge
Bear River	25	41.3283	-112.3600	0.5	Bear River Bay, 6.2 km N of GSL Minerals bridge
Bear River	26	41.3797	-112.3561	0.3	Bear River Bay, 11.9 km N of GSL Minerals bridge

The shallowest sites in Gilbert Bay were in water 2-3 m deep, where stromatolites covered the bottom. Deeper sites were near 7 m. Bear River Bay was only sampled in 2006 and 2009. Sites in this area were located in the main portion of the bay north of the Great Salt Lake Minerals Corporation bridge and aqueduct.

Field sampling

Water transparency was measured with a 25-cm diameter Secchi disk with black and white quadrants. Salinity was measured with refractometers with ranges of 0-10% or 0-30%. In instances when refractometer readings were not available, we converted specific conductivity (SC, mS) data to salinity with the relationship: Salinity (%) = $0.0707 * SC^{0.988}$. Troll 9500 multi-parameter sondes (In-Situ, Inc. Ft. Collins, CO) were used for continuous recording of water chemistry and real-time measurements of water chemistry profiles. The sonde's temperature sensor was a standard platinum resistance thermometer that did not need calibration. A double-junction glass pH sensor was calibrated before each use with pH 7 and pH 10 buffers, and kept moist before use. The sonde's high-range passivated stainless steel conductivity sensor was calibrated with 100 mS cm^{-1} (at 25° C) standard solution. Specific conductivity (corrected to 25° C) was recorded to enable comparison between temperatures. Salinity in practical salinity units for correcting dissolved oxygen (DO, see below) was approximated from relative salt mass (s, g kg^{-1}) calculated c (mS cm^{-1}) using a polynomial regression obtained from a table of s and c for NaCl (Weast and Astle 1983):

$$s = 0.00001698*(c)^3 - 0.00241*(c)^2 + 0.7952*(c)$$

The In-Situ sonde was equipped with an optical dissolved oxygen (DO) sensor that uses the principle of dynamic luminescence quenching. The oxygen sensor was calibrated in air-saturated tap water and in a 0% dissolved oxygen solution made by dissolving 67 g Na_2SO_3 L^{-1} in deionized water. Dissolved oxygen is affected by concentration of oxygen in the air, atmospheric pressure, water temperature, and salinity. The large changes in salinity found in the Great Salt Lake required correction

of the dissolved oxygen readings to obtain dynamic dissolved oxygen concentration (DO_{cd}) as well as the dynamic dissolved oxygen percent saturation (DO_{pd}) reported here. The following equations obtained from the In-Situ were used to make this conversion:

$$DO_{cd} = DO_{cf} * (d/f)$$

$$DO_{pd} = DO_{pf} * (d/f)$$

$$f = EXP(-s_f * (0.017674 - 10.754/K + 2140.7/K^2))$$

$$d = EXP(-s * (0.017674 - 10.754/K + 2140.7/K^2))$$

where DO_{cf} is the sonde-output DO concentration (mg/L), DO_{pf} is the sonde-output DO percent saturation (% of air saturation), s_f is fixed salinity entered during calibration (PSU), s is current salinity of the water (PSU), and K is water temperature (K). In 2003 diel oxygen changes in Gilbert and Farmington Bays were made with YSI Model 600XLM recording sondes (Yellow Springs, OH) with a membrane-type DO sensor.

Water samples for chemical and biological analyses were collected from the mixed layer with either with a 3-inch 8-cm diameter polyvinyl chloride (PVC) core sampler lowered into the mixed layer to a maximum depth of 1-1.5 m (2005, 2009), with PVC horizontal Van Dorn bottle at a depth of 0.5 m (2002-2005), or with a dip sample collected by immersing a polyethylene jug to a depth of 0.2 m (2006 and at all stations shallower than 0.3 m). A comparison of chlorophyll *a* (hereafter 'chlorophyll') concentrations from samples collected at 0.5 m and with the integrated tube sampler in 2005 indicated that plankton were usually homogeneously distributed ($Log\ Chl_{0.5m} = 1.034\ Log\ Chl_{Int}^{0.999}$; n = 62; r^2 = 0.99). This suggests that the collection depths from the mixed layer had little influence on parameter estimates.

Zooplankton were collected with a vertical haul of a 0.5-m diameter zooplankton net with 250 µM mesh that was lowered to within 0.1-m of the lake bottom. The large diameter net was used to minimize net avoidance by fast-swimming water boatmen (corixidae), and the relatively large mesh size was used because the abundance of filamentous cyanobacteria in Farmington Bay often caused excessive net clogging with smaller mesh sizes, even with tow lengths as short as 1 m. The large mesh size may have under-sampled some small crustaceans and captured few rotifers. Consequently, rotifers were not enumerated. A separate sample of zooplankton for metals analysis was collected by vertical or horizontal tows of the zooplankton net, which was then rinsed with deionized water to remove salts. Zooplankton samples were subsequently frozen and then dried at 70°C to constant weight prior to analysis.

Analytical methods for nutrients and metals

Water samples for ammonium-N and nitrate + nitrite-N analyses were filtered through 0.8 µm GF/F filters and preserved with HNO_3 to reduce the pH < 2. These samples were analyzed by the Utah Water Quality Monitoring Program. Sample bottles were received by the state lab within 3 days of collection. Ammonia was analyzed by automated colorimetry using EPA method 350.1, which utilizes the alkaline phenol-hypochlorite method with a detection level of 0.01 mg L^{-1} (NEMI 1993). Nitrate + nitrite was analyzed by an automated cadmium reduction method following EPA Method 353.2. The detection limit is cited as 0.05 mg L^{-1} (NEMI 1993). Filtered water samples were also analyzed for metals using ICP-MS, but the results were unreliable because the high salt content in the majority of the samples caused matrix interference.

Unfiltered water samples were frozen and subsequently analyzed for total nitrogen (TN) and total phosphorus (TP) using persulfate digestion (Valderrama 1981). When salinities were higher than seawater, they were diluted to 3.5% prior to analysis. Following digestion, the samples were analyzed for nitrate (cadmium reduction) and phosphate (ascorbic acid molybdenum reaction) using an Astoria autoanalyzer (Astoria Pacific International, Portland OR). Respective TN and TP detection limits were 0.006 and 0.003 mg L^{-1}. Water samples were also filtered through GF/F filters to measure total dissolved nitrogen (TDN) following the Valderrama protocol. Dissolved organic nitrogen (DON) was then calculated by subtracting the nitrate + ammonia concentrations from the TDN concentrations.

Metal concentrations in the zooplankton samples were measured at the Utah Veterinary Diagnostic Laboratory (http://www.usu.edu/uvdl/) in Logan, Utah. Test materials were digested in screw-cap Teflon tubes on a heat block at 90°C for 4 hours in 10 ml trace mineral grade nitric acid. The digests were diluted 1:20 with 18.2 MOhm ultrapure water in order to achieve a 5% nitric acid matrix prior to analysis. Such a matrix was necessary to match the standards and quality control samples. The nitric acid leachable mineral concentrations in the samples were quantified using inductively coupled plasma mass spectroscopy (ICP-MS). Standard curves for all elements excluding mercury consisted of five concentrations between 10 and 2500 µg l^{-1}. Standard curves for mercury consisted of three concentrations from 2.5 to 10 µg l^{-1}. A quality control (QC) test sample was analyzed with every 5 samples to validate analytical accuracy. The QC sample was required to measure within +/- 5% of the known mineral specifications to proceed. Any group of samples that had a failed QC test was re-analyzed. Metal concentrations in the zooplankton were compared against benchmarks (threshold effects concentrations) adopted by the U.S. Fish and Wildlife Service (Waddell et al. 1999) or calculated using a toxicity reference value for cadmium of 0.7 mg Cd $kg^{-1}day^{-1}$ (Stanton et al. 2010) and a food ingestion rate of 0.214 kg_{dry} $kg_{wet}^{-1}day^{-1}$ (EPA 2005).

Metal	Benchmark (µg g^{-1})	Source
Aluminum	5000	USFWS
Arsenic	30	USFWS
Boron	30	USFWS
Cadmium	3.3	Stanton
Chromium	10	USFWS
Copper	200	USFWS
Lead	5.0	USFWS
Mercury	0.4	USFWS
Nickel	31	EPA
Selenium	3.0	USFWS
Zinc	178	USFWS

Analytical methods for phytoplankton, cyanotoxins and zooplankton

Chlorophyll, a surrogate measure for total algal biomass, was analyzed by filtering 10 or 20-ml aliquots on 25-mm Gelman A/E filters with a nominal pore size of 1 µm. Normally, two replicate samples were filtered from each station. The filters were frozen to help lyse the phytoplankton cells. Within three weeks the filters were extracted in 95% ethanol overnight, and the chlorophyll concentrations were measured with a Turner 10AU fluorometer (Turner Designs, Sunnyvale, CA) using a non-acidification technique (Welschmeyer 1994). Phycocyanin pigment, an indicator of cyanobacterial biomass, was analyzed with the Turner 10AU fluorometer and Turner's phycocyanin optical kit that utilizes narrow-band interference filters with excitation and emission wavelengths of 600 ηm and 640 ηm, respectively. Three replicate measurements were made on each sample.

Phytoplankton densities and biovolume were analyzed from the 2009 samples by PhycoTech, Inc. (St. Joseph, MI) after filtration onto membrane filters and mounting in methacrylic resin (Crumpton 1987). A single sample was counted from each station. Although most samples were counted to the level of genus, six samples were identified to the species level. If a sample was dominated by cells smaller than 10-20 µm, or if the cells were fragile and difficult to identify, it was counted and measured at 400X-1000X power magnification. Samples that were dominated by cells >10-20 µm were counted by a combination of enumerations at 200X and 400X. This tiered counting method yielded a minimum of 400 natural units (cells, filaments, or colonies) per sample (well over 400 cells per sample). Because algal volumes can vary immensely between species, and because many ecological processes are more dependent on biovolumes than on densities, the volume of each taxon was also estimated. Measurements taken for biovolume calculations included the greatest axial linear dimension, and when necessary, additional measurements of width and depth. Cell and colony shapes were approximated to a geometric figure, and the appropriate calculation of biovolume was made. Between 10 and 30 natural units were measured per taxa depending on variability and number encountered for the purpose of making these biovolumetric approximations. Between 2002 and 2005, phytoplankton cell densities were determined by settling and counting samples in Utermöhl chambers on an inverted microscope at 1000X (Wetzel and Likens 1991). For Farmington Bay, only 1 ml was usually settled because cell densities were high. During this period phytoplankton were identified using Felix and Rushforth (1979). Length and width measurements were made on 10 individuals of each taxon and biovolumes were calculated using equations in (Hillebrand et al. 1999).

Zooplankton abundances and biomasses from a single sample at each of the replicate stations were measured at 10X-30X with a dissecting scope in our laboratory. If sufficient numbers were present, at least 200 individuals were counted from subsamples, thus insuring reasonable Poisson counting statistics (Prepas 1984). Most taxa were counted to the genus level, but species identifications of copepods were made from subsamples. Brine shrimp, *Artemia franciscana* (hereafter, *Artemia*) were counted separately as nauplii, juveniles, and adult males and females, but here only total biomass information is given. Lengths of ten individuals of each taxa were measured, and density estimates and sizes were used to estimate biomass utilizing length-weight regressions of Wurtsbaugh (1992) or Watkins et al. (No date).

Filtering rates of the zooplankton were calculated to estimate grazing pressure on the phytoplankton community. These were calculated utilizing geometric mean lengths of each taxon and the equations presented by Wurtsbaugh (1992) for *Artemia* and copepods, and those of Lampert (1987) for cladocera.

Plankton samples for cyanotoxin analysis were filtered on GF/C glass fiber filters until the filter clogged. The filters were frozen at -70°C until shipped for analysis to the Monitoring and Event Response for Harmful Algal Blooms Laboratory (MERHAB) of Greg Boyer (www.merhab-LGL.org). There the filters were extracted with 10 ml acidified 50% methanol using sonication. This protocol gave greater than 90% extraction efficiency for microcystins (Boyer 2007). These extracts were then assayed for cyanotoxins using three techniques: 1) the protein phosphatase inhibition assay (PPIA) via the method of Carmichael and An (1999) for microcystin and nodularin activity; 2) HPLC-MS for microcystin and nodularin variant identification, and; 3) HPLC-MS for anatoxin-a and cylindrospermopsin identification. Values for filtered samples represent only particulate toxin concentrations and were expressed in micrograms toxin per liter of starting lake water.

The PPIA analysis simultaneously detects the biological activity of all microcystin and nodularin variants. Results of samples run via this assay are traditionally given in µg microcystin-LR equivalents L^{-1} of starting lake water. Each sample was run in duplicate, and if individual readings did not agree to within 15%, they were re-run. Samples containing >0.05 µg microcystin(s) L^{-1} were considered to be "toxin-containing". They were subsequently analyzed with HPLC-MS following Boyer (2007) and a reverse phase column with an acetonitrile gradient. The mass spectrum was run in the scanning mode to assess any microcystins or nodularins with masses between 725 and 1150 atomic mass units, which also had the appropriate UV signature. Positive microcystins were quantified against a microcystin LR standard curve.

The PPIA analysis and the HPLC analysis yielded somewhat different estimates of nodularin concentrations. PPIA is quantified using an MC-LR standard instead of nodularin, since MC-LR is much more common in freshwater systems. For HPLC-MS, we used a mixed microcystin/nodularin standard which allowed us to quantify your samples directly for nodularins. The difference in biological activity between these two toxins explains the difference in the results obtained by the PPIA. A regression analysis of the HPLC-MS data using nodularin and microcystin standards indicated that actual nodularin concentrations were only 62% of those indicated by the PPIA analysis using microcystin-defined responses. Nevertheless, following standard protocols (Chorus and Bartram 1999), we have expressed our results as the much more common microcystin-LR equivalents.

We also analyzed for the neurotoxin anatoxin-*a* and the hepatotoxin cylindrospermopsin using HPLC-MS. These toxins were not encountered in the data presented here, but anatoxin-*a* has been found previously in Farmington Bay zooplankton and benthic periphyton (Wurtsbaugh 2011).

Bird surveys

In 2002-2003 bird densities were assessed while traveling between limnological sampling stations. One or two observers counted each bird taxa in a swath 100 or 200 m on each side of the boat while we were traveling at known speeds of 40-52 km h^{-1}. The area surveyed was computed by either the time of travel and speed, or by utilizing distances between GPS coordinates. Usually five transects were completed in each bay, but numbers varied from three to seven on different dates. The visual estimates were only approximate, particularly when densities were high in Gilbert Bay. Nevertheless, any observer bias was constant, so that comparisons of relative densities in the two bays should be valid.

Odor survey of people living near the Great Salt Lake

To assess how individuals were influenced by lake odors, citizens who lived or worked around the lake were contacted and asked to make daily entries on lake odors. They rated odors on a scale of 1-5 (1 = none; 2 = mild; 3 = moderate; 4 = strong, and; 5 = unbearable) (Appendix 1). They were also asked to provide a qualitative description of the odor based on the "odor wheel" (Suffet et al. 1999) with categories such as "earthy" (musky, swampy) or "fishy" (dead fish, ocean) or "offensive" (decay, rotten eggs, sewage). A total of 505 odor survey responses were obtained between 19 August and 23 December, 2003. Despite this relatively high sample size, the distribution of participants was not even across the different zones of the lake. For the area around Farmington Bay, responses came from the gate at the east end of the causeway to Antelope Island State Park, from park staff on Antelope Island Visitor Center, from tourists at the Visitor Center, from staff at the Farmington Bay Refuge headquarters, and from a resident living nearby. For Bear River Bay, all responses were from staff at the Bear River Migratory Bird Refuge. Responses for Gilbert Bay came primarily from staff at the Great Salt Lake State Park at the south end of the bay, and from a single respondent who lived at the tip of Promontory Point near the north end of the bay.

Statistical analyses

Regression analyses and t-tests were done utilizing MS Excel 2010. Analyses of variance and post-hoc tests were done utilizing SYSTAT 8.0.

Results

Physical Conditions and Nutrients

Salinities in the upper mixed layer were relatively stable in Gilbert Bay, but variable in Farmington and Bear River Bays (**Fig. 3**). During the study, salinities in Gilbert Bay ranged from approximately 13-15% (ca. 130-150 ppt). In contrast, salinities in the northern end of Farmington Bay ranged from near 1% to as high as 9%. Salinities were always lower in Farmington Bay during spring runoff (May-June) and climbed throughout the summer with a typical peak in mid-August. In the fall, when river flows were restored and evaporation decreased, salinities decreased 2-3%. In addition to these seasonal differences, there was also significant salinity variation between years: for example, in 2007 salinities in the northern end of Farmington Bay were never less than 4%, whereas in 2005 and 2009 spring salinities were near 1%. Salinities were even more variable in Bear River Bay, with springtime values near 0%. However, when April irrigation began in the basin and flows were diverted from the Bear River, the bay began drying up and was augmented with salts from solar evaporation ponds (see below), and salinities of the surface water climbed above those of Gilbert Bay, reaching 26% in August 2006 and 24% in September 2009. Fall precipitation, and the end of irrigation season for agricultural use, allowed more water to flow down the Bear River, thus decreasing salinities again in early fall.

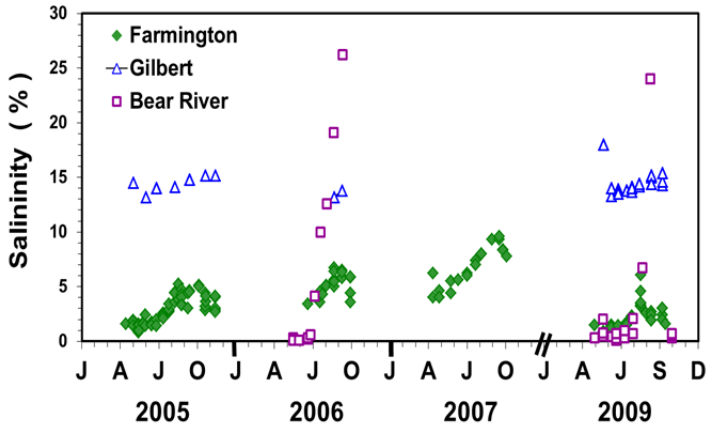

Fig. 3. Annual and seasonal trends in the surface water (0.2 -1 m) salinity of Farmington, Gilbert and Bear River Bays of the Great Salt Lake in four years. Salinities shown here are only for areas of Farmington and Bear River Bays that are distant from river inflows.

All three bays exhibited salinity-stratification, at least during parts of the years. In Gilbert Bay, mixed-layer salinities were near 15% to a depth of 6 m, but increased to nearly 21% in the deep brine layer (**Fig. 4A**). In Farmington Bay, a monimolimnion (deep-brine layer) usually began at depths near 1 m. For example, in June 2009, the mixed layer salinity was 1.4%, but reached 10% in the deep-brine

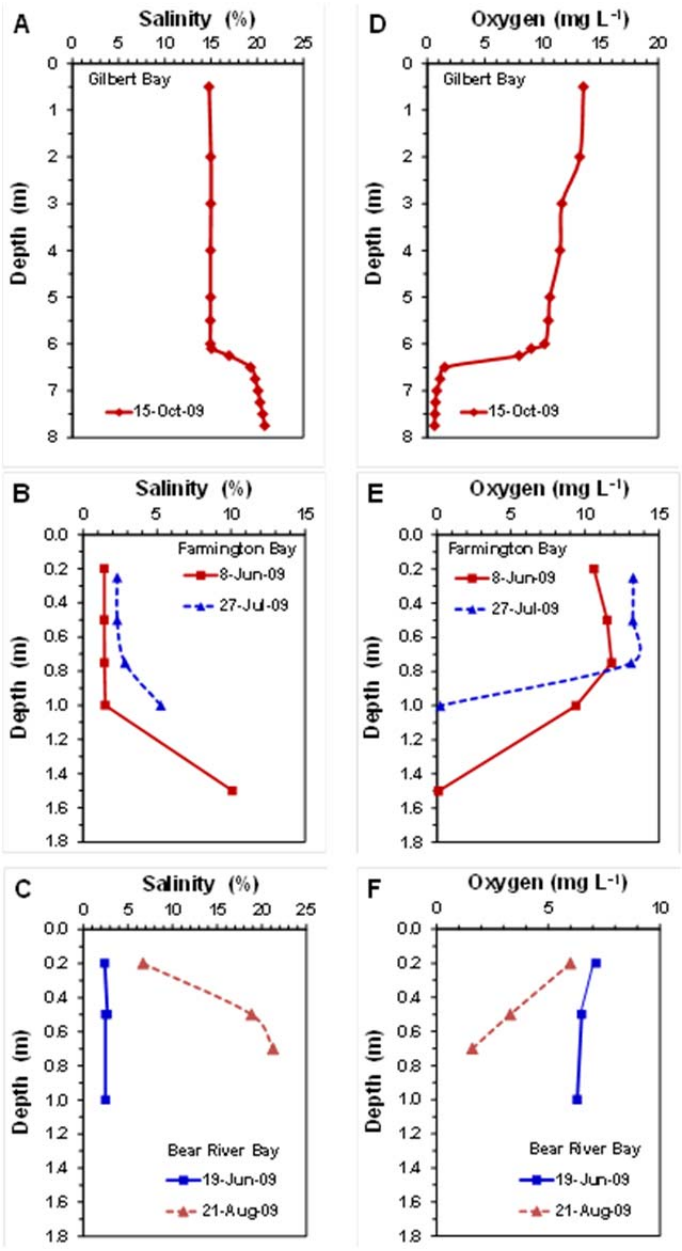

Fig. 4. A-C. Vertical profiles of salinity in Gilbert Bay, Farmington Bay (Sta. 1) and Bear River Bay (Sta 24). **D-F.** Vertical profiles of dissolved oxygen in the three bays. Note that the profiles were always measured to near the sediment-water interface. In Farmington and Bear River Bays depth decreased markedly over the summer, so profiles measured in the fall were not as deep. Also note differences in depth scales.

layer (**Fig. 4B**). This deep-brine layer is derived from the intrusion of a salt wedge of Gilbert Bay water through a breach in the causeway that separates the two bays (Fig. 1). In Bear River Bay, the entire 1-m water column was nearly fresh and completely mixed during spring runoff (June). However, by August, salinities of the surface water had climbed to 6.7% and the bottom water was 21%.

The deep brine layers in Gilbert and Farmington Bays were always anoxic or hypoxic (**Fig. 4D, E**) with highly negative redox potentials. For example, during the October 15, 2009 sampling in Gilbert Bay (**Fig. 4D**), the redox potentials below 6.25 m ranged from -200 to -280 mV. In Farmington Bay, redox declined to -368 mV in the bottom water (1 m) during the July 27th sampling (redox data not shown). In Bear River Bay the deep brine layer that appeared in mid-summer also had low oxygen (**Fig. 4F**) and redox potential. On some dates, our optical D.O. sensor recorded oxygen concentrations between 0.1-1.0 mg L^{-1} in the deep brine layers, even though H_2S was noted and redox potentials were highly negative. At equilibrium, H_2S, negative redox potentials, and oxygen do not normally exist together (Stumm and Morgan 1981). Consequently, these low oxygen concentrations are believed to be a consequence on either non-equilibrium conditions, interferences (In-Situ 2012), or the failure to allow the sensor to reach equilibrium as it was lowered into the deep brine layer. Regardless of the reason for the occasional measurement of oxygen in the deep layers, concentrations were <1 mg L^{-1} and H_2S was present, and thus these layers are not suitable for aquatic invertebrates.

Water temperatures in the open waters of the three bays were relatively similar and followed a normal temperate zone seasonal progression (**Fig. 5**). Farmington Bay freezes in winter, but by April of 2009, temperatures had reached 7°C. Temperatures in the open water peaked during summer near 28°C. Bear River Bay also freezes in winter, and it followed the same temperature progression as Farmington Bay. Some of the irregularity in the temperature pattern shown in **Fig. 5** may be due to pronounced diel changes (see below), as the timing of sampling varied from date-to-date. Because of the very high salinity of Gilbert Bay, it does not freeze during winter, but approaches and sometimes decreases below 0°C. During 2009,

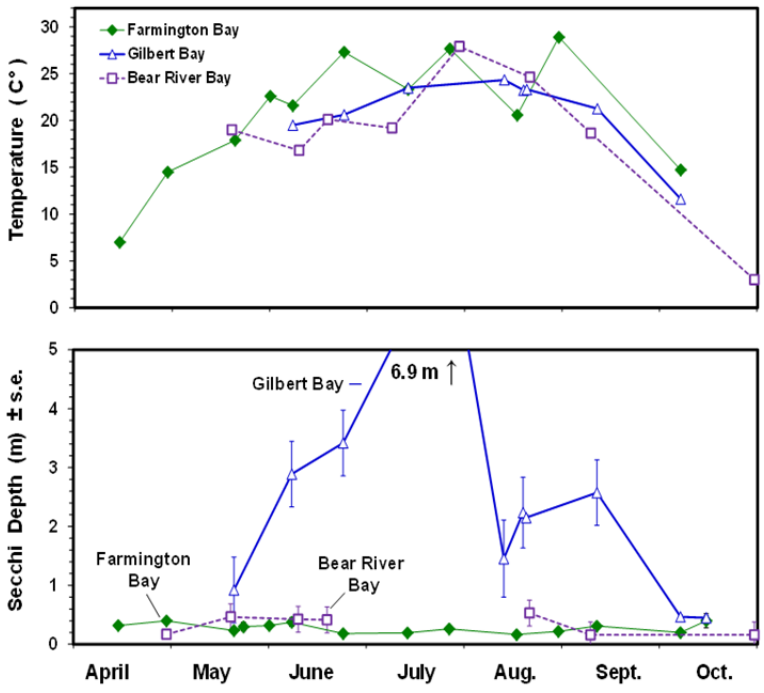

Fig. 5. Daytime temperatures (above) and Secchi depth transparencies in Farmington, Gilbert and Bear River Bays during 2009. Temperature data is from 0.2 m (Farmington and Bear River Bays) or 1 m (Gilbert Bay). Error bars for Secchi depth show the standard error from multiple stations. All the Secchi depth error bars for Farmington Bay lie within the symbol size.

temperatures reached 24°C in Gilbert Bay. These were cooler and more stable than temperatures in the shallower bays, presumably because of greater thermal inertia.

Water transparencies measured with a Secchi disk indicated that transparency was very limited in Farmington Bay with mean values near 0.25 m (**Fig. 5**). Transparencies were also low in Bear River Bay, although the shallow water in mid-summer precluded taking measurements. Transparencies were highly variable in Gilbert Bay, with spring and fall measurements < 0.5 m. However, when *Artemia* grazing on phytoplankton increased during mid-summer, Secchi depths increased to > 3 m.

Dissolved nitrogen measurements taken in 2009 indicated that approximately 80-90% of the nitrogen was present as dissolved organic nitrogen in all three bays (**Fig. 6**). Ammonia concentrations were usually undetectable in Bear River Bay, except in August when the bay was evaporating in the hot summer temperatures. In Farmington Bay, geometric mean concentrations of ammonia were 0.13 mg N L^{-1}. However, a concentration of 2.7 mg N L^{-1} was measured in Farmington Bay during spring runoff, and a concentration of 0.75 mg N L^{-1} was encountered at the south end of the bay near the discharge of the Sewer Canal during the August transect sampling. Ammonia

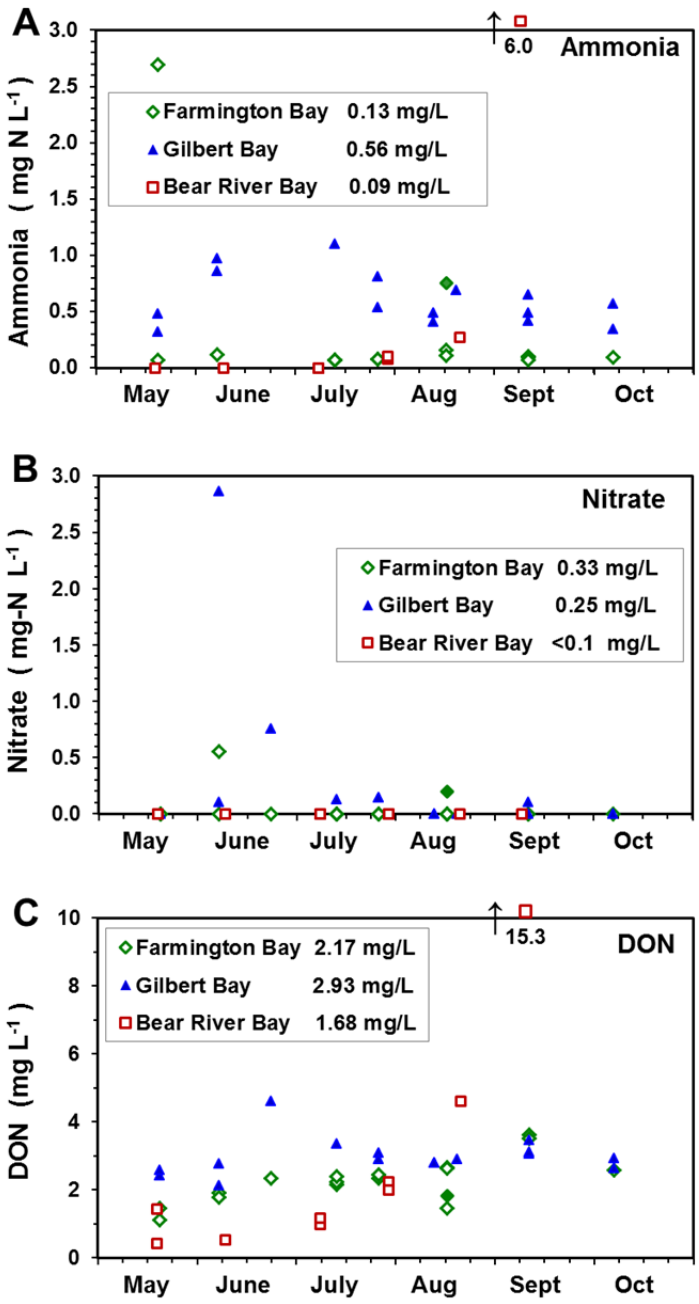

Fig. 6. Dissolved nitrogen in three bays of the Great Salt Lake during 2009. A. Ammonia-N; B. Nitrate + Nitrite N; C. Dissolved inorganic nitrogen (DON). Values for Farmington Bay are for the north end (Sta. 1, 3) except the solid green diamond in August which shows the value for Sta. 6 at the south end of the bay. Legends show geometric mean concentrations.

concentrations were relatively high throughout the sampling period in Gilbert Bay, with a geometric mean of 0.56 mg N L^{-1}.

Concentrations of nutrients that can limit phytoplankton growth were high in all three bays, but were found to be in particular abundance in Farmington Bay (**Fig. 7**). Over the three years that data was collected, respective geometric mean total phosphorus (TP) and (TN) concentrations for Farmington Bay were 0.40 and 5.0 mg L^{-1}. In Farmington Bay, there was a general trend for TP to rise over the summer, but in 2009 this trend was not obvious. In Bear River Bay, respective concentrations of TP and TN averaged 0.21 and 2.0 mg L^{-1}. However, these high values were due primarily to the dramatic increases in concentrations that were observed during mid-summer as the bay was drying up. At other times of the year, nutrient concentrations were considerably lower in Bear River Bay than in Farmington Bay. For example, in 2009, total nutrient concentrations from spring through mid-July were 300-350% higher in Farmington Bay than in Bear River Bay (**Fig. 7**). In Gilbert Bay, mean TP and TN concentrations were 0.32 and 4.7 mg L^{-1}, respectively. These remained relatively stable over the sampling period. Mean molar TN:TP ratios were near 25:1 in Farmington and Bear River Bays, and 32:1 in Gilbert Bay. However, the 2009 dissolved nitrogen data indicates that much of the nitrogen was present as dissolved organic nitrogen (DON; **Fig. 6c**), and thus not entirely immediately bioavailable for phytoplankton (Lewis and Wurtsbaugh 2008, Filippino et al. 2011).

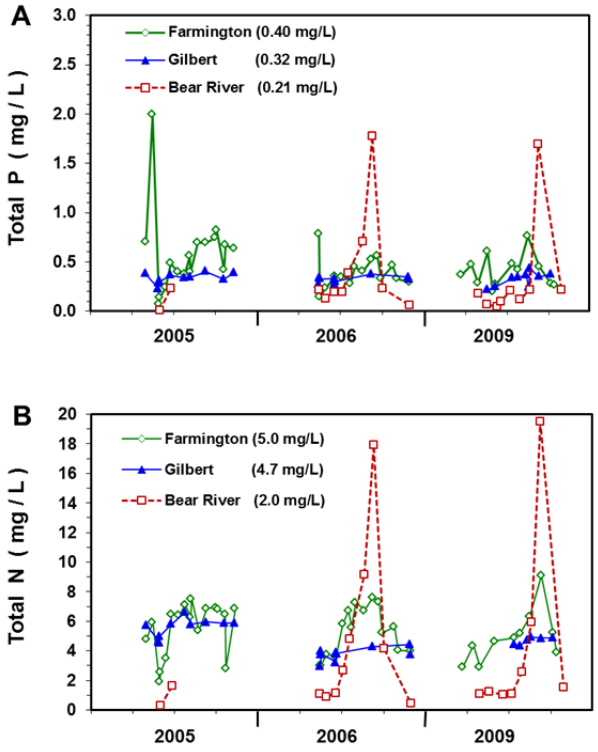

Fig. 7. Total phosphorus (top) and total nitrogen in the surface waters of three bays of the Great Salt Lake for 2005, 2006 and 2009. Values in legend show geometric mean concentrations over the three years.

Phytoplankton populations, chlorophyll and phycocyanins

Algal counts and identifications were available for four years of data. During this period in Farmington Bay, 51 genera of phytoplankton were described with a diverse representation from several divisions (Appendix 2). In contrast, in more saline Gilbert Bay, only 27 genera were described. In Bear River Bay, 44 taxa were encountered, but more may have been present since this bay was sampled less than the others. In 2009, a portion of the samples were analyzed to the species level. These results, which include the genera and species encountered, are shown in Appendix 3.

The phytoplankton biomass in the north end of Farmington Bay was high and overwhelmingly dominated by cyanobacteria, whereas Bear River Bay and Gilbert Bay had far lower algal biomasses and (**Fig. 8; Appendix 4a**). In Farmington Bay, 95% of the cyanobacterial biovolume measured in 2009 was *Nodularia spumigena*, with small amounts of *Aphanothece* sp. and *Limnothrix* sp., and trace amounts of four other taxa. The remainder of the algal biovolume in Farmington Bay was composed of diatoms (primarily *Chaetoceros* sp., *Cyclotella* sp. and *Nitzschia* sp.) and12 taxa of green algae (primarily *Chlamydomonas* sp.). This result was similar to what was encountered in other years when sampling was less thorough (**Appendix 4a**).

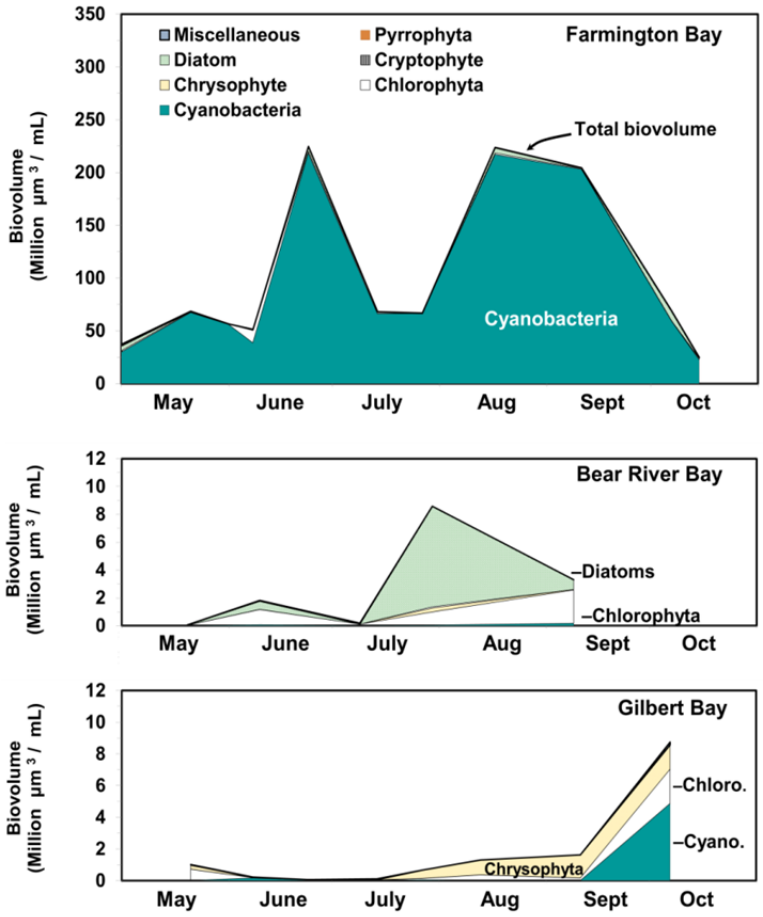

Fig. 8. Phytoplankton biovolumes in Farmington (top; Sta. 1; Sta. 0, 1, 3), Bear River (middle; Sta. 24) and Gilbert Bays (bottom; Sta. 18 and 2767) of the Great Salt Lake during 2009. The top line of these stacked polygon graphs shows the total biovolume. Note that the scale for Farmington Bay is 35X greater than for the other bays. When averaged over the entire sampling period and all stations, *Nodularia spumigena* represented 91% of the total cyanobacteria, and 86% of total algal biovolume in Farmington Bay.

The dominance of *Nodularia* in Farmington Bay occurred when salinities were between approximately 1 and 5% (**Fig. 9**). At these salinities, *Nodularia* cell densities frequently exceeded 0.5 million per ml and reached a maximum of 1.65 million cells per ml. The exception to this relationship was at the south end of Farmington Bay (Sta. 5-6) which was sampled during transects in 2005 and 2009. *Nodularia* were absent in these samples, even in the 1-3% salinity range.

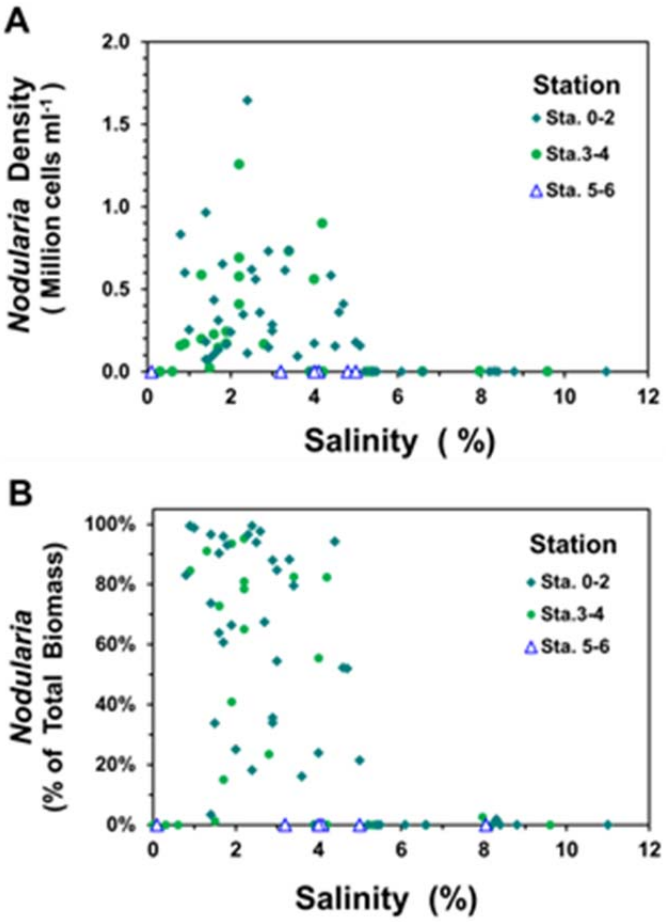

Figure 9. Densities (A) and relative biovolume (B) of *Nodularia spumigena* in Farmington Bay in relation to salinity. Stations 0-2 were in the northern part of the bay, 3-4 were centrally located, and 5 and 6 were in the south. Open circles and diamonds show data from November-February when temperatures were < 8°C. Data from 2002, 2003, 2005 and 2009 are included.

In Bear River Bay, 46% of the biovolume in 2009 was composed of green algae (primarily *Geminella* sp., *Pyramichlamys* sp., *Dunaliella viridis*, and *Nannochloris* sp.) and 46% were diatoms (primarily *Nitzschia* sp. and *Cylindrotheca* sp.). Only 1.5% of the biovolume was composed of cyanobacteria (primarily *Pseudanabaena* sp.). Again, these results are consistent with limited sampling conducted in 2002 and 2005 (**Appendix 4b**).

In 2009 the phytoplankton biovolume in Gilbert Bay was composed of 28% chrysophyte (*Chromulina* sp.), 20% green algae dominated overwhelmingly by *Dunaliella viridis*, and 49% cyanobacteria (**Fig. 8**). However, the large amount of cyanobacteria was probably due to *Nodularia* exported from Farmington Bay. *Nodularia* represented 97% of the cyanobacteria in Gilbert Bay, yet it cannot grow or compete well above salinities of ~5% (Moisander et al. 2002, Marcarelli et al. 2006, Roney et al. 2009), so it is unlikely it was produced in Gilbert Bay where salinities were above 13%. A study of the Farmington Bay overflow plume in Gilbert Bay demonstrated that Nodularia decreases quite rapidly within a few kilometers of exiting Farmington Bay (Wurtsbaugh and Epstein 2011). In all years sampled, the green algae *Dunaliella viridis* was the numerical dominant alga in Gilbert Bay (**Appendix 2**), but during some periods other taxa with larger cell sizes contributed more to the biovolume (**Appendix 4c**).

Chlorophyll levels in the three bays were consistent with the biovolume measurements, and showed exceedingly high concentrations in Farmington Bay and relatively moderate concentrations in Bear River and Gilbert Bays (**Fig. 10**). Over six years, the mean chlorophyll level in Farmington Bay was

141 µg L^{-1}, but climbed over 470 µg L^{-1} in August 2005. There was considerable year-to-year variation. Chlorophyll levels were nearly always above levels considered to be hypereutrophic (56 ug L-1; Carlson and Simpson 1996), except for rare occasions in the spring when zooplankton grazing rates were high (see below, **Fig. 19**). Mean chlorophyll levels in Bear River Bay were 22 µg L^{-1} (eutrophic). In Gilbert Bay, the mean value for spring through fall sampling was 16 µg L^{-1}, but concentrations climbed above 50 µg L^{-1} in winter and early spring when grazing by *Artemia* was reduced.

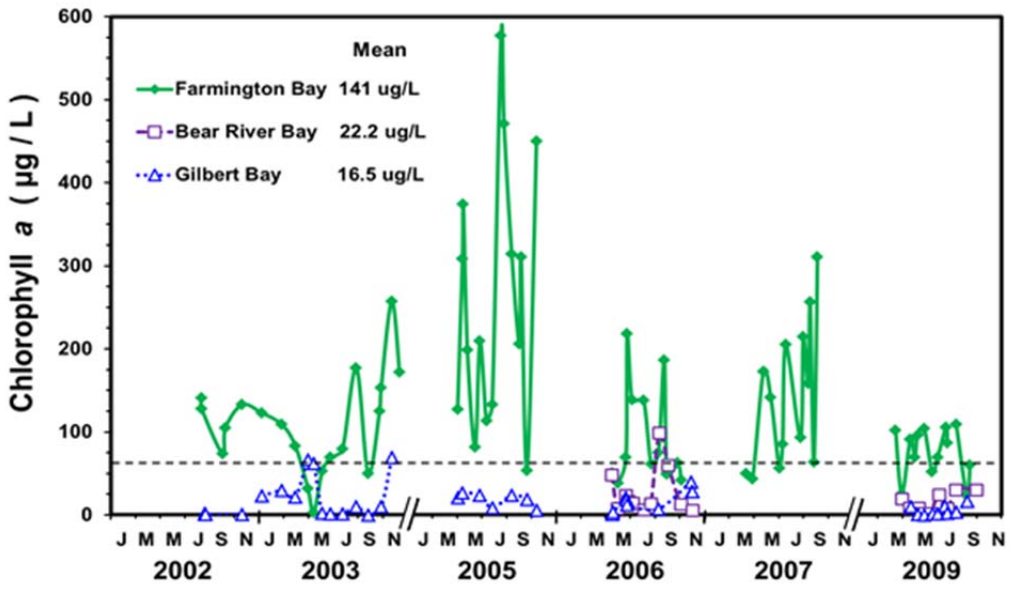

Fig. 10. Chlorophyll *a* levels of phytoplankton in three bays of the Great Salt Lake, spanning the years 2002-2009. Note that sampling was not done in 2004 or 2008, and that Bear River Bay was only sampled in 2006 and 2009**.** Most points show the mean of 2-4 stations. The mean concentrations for the entire sampling period are shown in the legend. Note that relatively little sampling was done in the winter months, and chlorophyll concentrations in Gilbert Bay often climb above 50 µg L-1 when brine shrimp grazing ceases during this period (Wurtsbaugh and Gliwicz 2001, Belovsky et al. 2011). The dotted line shows the minimum level for hypereutrophic classification (Carlson and Simpson 1996).

Although *Nodularia* abundance and chlorophyll concentrations were exceedingly high in Farmington Bay, surface blooms (scums) were not commonly encountered in the open water of the bay. However, on a few occasions large scums of floating *Nodularia* were present (**Fig. 11**). These scums did not appear to cause bias in the analysis of chlorophyll or algal biomass. For example, on the May 15, 2005 date shown in **Fig. 10**, the chlorophyll was measured with a 1.1-m long tube sample, and thus integrated the full mixed layer, not just the surface scum. Additionally, even higher chlorophyll levels were encountered on other dates when surface scums were not present. The general lack of large surface scums was likely due to the large fetch and wind action over Farmington Bay which mixes the water column, combined with the fact that no sampling was conducted close to shore where scums are usually pushed.

Fig. 11. Surface bloom of toxic *Nodularia spumigena* in Farmington Bay (Station 2) on 15 May 2005. The bloom covered an area of approximately 5-10 km^2. Antelope Island is in the background.

Phycocyanin concentrations, a measure of cyanobacterial abundance, were also far higher in Farmington Bay than in Gilbert or Bear River Bays (**Fig. 12a**). The phycocyanin concentrations were highly correlated ($R^2 = 0.89$) with cyanobacterial biovolumes (**Fig. 12b**), indicating that the simple measure of this pigment provides a reasonable index of cyanobacterial abundance.

Cyanotoxin forms and concentrations

Liquid-chromatographic mass-spectrometric (LCMS) analyses indicated that the only cyanotoxins present in Farmington Bay were two common variants of nodularin: arg(2)- nodularin and demethyl nodularin. No microcystin variants were found.

Cyanotoxin concentrations were often very high in Farmington Bay, reaching a concentration over 600 µg L^{-1}

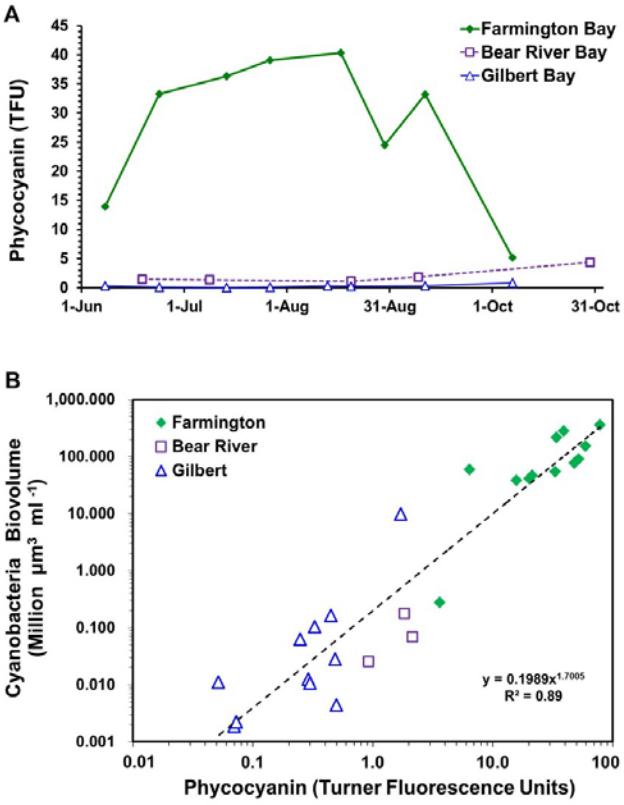

Fig. 12. **A.** Changes in the mean relative fluorescence (Turner Fluorescence Units, TFU) of the cyanobacterial pigment phycocyanin in three bays of the Great Salt Lake during the spring-fall period of 2009. **B.** Relationship between phycocyanin fluorescence and the biovolume of cyanobacteria in three bays of the Great Salt Lake during 2009.

microcystin-LR equivalents at one station in October 2009 (**Fig. 13**). Over the entire study, mean concentrations in Farmington Bay were 41 µg L^{-1}, but there were large differences between years. Concentrations of cyanotoxins tracked *Nodularia* abundances in Farmington Bay, and were highest when salinities were between 1-5% (c.f. **Figs. 3, 13**). Concentrations generally were high following spring runoff, but declined later in the summer when salinities rose above 5%. In 2007 this occurred in mid-June, and cyanotoxins were low for the rest of the summer. In 2009, however, salinities were below 5% for most of the summer, and cyanotoxin concentrations remained high. Mean cyanotoxin levels from May-August in 2006, 2007 and 2009 were 20, 14 and 104 µg L^{-1} respectively. In 2009, when both algal counts and cyanotoxin measurements were available, the concentrations of cyanotoxins were significantly correlated with the abundances of *Nodularia* in Farmington Bay ($p < 0.001$; **Fig. 14**).

In contrast to Farmington Bay, cyanotoxin levels in Bear River and Gilbert Bays were usually undetectable or present at low concentrations (**Fig. 13**). In Bear River Bay, cyanotoxins were found on only a single date (7 July 2006) when microcystin LR equivalents reached 5.8 µg L^{-1}. Mean overall concentrations for the two years cyanotoxins were measured in Bear River Bay was 0.3 µg L^{-1}. In Gilbert Bay, cyanotoxins at < 1 µg L^{-1} were frequently detected, but the mean concentration for the two years was only 0.5 µg L^{-1}. The highest concentration detected during this time was 5.2 µg L^{-1}.

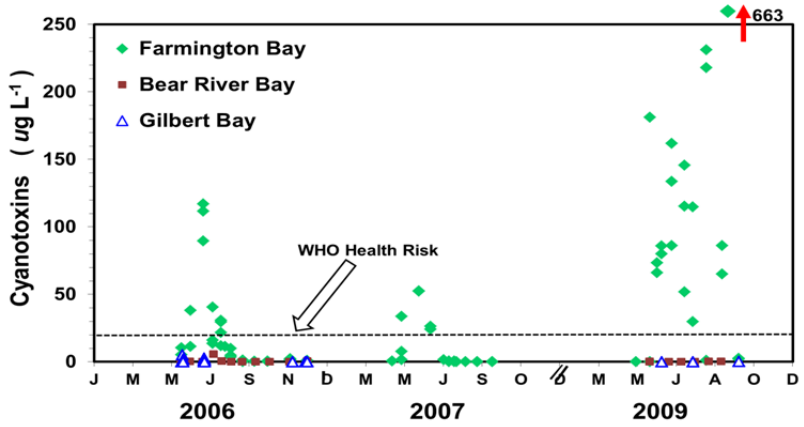

Fig. 13. Cyanotoxin levels determined by PPIA analysis in three bays of the Great Salt Lake for three years. Values for Farmington Bay are for the northern end of the embayment, and span three years. Values are expressed as microcystin LR equivalents, but in Farmington Bay, mass spectrometer analyses indicated that all of the toxin was nodularin. The dotted line shows the level for moderate risk for contact recreation as determined by the World

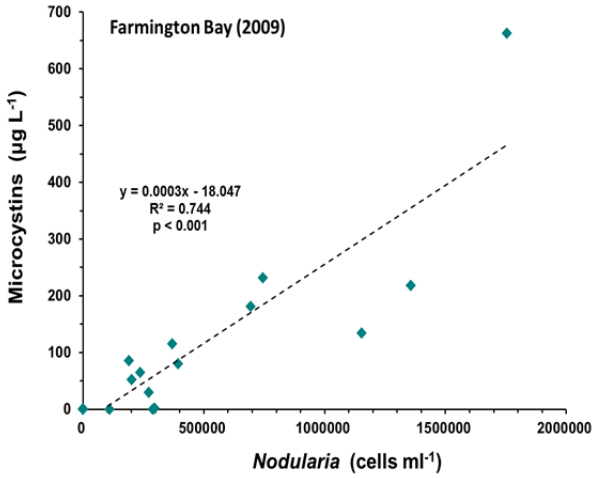

Fig. 14. Relationship between *Nodularia spumigena* densities and microcystin L-R equivalents in Farmington Bay in 2009.

Cyanobacterial gradient in the Farmington Bay "estuary"

In many years there is a strong gradient in many variables from the southern to the northern end of Farmington Bay because nearly all freshwater inflows enter from the south (Jordan River, Sewer Canal, South- and Central Davis wastewater discharges). Conversely, high-salinity water enters the north end of the bay as a salt wedge through the breach in the Antelope Island automobile causeway. During high wind events, a portion of the salt wedge (deep brine layer) likely mixes into the upper layer, although the magnitude of this mixing has not been quantified. Our limited sampling of dissolved nutrients suggests that they are also higher at the south end of the bay (**Fig. 6**), likely because of wastewater discharges from the Sewer Canal and other facilities.

These chemical gradients contribute to a gradient in cyanobacterial biomass and cyanotoxins from the south to the north end of the bay (**Fig. 15**). On the August, 2009 sampling date, salinity at the south end of the bay was 0.3%, but it increased steadily, reaching 6% at a sampling point 3-km south of the automobile causeway (**Fig. 15a**). An unexpected drop in salinity at the causeway bridge was also observed, perhaps reflecting a surface flow of wastewater from the North Davis Sewer Improvement District discharge. Chlorophyll levels were lowest at the south end of the bay, but still were at a concentration of 46 µg L^{-1}. Chlorophyll peaked at over 180 µg L^{-1} in a sample collected 16 km from the causeway bridge, and then declined to levels near 100 µg L^{-1} in the northern end of the bay. Phycocyanin levels, a measure of cyanobacterial biomass, were low at the southern end of the bay and increased in concentration along the transect. By station 4, where the salinity was 3.3%, the concentration of phycocyanin was 15-fold higher than at the southern end of the bay (**Fig. 15b**). There was a moderate decline in phycocyanin north of station 4. *Nodularia* biovolume (**Fig. 15c**) was negligible at the southern end of Farmington Bay, peaked 11 km from the bridge, and then declined unexpectedly to intermediate levels at a site 4 km south of the bridge.

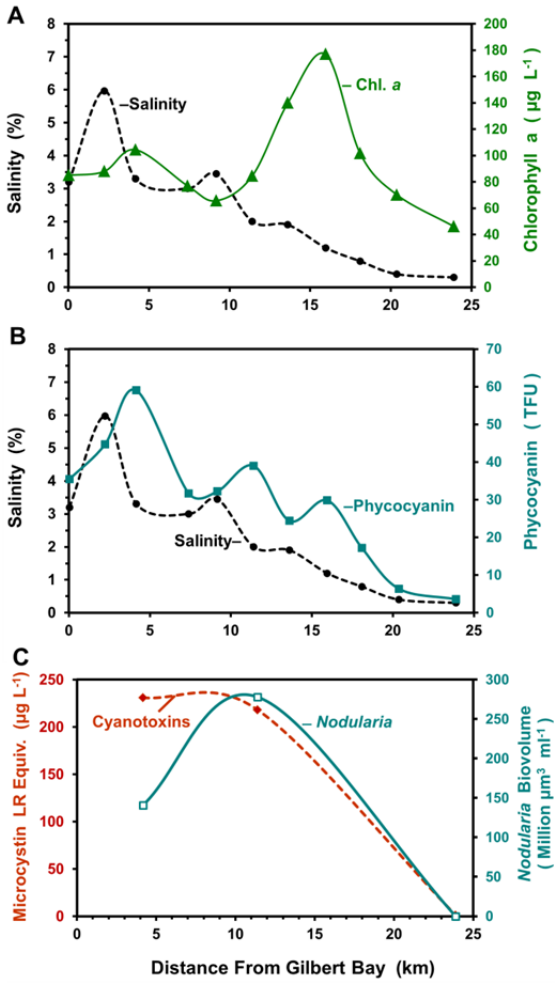

Fig. 15. Longitudinal gradients in salinity, phytoplankton and cyanotoxins along a longitudinal transect in Farmington Bay, 17 August 2009. Station 0, at the Causeway Bridge, was at a distance of 0 km from Gilbert Bay and Station 6 was at 24 km in the south end of Farmington Bay. **A.** Salinity and chlorophyll levels along the transect. **B.** Phycocyanin concentrations (in arbitrary Turner Fluorescence Units, TFU) and salinity along the N-S gradient. **C.** Cyanotoxins and *Nodularia* biomass (only measured at stations 1, 3 and 6).

Cyanotoxin levels were also negligible at the south end of the bay, but were exceedingly high in the central and northern part of the bay (**Fig. 15c**). More transect sampling is necessary to better characterize the longitudinal gradients in Farmington Bay, and to determine how salinity and nutrients control the algal communities that develop.

Dissolved oxygen and pH

Diel changes in dissolved oxygen, pH and temperature were high in Farmington Bay. A recording sonde in the open water of the northern region of Farmington Bay (Sta. 1) indicated that oxygen concentrations in the mixed layer frequently declined to zero at night, and became supersaturated (>100%) during the day (**Fig. 16a**). Diel temperature fluctuations were typically 5-6°C, with temperatures climbing to over 30°C (86°F) during the day. Fluctuations in pH also occurred, and pH reached 9.5 on some afternoons when photosynthesis was high (photosynthesis utilizes carbon dioxide, an acid: removing it causes the pH to rise). Readings from the pH sensor, however, drifted through time, making values recorded after one week of deployment suspect.

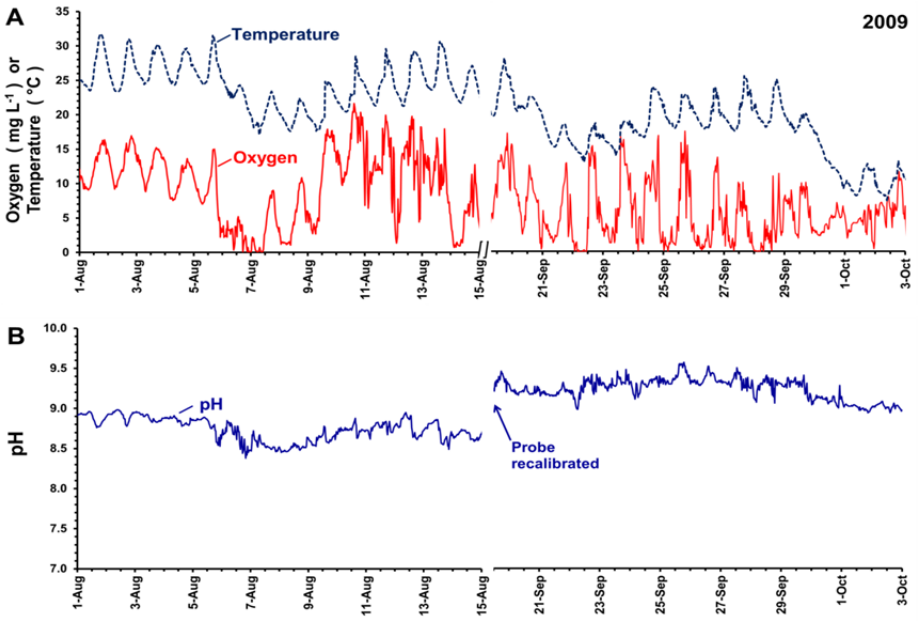

Fig. 16. Oxygen and temperature (A) and pH fluctuations in August and September-October 2009 in the open water of Farmington Bay (Station 1), measured at a depth of 0.2 m. Note the scale break after August 15. Measurements were taken at 30-minute intervals with an InSitu recording sonde utilizing an optical dissolved oxygen sensor.

In the shallower waters of Farmington Bay, the diel changes were even greater than in the open water. At the south end of Farmington Bay, oxygen dropped to zero for 6 hours or longer each night, and reached concentrations as high as 40 mg L^{-1} during the day (**Fig. 17**). On cloudy days, anoxic periods were longer, and oxygen levels did not climb as high during the day. At a 0.28-m deep site on the NE side of the bay, oxygen cycles were not as pronounced, but nighttime anoxia and daytime

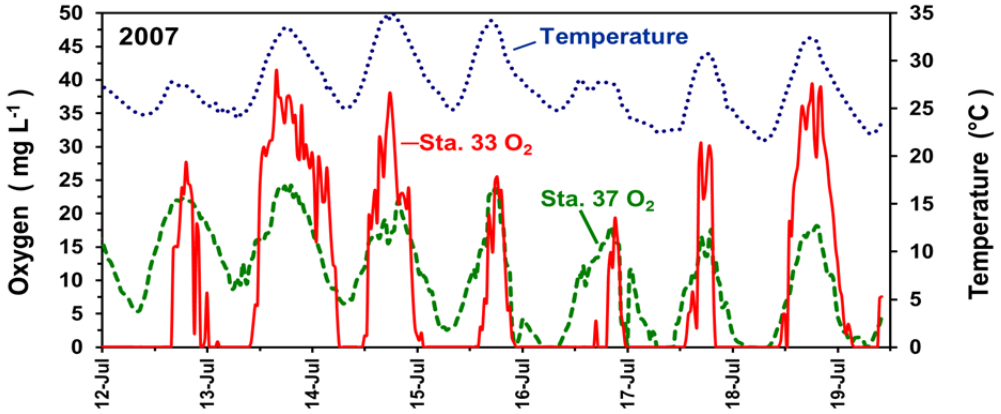

Fig. 17. Dissolved oxygen concentrations in July, 2007 at shallow stations in Farmington Bay at the south end (Sta. 33; 0.28 water depth) and on the NE side of the bay (Sta. 37; 0.28 m water depth). The temperatures for station 37 are also shown. The days with lower peak oxygen, and longer periods of hypoxia, were cloudy. Measurements were taken at 30-minute intervals with InSitu recording sondes.

supersaturation were common. In the shallow waters, diel temperature fluctuations were as much as 10°C, with temperatures reaching35°C during sunny July days (**Fig. 17**).

Oxygen fluctuations in Gilbert Bay were much less than in Farmington Bay (**Fig. 18**). This makes sense given Gilbert Bay's deeper waters. A comparison of diel changes in oxygen in the two bays is only available for a single 20-hour period. During this measurement period, oxygen varied only moderately in Gilbert Bay, whereas concentrations in Farmington Bay went from supersaturation during the afternoon to zero during the early morning. During this period strong winds began at night, and mixing of Farmington Bay's deep brine layer into the surface water may have contributed to the decline in oxygen. This is likely because the deep layer water contains substantial hydrogen sulfide (H_2S) that can react with dissolved oxygen and remove it from the mixed layer (see below).

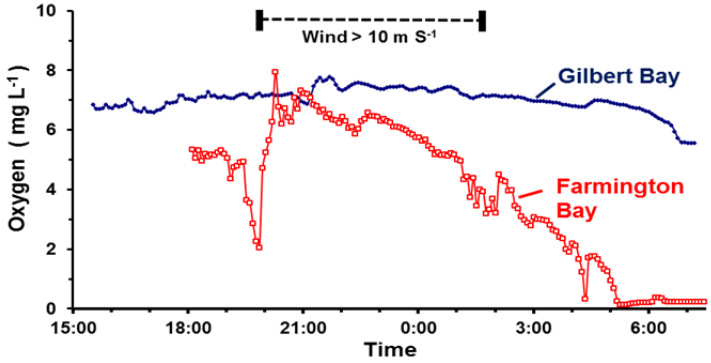

Fig. 18. Diel changes in oxygen concentration in Farmington Bay (Station 1) and Gilbert Bay (Bridger Bay) on October 3-4, 2003 recorded with YSI sondes. The sondes were not calibrated for the high-salinity water of Farmington and especially Gilbert Bay, so the absolute values are suspect. A strong wind with gusts as high as 14 m s^{-1} (32 mph) began blowing at 20:00 hours and continued until 02:00 the following morning. The dip in oxygen at 20:00 in Farmington Bay may have been due to entrainment of deep brine water with H_2S which may have been oxidized by the DO.

Zooplankton biomass and grazing rates

Zooplankton composition, biomass and grazing rates differed markedly between the three bays (**Fig. 19**). In Farmington Bay, zooplankton biomass was very high and dominated by a mix of cladocera (primarily *Moina* sp. and *Daphnia* spp.), calanoid copepods (primarily *Leptodiaptomus connexus*), cyclopoid copepods (*Acanthocyclops robustus*), harpactocoid copepods (*Cletocamptus albuquerquensis*), *Artemia*, and water boatmen (primarily *Trichocorixa verticalis*). A very large peak in *Daphnia* occurred during mid-May, but their overall biomass during the study period was near 1000 $\mu g\ L^{-1}$. Corixids did not become abundant until mid-summer (**Fig. 19a**).

In Gilbert Bay, the biomass of *Artemia* was very high in the spring (ca. 2000 $\mu g\ L^{-1}$), but it declined steadily over the summer, reaching 112 $\mu g\ L^{-1}$ by October (**Fig. 19b**). In addition to *Artemia*, a small biomass of brine fly larvae (*Ephydra* sp.) was found, but these were likely transients migrating between different benthic habitats.

In Bear River Bay zooplankton biomass was much lower than in the other two bays (**Fig. 19c**). There was a small peak in cladocera in mid-May, but subsequently the biomass was dominated by a mixture of different species of water boatmen (Corixidae). We did not encounter *Artemia* in Bear River Bay.

Estimated grazing rates of zooplankton on the phytoplankton also differed considerably between bays (**Fig. 19d-f**). In Farmington Bay, the high biomass of grazers produced estimated rates nearing, or even exceeding, 100% of the water column grazed per day (**Fig. 19d**). Cladocera were the dominant grazers, but *Artemia* were moderately important in the spring. Grazing rates were also high in Gilbert Bay in the spring and early summer, but with the decline of *Artemia* biomass in the late summer and fall, estimated grazing rates dropped to around 10% per day (**Fig. 19e**). The very low biomass of grazers in Bear River Bay (**Fig. 19c**) had estimated grazing rates of less than 2% per day throughout the summer (**Fig. 19c**).

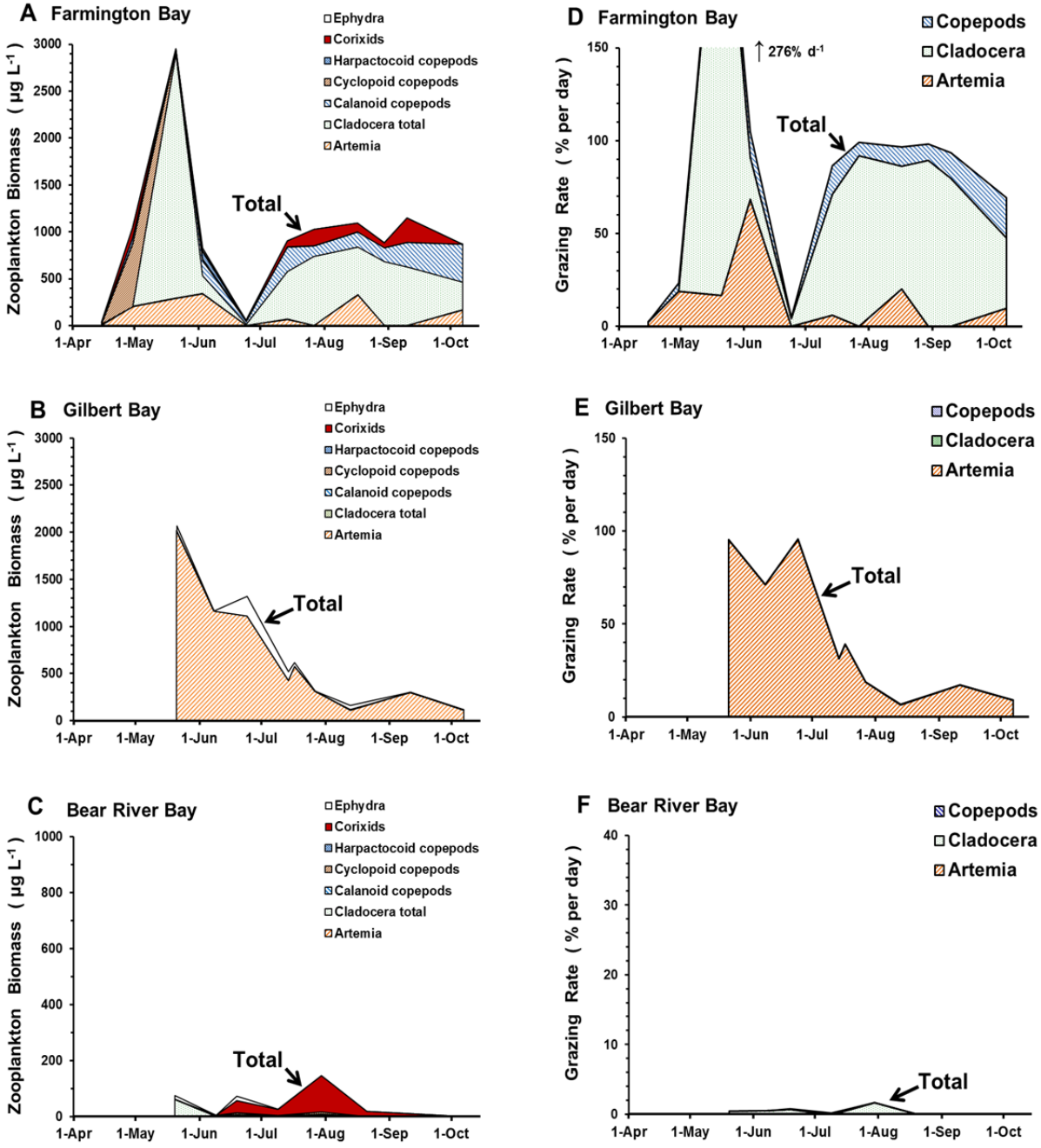

Fig. 19. Left (A-C): Zooplankton biomasses in three bays of the Great Salt Lake during 2009. Right (D-F): Estimated grazing rates of three taxonomic groups in each of the three bays expressed as percent of the water column filtered per day. The total biomass or community grazing rate is indicated by the top line in each graph. Note the different vertical axis for Bear River Bay.

Bird density survey

The transect surveys indicated that birds were much less abundant in the open water area of the northern section of Farmington Bay than in Gilbert Bay (**Fig. 20**). In August, eared grebes (*Podiceps nigricollis*) were only 21% as abundant in Farmington Bay as in Gilbert Bay (**Fig. 20a**), and phalaropes (*Phalaropus* spp.) in Farmington Bay were only 4% as abundant as in Gilbert (**Fig. 20b**). Similarly, Franklin gulls (*Leucophaeus pipixcan*) and other gulls (primarily California gulls, *Larus californicus*) were far more abundant in Gilbert than in Farmington Bay (**Fig. 20c, d**). Ducks, although not abundant during the surveys, were also more abundant in Gilbert than in Farmington Bay (**Fig. 20e**). On most survey dates there was considerable spatial variability in the abundances of birds within each bay, leading to

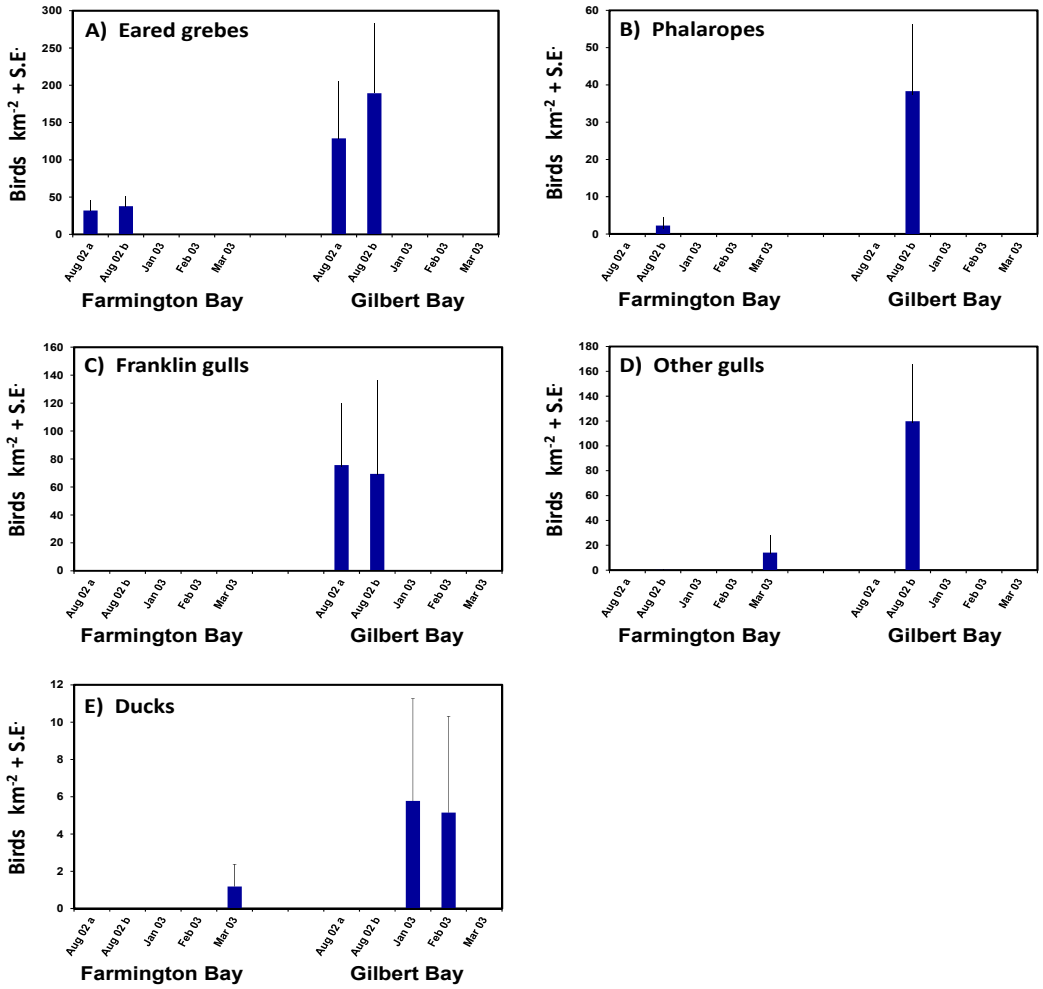

Fig. 20. Estimated bird densities in the open waters of Farmington and Gilbert Bays during five periods in 2002 and 2003. Each histogram is the average of 5 individual transects in Farmington Bay or 3-7 in Gilbert Bay. Dates of surveys were 13-19 Aug 2002, 27 Aug 2002, 21 Jan 2003, 26 Feb 2003 and 31 Mar 2003. Densities were estimated by visual counts from a moving boat, and therefore are approximate, but relative densities between bays should be comparable. Error bars are standard errors of the individual transects within each bay.

high error estimates. Nevertheless, even though the temporal extent of the surveys was limited and there was potential for observer bias, the magnitude of the differences indicates that bird densities in the pelagic area of the northern half of Farmington Bay are considerably less than along the eastern margin of Gilbert Bay.

Odor survey of people living near the Great Salt Lake

The survey of people living or working near the Great Salt Lake indicated that offensive odors were primarily associated with Farmington Bay and not Gilbert or Bear River Bays (**Table 3**). A total of 505 responses were obtained. Responses of people driving to Antelope Island across the automobile causeway were most negative, with frequent ratings of "strong" and "unbearable". However, without wind direction data, it is unclear whether those odors derive from Farmington Bay or from the shallow waters of Ogden Bay on the north side of the automobile causeway.

Table 3. Odor survey of residents, workers and visitors to the Great Salt Lake, August-December, 2003. Participants were asked to rate the odor level for each day on the following scale: 1-None; 2-Mild; 3-Moderate; 4-Strong; 5-Unbearable. Average, minimum (Min.) and maximum (Max.) scores are shown.

		Score		
Location	Responses	Average	Min.	Max.
Farmington/Ogden Bays: Responses of people driving to Antelope Is.	109	3.3	1	5
Farmington/Ogden Bays: Gate for Antelope Island State Park	94	1.6	1	5
Farmington Bay: Farmington Bay Refuge	92	1.2	1	3
Bear River Bay: Bear River Migratory Bird Refuge	17	1.2	1	3
Gilbert Bay/Farmington Bay: Antelope Island	12	1.7	1	3
Gilbert Bay: Great Salt Lake State Park - Saltair	97	1.1	1	4*
Gilbert Bay: Promentory Point	84	1.5	1	3

* Wind from east (i.e. Farmington Bay)

Responses from people working on Antelope Island were limited, but showed only moderate levels of objectionable odors. Responses from the Farmington Bay refuge at the south end of Farmington Bay, the Great Salt Lake State Park, and the Bear River Migratory Bird Refuge (north end of Bear River Bay), were the most favorable. The only "strong" rating from this group occurred when winds were blowing from Farmington Bay towards the Great Salt Lake State Park on the south end of Gilbert Bay. Responses from the single household on Promontory Point were modest, and the worst odor rating was "moderate". The residents at this site would have experienced odors primarily from Gilbert Bay, but rare NE or E winds would have advected odors from Bear River Bay or Ogden Bay.

Most (75%) of the category 2-3 odors were placed in the "earthy" (musky, swampy), "fishy" (dead fish, ocean) or an "other" categories, whereas category 4-5 odors were classified as "offensive" (decay, rotten eggs, sewage) 53% of the time, or as earthy (39%).

Metal concentrations in zooplankton

Concentrations of several metals or metalloids in zooplankton exceeded US Fish and Wildlife Service or other benchmark concentrations of concern on some dates or at some stations (**Fig. 21**). In Gilbert Bay, visual inspection of the zooplankton samples indicated that they were composed entirely of *Artemia*. In Bear River Bay, the zooplankton were composed primarily of water boatman (corixids; 81%), whereas in Farmington Bay the samples were split primarily between cladocera (58%) and corixids (28%).

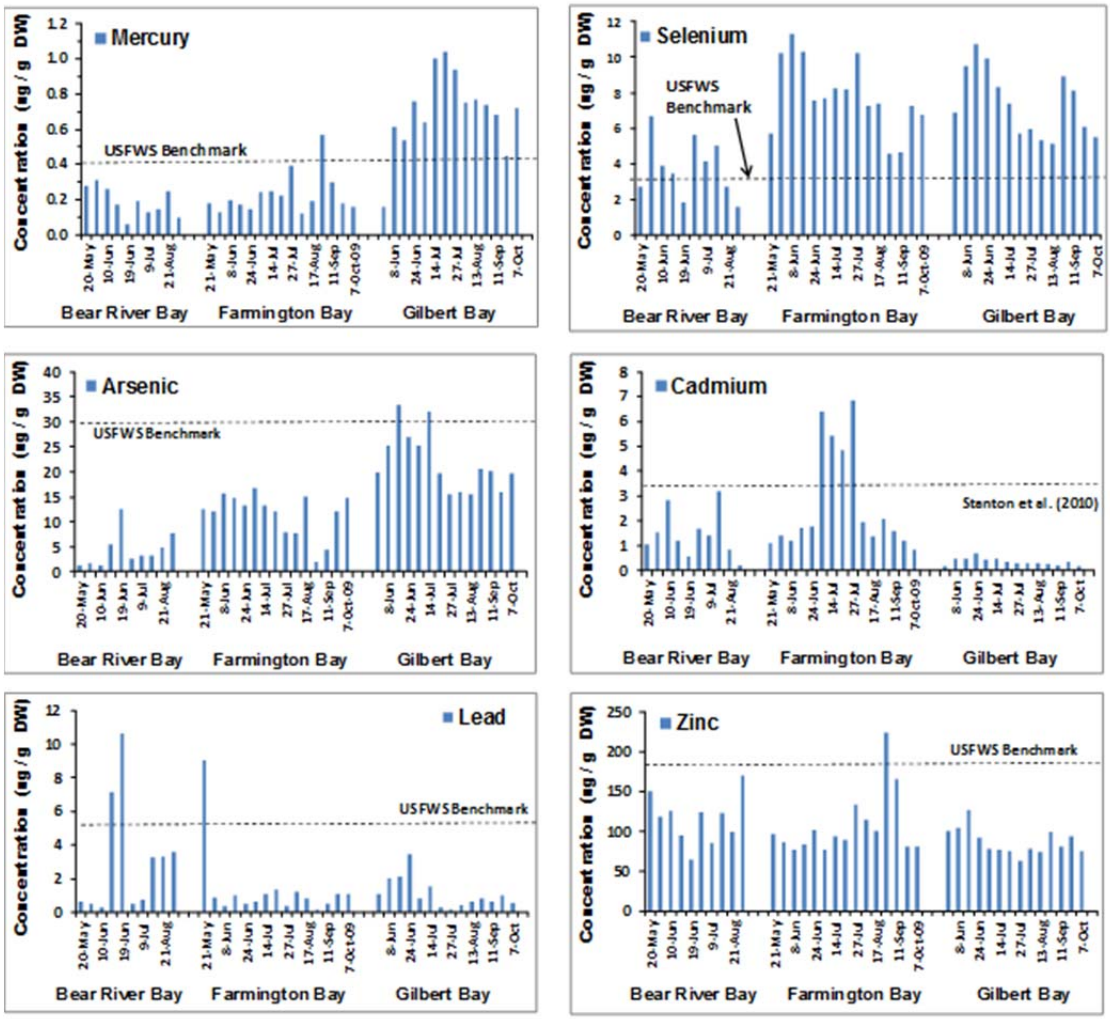

Fig. 21. Concentrations of six metals in zooplankton collected from Bear River Bay, Farmington Bay and Gilbert Bay in 2009. On most dates, two different stations were sampled. Only metals that exceeded benchmark reference concentrations in one or more samples are shown here. Benchmark concentrations for most of the toxins are from the U.S. Fish and Wildlife Service (USFWS). The benchmark for cadmium (3.3 µg g^{-1}) was estimated from a consumption toxicity reference value of 0.7 mg Cd $kg^{-1}d^{-1}$ (Stanton et al. 2010) and an assumed food ingestion rate of 0.214 kg_{dry} food $kg_{wet}^{-1}d^{-1}$ (EPA 2005). Zooplankton in Gilbert Bay were exclusively *Artemia franciscana*, whereas those in Bear River and Farmington Bays were combinations of cladocerans, corixids and other taxa. Concentrations of other metals are given in Table 4 and Appendices 5-7. Metal concentrations are expressed relative to the dry weight (DW) of the zooplankton.

Mercury concentrations in *Artemia* of Gilbert Bay exceeded the benchmark concentration of 0.4 µg g^{-1} dry weight on most sampling dates, and the concentrations were significantly higher than in the two other bays (**Fig. 21; Table 4**). Concentrations of mercury in *Artemia* were highest (>0.8 µg g^{-1}) in three samples collected in July. Respective mean mercury concentrations in *Artemia* were 0.65, 0.21, 0.17 µg g^{-1} in Gilbert, Farmington, and Bear River Bays (**Table 4**).

Metal/metalloid	Symbol	Geometric Mean Concentration (mg g^{-1} ; ppm)			Probability of Significant Differences			
		Gilbert Bay	Bear River Bay	Farmington Bay	ANOVA p	Gilbert vs Bear River	Gilbert vs Farmington	Farmington vs Bear River
Antimony	**Sb**	**0.084**	**0.050**	**0.049**	**0.04**	0.10	**0.05**	1.00
Arsenic	**As**	**21.09**	**3.44**	**10.44**	**0.00**	**0.00**	**0.00**	**0.00**
Cadmium	**Cd**	**0.34**	**1.16**	**2.08**	**0.00**	**0.00**	**0.00**	0.07
Chromium	Cr	1.36	1.26	1.22	0.91	0.95	0.90	1.00
Cobalt	**Co**	**0.40**	**0.61**	**0.19**	**0.00**	0.16	0.01	**0.00**
Copper	Cu	15.27	19.14	16.94	0.62	0.59	0.87	0.85
Lead	Pb	0.85	1.60	0.82	0.20	0.27	1.00	0.22
Mercury	**Hg**	**0.65**	**0.17**	**0.21**	**0.00**	**0.00**	**0.00**	0.52
Molybdenum	**Mo**	**0.38**	**0.63**	**0.74**	**0.01**	0.09	0.01	0.77
Nickel	Ni	1.11	1.22	0.66	0.12	0.95	0.21	0.16
Selenium	**Se**	**7.18**	**3.43**	**7.56**	**0.00**	**0.00**	0.91	**0.00**
Silver	**Ag**	**0.006**	**0.009**	**0.065**	**0.00**	0.48	**0.00**	**0.00**
Strontium	**Sr**	**15.0**	**100.1**	**62.9**	**0.00**	**0.00**	**0.00**	0.52
Tin	**Sn**	**0.077**	**0.038**	**0.024**	**0.02**	0.28	**0.02**	0.53
Vanadium	**V**	**0.69**	**1.03**	**0.44**	**0.05**	0.49	0.31	**0.04**
Zinc	**Zn**	**85.7**	**111.4**	**101.6**	**0.06**	**0.05**	0.20	0.67

Table 4. Geometric mean concentrations of metals and metalloids in zooplankton that exceeded threshold concentrations on at least one date. The samples were collected in the three bays during 2009. Concentrations are in mg per gram dry weight of zooplankton. The columns on the right show significant differences between bays determined by Tukey's HSD post-hoc test (after ANOVA). Data in bold indicate significant differences between stations ($p < 0.05$). For data that have significant differences, the highest concentration among the three bays is underlined.

Selenium concentrations in the zooplankton consistently exceeded the benchmark concentration of 3 µg g^{-1} in Gilbert Bay and Farmington Bay, and also exceeded benchmarks on several dates in Bear River Bay (**Fig. 21**). Respective mean concentrations during the study were 7.2, 7.6 and 3.4 mg g^{-1} dry weight for Gilbert, Farmington and Bear River Bays. Concentrations in Gilbert and Farmington Bay did not differ markedly, but both were significantly higher than in Bear River Bay (**Table 4**).

Arsenic concentrations in the zooplankton differed significantly among all three bays, but were highest in Gilbert Bay, where concentrations exceeded the benchmark level of 30 µg g^{-1} in only two of the fourteen samples (**Fig. 21**; **Table 4**). The mean concentration in Gilbert Bay was 21 µg g^{-1}. Mean arsenic concentrations in zooplankton from Farmington Bay (10 µg g^{-1}) were about 50% of those in Gilbert Bay. Arsenic concentrations in the Bear River Bay zooplankton were low (3.4 µg g^{-1}).

In contrast to the metals discussed above, mean cadmium concentrations in zooplankton (0.3 μg g^{-1}) from Gilbert Bay were significantly lower than in Farmington (2.1 μg g^{-1}) or Bear River Bay (1.2 μg g^{-1}). Cadmium concentrations were particularly high in Farmington Bay during July, and the benchmark concentration of 3.3 μg g^{-1} was exceeded in 4 samples (**Fig. 21; Table 4**).

Lead was considerably below benchmark concentrations in nearly all of the zooplankton samples, but two samples in Bear River Bay and one in Farmington Bay exceeded the 5 μg g^{-1} threshold (**Fig. 21**). Because of the high variability between sample dates and stations, there were no significant differences in lead concentrations between the three bays (**Table 4**).

Zinc concentrations in zooplankton were always below the threshold concentration of 178 μg g^{-1} except for a single sample taken in Farmington Bay (**Fig. 21**). Zooplankton zinc concentrations were marginally lower in Gilbert Bay than in Bear River Bay (t-test; p =0.05), but the mean concentrations differed only slightly (86 vs. 111 μg g^{-1}; **Table 4**).

Geometric mean concentrations of these and other metals (antimony, chromium, cobalt, copper, molybdenum, nickel, silver, strontium, tin, and vanadium) in zooplankton are shown in **Table 4**. An interesting observation from this table is that across the suite of metals, none of the bays exhibited consistently high concentrations. For example, Gilbert Bay zooplankton had significantly higher concentrations of antimony, arsenic, mercury, and tin, whereas Farmington Bay had significantly higher concentrations of cadmium, molybdenum, selenium, and particularly silver. Additionally, the zooplankton in Bear River Bay had significantly higher concentrations of cobalt, strontium, and vanadium than the other bays.

Discussion

Nutrient, salinity and grazer control of eutrophication in the Great Salt Lake

Nutrients–Although thorough nutrient loading estimates to the bays of the Great Salt Lake are not available, preliminary estimates indicate that N and P discharges are high, particularly to Farmington Bay. In a preliminary analysis Wurtsbaugh (2007) estimated that P loading to Farmington Bay was near 2.5 g P m^{-2} yr^{-1}, with most of the phosphorus coming from discharges of wastewater treatment plants. The amount of P loading to Farmington Bay is far above the 0.1 mg P m^{-2} yr^{-1} estimated to cause "dangerous loading" (*sensu* Vollenweider 1968) in shallow freshwater lakes (Wetzel 2001). Wurtsbaugh's loading estimate did not, however, account for nutrients removed from Jordan River water as it passes through wetlands at the south end of Farmington Bay. Nevertheless, direct loading alone to the bay from the Sewer Canal and secondary-treated wastewaters from Davis and Salt Lake Counties appears to exceed the dangerous loading criteria. Additionally, nitrogen fixation rates by the cyanobacteria in Farmington Bay are among the highest recorded for any lake, and are conservatively estimated to contribute 5 g N m^{-2} yr^{-1} (Wurtsbaugh and Marcarelli 2006), thus allowing the bay to be phosphorus limited (Marcarelli et al. 2006). This fixation in Farmington Bay also likely increases the nitrogen loading to Gilbert Bay where nitrogen *is* the primary limiting nutrient (see below).

Wurtsbaugh et al. (2008) did a partial estimate of loading to Gilbert Bay from May-December, and found that respective N and P loadings were 1.2 and 0.09 g m^{-2} yr^{-1}. An extrapolation of those data to include the January-April period, plus loading from the Goggin Drain that was not originally sampled, suggests that the original estimate was only about 50% of the actual total. This correction yields estimated loadings of 2.4 and 0.18 g m^{-2} yr^{-1} for N and P, respectively. Because bioassay experiments have documented that Gilbert Bay is N-limited (Stephens and Gillespie 1976, Wurtsbaugh 1988, Marcarelli et al. 2006), loading of this nutrient can be compared to the value of 2.0 g N m^{-2} yr^{-1} estimate of dangerous loading for a lake with a 5-m mean depth (Vollenweider 1968; Wetzel 2001). Nutrient loading estimates have not been conducted for Bear River Bay, but they are likely high due to the size of the Bear River, which feeds the system. Although complete nutrient loading measurements are needed for each of the lake's bays, it is clear that there are extremely high discharges of nutrients into Farmington Bay from the metropolitan area and from non-point sources, thus explaining its hypereutrophic status.

Both Bear River Bay and Gilbert Bay were moderately eutrophic over the entire study period, with mean chlorophyll levels ranging from 17 to 22 µg L^{-1}. This resulted in trophic state indices (Carlson and Simpson 1996) of 58 and 61, respectively. By contrast, the mean chlorophyll level in Farmington Bay from 2002-2009 was 141 µg L^{-1} with a TSI index of 79.

There were, however, marked year-to-year differences in the chlorophyll levels in Farmington Bay, and in 2009 the mean concentration declined to 63 µg L^{-1}, but which is still within the hypereutrophic range. The factors controlling the year-to-year differences in chlorophyll levels in Farmington Bay are not fully understood. Phosphorus levels in the bay were very high (0.40 µg L^{-1}) and were relatively stable from year to year (Fig. 7), yet chlorophyll levels in 2005 were more than double those in 2009 (Fig. 10). Phosphorus levels of 0.40 µg L^{-1} in Farmington Bay should be able to support 160-400 µg L^{-1} of chlorophyll if other factors are not limiting (Smith 1982).

N:P ratios have been used to determine which of these nutrients limit phytoplankton growth, but it may be difficult to apply these ratios to the Great Salt Lake. Waters receiving effluents from wastewater treatment plants generally have low N:P ratios. Nevertheless, the mean molar TN:TP ratios in all three bays of the Great Salt Lake were >25:1, and above the 25:1 ratio where N is assumed to be non-limiting (Morris and Lewis 1988) and where the phytoplankton would presumably be controlled by phosphorus supplies. However, this use of the N:P ratio assumes that the nutrients are bioavailable for phytoplankton growth, and since much of the nitrogen in the lake is in the form of dissolved organic nitrogen, bioavailability may be limited (Lewis et al. 2011). As mentioned previously, phytoplankton growth in Gilbert Bay is controlled by nitrogen. The situation is more complex in Farmington Bay where nitrogen is limiting when salinities are too high for nitrogen-fixing cyanobacteria to grow, but phosphorus is limiting at salinities <5% when *Nodularia* is dominant (Marcarelli et al. 2006). Nutrient limitation has not been studied in Bear River Bay. The differences in nutrient limitation between bays will complicate management efforts to control nutrients, because both nitrogen and phosphorus loading need to be considered.

Salinity–In addition to the heavy nutrient loading to the Farmington Bay, salinity is important because it determines whether the nitrogen-fixing cyanobacteria *Nodularia* can grow. For example, in 2002, salinities in Farmington Bay were above 8%, *Nodularia* was absent (W. Wurtsbaugh, unpublished data), and chlorophyll levels were near 100 µg L^{-1}. Lakes fed by wastewater treatment plants generally have low N:P ratios (Downing and McCauley 1992), and the phytoplankton in them are frequently N-limited. If nitrogen-fixing cyanobacteria can grow, they can partially alleviate the N-limitation (Marcarelli et al. 2006), and utilize a larger proportion of the phosphorus coming into the lake. However, if salinities or other factors are limiting, the amount of algal growth can be constrained by the amount of N entering the system coupled with the nitrogen that gets recycled from the sediments. When salinities are 1-4% in Farmington Bay, *Nodularia* is abundant and nitrogen fixation rates are extremely high (Wurtsbaugh and Marcarelli 2006). This occurred in 2005, and mean chlorophyll levels were 250 µg L^{-1}. This high value approaches maximum attainable chlorophyll levels because denser phytoplankton populations become light limited due to self-shading (Westlake 1980).

Zooplankton grazing–The abundance of grazing zooplankton can also be important in regulating the phytoplankton populations in the bays of the Great Salt Lake. In 2009, salinity levels in Farmington Bay were also suitable for *Nodularia* growth, but chlorophyll levels were only in the lower hypereutrophic range. Zooplankton grazers, particularly cladocera, were extremely abundant in 2009 and may have exerted appreciable top-down control of the phytoplankton with grazing rates near 100% of the water column per day. This type of grazing control is evident in Gilbert Bay throughout most of the summer because *Artemia* are extremely efficient grazers (Wurtsbaugh 1992). The lowest chlorophyll level observed in Farmington Bay (3 µg L^{-1} in May 2003; Fig. 10) also occurred when *Artemia* were extremely abundant in the bay (7 adults L^{-1}; unpublished data). In comparison, mean adult densities in Gilbert Bay in the summer are 2 L^{-1} (Belovsky et al. 2012). A proliferation of the predaceous corixid (*Trichocorixa verticalis*) in Farmington Bay subsequently removed the *Artemia*, and chlorophyll levels rebounded. Salinity determines which zooplankton can persist, and thus there is likely an optimal salinity for maximum algal abundance where *Nodularia* can survive, but where salinities are too high for cladoceran grazers and too low for *Artemia* (because invertebrate predators are abundant).

In Bear River Bay, both phytoplankton and zooplankton populations were relatively low in 2009. The low zooplankton abundance in the spring may have be the result of abundant zooplanktivorous fish in the system (Moore 2012). Additionally, areal loading of bioavailable phosphorus and nitrogen may be lower in Bear River Bay than in Farmington Bay because far fewer people reside in the watershed. Nevertheless, total phosphorus levels are high in the Bear River due largely to non-point sources (DWQ 2002), so loading could be substantial when this river's water is allowed to reach Bear River Bay. Finally, benthic algae and macrophytes are abundant in much of Bear River Bay and can compete for nutrients with the phytoplankton (Vadeboncoeur et al. 2003). Nutrient analyses are now being undertaken in a portion of Bear River Bay by the Utah DWQ, so additional information may be forthcoming to explain why eutrophication there is far less than in Farmington Bay.

Hydrological impacts on water quality and the biotic communities

Fig. 22. The Southern Pacific Railway causeway separating Gunnison Bay (left) from Gilbert Bay (right).

Hydrological modifications of the Great Salt Lake have had a large impact on water quality in the four bays. The railroad causeway construction (**Fig. 22**) in 1959 has had a major influence on salinities in Gilbert Bay, as there has been a net movement of salt to Gunnison Bay, and subsequent deposition of it on the lake bottom there. Consequently, salinities are far lower in Gilbert Bay than they would be with an undivided lake. For example, Loving et al. (2002) calculated that the salinity of an undivided lake would have been 190 g L^{-1} in 1998, whereas the actual salinity in Gilbert Bay was only 90 g L^{-1}. The continued movement of salt into the northern part of the lake could eventually decrease the salinity in Gilbert Bay to levels that would not support *Artemia*. Potential modifications of the culverts and breach in the causeway would have a large influence on salt movements (Loving et al. 2002), so it may be possible to manipulate salinities to desirable levels in order to serve beneficial uses. Additional modeling of the salt balance under variable climatic regimes, proposed water withdrawals in the watershed, and causeway modifications are needed to assess how conditions may change in the future and influence the lake's biota.

Another consequence of the Railway Causeway is that deep return flows from Gunnison Bay cause a deep brine layer (monimolimnion) to form at a depth of about 6 m and cover approximately 50% of the bottom of Gilbert Bay (**Fig. 23**; Gwynn 2002, Wurtsbaugh and Jones 2012). Without this dense brine layer, wind and the large fetch of the lake would mix the water column to the bottom. The sedimentation of organic matter, followed by microbial decomposition, makes the deep brine layer anoxic, which leads to sulfur reducing bacteria producing significant levels of toxic hydrogen sulfide (Wurtsbaugh and Marcarelli 2004). This "dead zone" cannot be utilized by *Artemia* or brine fly larvae. Collins (1980) found that brine fly larvae inhabited the sediments of Gilbert Bay down to the depth of the deep brine layer, but not below. Additionally, the deep brine layer generates or accumulates large quantities of toxic methyl mercury (Naftz et al. 2009). Preliminary estimates indicate that approximately 40% of the mercury-laden deep brine water is mixed into the upper layer of Gilbert Bay each year (Wurtsbaugh and Jones 2012), and thus this layer may contribute to the high mercury levels observed in *Artemia* and birds that utilize the lake.

The automobile causeway to Antelope Island has similar effects on Farmington Bay. Because of the inflow of the Jordan River and domestic wastewater effluents, the salinity in Farmington Bay is

considerably lower than in Gilbert Bay (Fig. 3). This allows an entirely different biotic community to develop. *Artemia* and brine flies are largely absent from Farmington Bay, but there are often high densities of meso-haline adapted zooplankton. The high density of shorebirds, moreover, indicates that benthic invertebrates are abundant, and preliminary sampling has found high densities of salt tolerant gnats (chironomids) and other species in shallow waters (unpublished data of S. Miller, Utah State University). An undesirable consequence of the reduced salinities is the proliferation of *Nodularia* when salinities are between approximately 1-5%. An additional undesirable consequence of the causeway is that it causes a deep brine layer to form in Farmington Bay when saltier and denser water from Gilbert Bay enters as a salt wedge though the breach (bridge) at the west end of the causeway. However, in Farmington Bay, this layer is usually encountered at a depth of only about 1 m (Fig. 4). The lateral extent of the deep brine layer in Farmington Bay is not as well characterized as in Gilbert Bay, in part because the morphometry of Farmington Bay has not been carefully mapped. We have, however, found the deep brine layer extending as far south as Station 3 (Fig. 1), so the layer can cover much of the bay so long as water depths exceed 1 m.

Fig. 23. 10-L containers of water collected from the mixed layer (3 m) and the deep brine layer (7 m) of Gilbert Bay on October 16, 2009. The deep brine layer water contains high concentrations of dissolved organic material, suspended detritus, and toxic hydrogen sulfide and methyl mercury.

The deep brine layer in Farmington Bay is also an anoxic "dead zone" with high concentrations of hydrogen sulfide (Wurtsbaugh and Marcarelli 2004) where zooplankton and benthic invertebrates cannot survive. Methyl mercury concentrations in this layer have not been measured, but work is currently underway to describe metal concentrations there. Because Farmington Bay's deep brine layer occurs at a depth of only about 1 m, it is more easily disturbed during high wind events than is the deep brine layer in Gilbert Bay. Wind-induced mixing of the hydrogen-sulfide containing water into the surface layer causes periods of complete anoxia in the water column for up to two days as the sulfide is oxidized to sulfate (Wurtsbaugh and Marcarelli 2006, Wurtsbaugh 2007). Comparable events occur in the Salton Sea (CA) when sulfide-containing water is mixed into its upper layer. When this occurs, extensive mortalities of fish, zooplankton, and phytoplankton occur (Watts et al. 2001, Tiffany et al. 2007a, Tiffany et al. 2007b). Similar mortalities have not been observed in Farmington Bay, but the complete and prolonged anoxia, coupled with toxic hydrogen sulfide produces a highly inhospitable environment for aquatic organisms. The release of hydrogen sulfide during these wind events also likely contributes to the "lake stink" problem (see below).

Another hydrological factor negatively influencing Farmington Bay is that during spring runoff potential flushing flows of relatively clean water are diverted from the bay and discharged via the Goggin Drain directly into Gilbert Bay (CH2MHill 2012). On average, 36% of the annual flow of the Jordan River is diverted to Gilbert Bay via the Goggin Drain, but the percentage would be considerably higher during spring flood flows. Because of this diversion, and the fact that considerable water from the watershed is utilized for irrigation and domestic use, relatively little river water is available to flush through Farmington Bay. Consequently, wastewater treatment plant discharges entering directly into the bay, and those coming down the Jordan River, contribute approximately 50% of the water entering Farmington Bay (**Table 5**). All of these treatment plants utilize only secondary or advanced secondary treatment, so nutrient levels are high. The low overall flow into Farmington Bay also produces a moderately long hydraulic residence time of 0.5 years (= bay volume/annual inflow; 334,000,000 m^3/(690,000,000 m^3 yr^{-1}). The high nutrient loading, the long residence time that retains nutrients in the bay, warm summer temperatures, and a mean depth of only 1.1 m that allows phytoplankton to remain in the photic zone, all combine to make Farmington Bay an archetypical site for producing massive algal blooms.

Table 5. Water sources for Farmington Bay.

Water Source	Discharge (m^3 x 10^6 per year)	% of Discharge
Jordan River[1]	307	44%
Davis County Creeks[1]	30	4%
Wastewater treatment discharges[2]	354	51%

[1] CH2MHill; [2]Meyers (no date)

Modification of the automobile causeway to allow free exchange of water with Gilbert Bay would have several beneficial effects on water quality. The increased mixing of Farmington Bay would allow nutrients to flush faster from the system. The increased salinity would greatly reduce *Nodularia* blooms and nitrogen fixation, although there would still likely be a south-to-north salinity gradient and a small zone where these cyanobacteria might still grow. The existing zooplankton would likely be replaced by *Artemia* which are preferred foods of many birds that utilize the lake. A potential negative effect of increasing circulation between the bays is that the increased salinity would limit the production of chironomids and other invertebrates, at least in the northern end of Farmington Bay. These might, however, be replaced with brine flies that utilize mud substrates in other portions of the lake (Collins 1980). A free exchange of water would also likely reduce the extent of the deep brine layer, but hydrological modeling would be needed to confirm this prediction. A reduction in the dead zone of the deep brine layer would provide additional area for the production of benthic invertebrates and would likely reduce the production of hydrogen sulfide, and thus allay odor problems.

Water diversions also severely impact Bear River Bay, causing it to dry up during some years. For example, in 2009, which was a moderately wet year, the flow of the Bear River into the Fish and Wildlife Services' Bear River Migratory Bird Refuge dropped to 2.8 m^3 s^{-1} (100 ft^3 s^{-1}) in the summer, and most of this water was likely lost to evaporation before reaching Bear River Bay itself. In late July,

maximum water depth in the bay had declined to 0.14 m (5”), and water covered only a few square kilometers. Salinity at this time, however, was only 2.1%. In August, Bear River Bay was salt-stratified with a surface salinity of 6.7% and a bottom layer that was 21% (**Fig. 4C**). This high-salinity bottom layer likely came from seepage or flushing of the adjoining solar evaporation ponds. Advection of Gilbert Bay water could not have contributed this deep brine layer because the surface water salinity in Gilbert Bay at this time was only 17% (data not shown), and wells along the margin of Bear River Bay do not indicate that there is saline groundwater entering the bay (D. Naftz, personal communication). By September, river flows had increased only slightly, but the bay had increased in depth to 1.50 m, and salinities had jumped to 24%, much higher than the salinity of Gilbert Bay (15%). A salinity of 24% is higher than that tolerated by almost all invertebrates (Hammer 1986, Williams et al. 1990). The zooplankton community in Bear River Bay at this time had declined and consisted of only of a negligible number of air-breathing corixids (**Fig. 19**). Consequently, both the overall area and the salinity in the bay have severe consequences for the biological community, and presumably for the birds that utilize this food resource. Although salt intrusions contribute to this problem, the most important anthropogenic impact on the bay is dewatering because of diversions of the Bear River.

Cyanobacteria and cyanotoxins

High densities of cyanobacteria and high concentrations of cyanotoxins were found in Farmington Bay, whereas Gilbert and Bear River Bays largely lacked these toxic phytoplankton. The high salinity of Gilbert Bay normally precludes the growth of most cyanobacteria, although Stephens (1990) did find *Nodularia spumigena* in the bay when salinities dropped to 6% in the mid-1980s. Although salinities in Bear River Bay were appropriate for cyanobacterial growth through early June and also in the fall, cyanobacteria densities there were negligible. This suggests that it is the high nutrient loading to Farmington Bay, combined with appropriate salinities, that allows the very large blooms of *Nodularia* to develop. There is a north to south gradient in the density of *Nodularia* in Farmington Bay, with much lower densities in the southern, fresher end (Hayes 1971; Fig. 15b,c). Nevertheless, salinities in all but the southernmost station were within the range in which *Nodularia* grows well, suggesting that some other factor(s) was limiting its growth. High levels of dissolved inorganic nitrogen that presumably enter the south end of the bay from the discharges of the Sewer Canal and the Central Davis Sewer District may reduce the competitive advantage that nitrogen-fixing *Nodularia* has further north in the bay. Moisander et al. (2003), for example, found that *Nodularia* in some areas of the Baltic Sea was less competitive when N:P ratios were high than when N:P dropped to <15:1 (atom ratios). Research is currently underway to determine if a nutrient gradient, or some other factor, influences *Nodularia* abundances in different parts of Farmington Bay.

Cyanotoxin concentrations and *Nodularia* densities were not always exactly correlated (Fig. 14; 15c). Although this could be due to toxins from other cyanobacteria, this is unlikely because the HPLC analyses did not detect non-Nodularin cyanotoxins. More likely the lack of exact correspondence between the two parameters was due to errors in our analyses, or to different toxin concentrations per cell that can occur under different growth conditions of salinity, light and nutrient availability (Lopes and Vasconcelos 2011).

The *Nodularia* densities and cyanotoxin concentrations found in Farmington Bay were well above standards established by the World Health Organization (Chorus and Bartram 1999) for contact recreation, particularly in 2009. There are three primary health risks. First, 10-20% of the population is sensitive to contact with cyanotoxins. For those affected, contact can cause severe skin rashes (Chorus and Bartram 1999). In 2005 we observed a prominent rash in a child collecting *Artemia* in the shallow waters near Bridger Bay where there was an overflow of the fresher water from Farmington Bay. The second health risk is that swimmers may ingest a cyanobacterial hepatotoxin, thus causing gastroenteritis and potentially liver damage. The World Health Organization (Chorus and Bartram 1999) indicates that there is a moderate probability of adverse health effects in recreational waters when cyanobacterial densities exceed 0.1 million cells mL^{-1} or when chlorophyll levels dominated by cyanobacteria exceed 50 $\mu g\ L^{-1}$. The microcystin LR-equivalents guideline for the protection of human health is 20 $\mu g\ L^{-1}$. In Farmington Bay, all of these levels were frequently exceeded by a factor of 10. Microcystin LR equivalents in Farmington Bay were over this limit throughout the summer of 2009, and reached a maximum of 660 $\mu g\ L^{-1}$ at one station during August. When dense surface scums of cyanobacteria are present (**Fig. 11**), there is the potential for acute poisoning, potential long-term illness, and short-term adverse health outcomes. Surface blooms are not frequent in the open waters of Farmington Bay, but since sampling did not occur near the shoreline where scums are often pushed by winds (Chorus and Bartram 1999), the most severe conditions may have been missed. When a moderate probability of health effects is suspected, the WHO suggests that on-site risk advisory signs be posted. Most incidences of severe problems occur when cyanotoxins are in drinking water of humans or animals. Since Great Salt Lake water is not used for culinary purposes, risks to humans are limited to direct contact or ingestion during swimming. Since Farmington Bay and the outflow waters that influence the Bridger Bay swimming area on Antelope Island have designated uses for contact recreation, the public needs to be cautioned about swimming in these waters. We note, however, that our sampling did not include waters at Bridger Bay and the sole indication of adverse reactions there was in the skin rash observed on the child exposed to overflow water from Farmington Bay. More sampling at the swimming beach at Bridger Bay would be desirable given the potential problem from cyanotoxins and from pathogens that have been found there (Gast et al. 2011).

Fig. 24. Children and their teacher investigating the stromatolites and brine shrimp at Bridger Bay on the NW corner of Antelope Island.

A third *potential* adverse health effect of large cyanobacterial blooms is amyotrophic lateral sclerosis (ALS) and other neurological diseases such as Alzheimer's and Huntington's diseases (Pablo et al. 2009). ALS, in particular, has been linked to the neurotoxic amino acid beta-N-methylamino-l-alanine (BMAA) that is produced by nearly all cyanobacteria (Cox et al. 2005). The definitive study showing BMAA's causal relationship with ALS in humans was in a terrestrial food chain on the Island of Guam where residents ingested significant quantities of the neurotoxin, but a less conclusive study in New Hampshire has associated the disease with cyanobacteria growing in a eutrophic lake (Caller et al. 2009). The normal mode of ingestion of BMAA from cyanobacteria is via drinking water, but substantial intake from inhalation of dust (Metcalf et al. 2012) has been associated with ALS in military personnel who fought in Iraq (Cox et al. 2009). Although scientific understanding of the epidemiology of BMAA and neurological diseases is in its infancy, the extremely high concentrations of *Nodularia* in Farmington Bay, and the presence of dust storms that can transport dried cyanobacteria into urban centers, suggests that researchers should determine if there are clusters of these neurological diseases in the area. The ALS cluster in New Hampshire was associated with cyanobacterial blooms where the highest cell densities were only 0.2 million cells mL^{-1} in a limited area of the lake (Caller et al. 2009), considerably less than the *mean* density of cells of 135 million mL^{-1} found dispersed in the water column of Farmington Bay during the summer of 2009.

Cyanobacterial toxins have also been shown to cause flamingo, duck, and bald eagle mortalities (Matsunaga et al. 1999, Alonso-Andicoberry et al. 2002, Wilde et al. 2005). These mortalities were associated with cyanobacterial densities far less than those in Farmington Bay. Toxic cyanobacterial blooms have been associated with, and suspected of, causing mortalities and initiating botulism in other aquatic bird populations (Murphy et al. 2000, Murphy et al. 2003). However, a direct cause and effect relationship between cyanobacterial densities and botulism has yet to be established. In 2007 we attempted to find a relationship between botulism and cyanotoxins in Farmington Bay (Wurtsbaugh 2011), but high salinities in the bay that year limited *Nodularia* blooms to the period during early spring during runoff. Incidences of botulism did occur in American avocets (*Recurvirostra americana*) during the small *Nodularia* bloom that year, but because the target species for the study was the northern shoveler duck (*Anas clypeata*), the study was inconclusive. Given the very high abundance of cyanobacteria in Farmington Bay, additional efforts are warranted to determine if *Nodularia* blooms are linked with bird deaths and botulism. Additional work on cyanobacterial abundance in Bear River Bay would also be useful. Although we detected little cyanobacteria in Bear River Bay in 2009, year-to-year differences could be substantial, and blooms could occur there because nutrient levels are relatively high. Massive botulism-caused mortalities in both Farmington and Bear River Bays are largely unexplained, so more work is needed to understand this problem.

Bird densities

The low bird densities observed in the open waters of Farmington Bay were unexpected, because shorebird and other bird densities observed from aerial and shore-based surveys are high there (see Paul and Manning 2008). However, our observations are not necessarily contrary to those of Paul and Manning. Most of their analyses were done from shore where only shallow waters could be surveyed. Aerial surveys were made of the open waters of Farmington Bay, but the results from these are lumped

into a single open water area. During the few times we have assessed bird densities along the entire length of the open water region we have seen huge numbers of birds in the southern section, but few in the northern area where cyanobacteria are abundant and there is a dead zone of underlying water. Consequently, to accurately compare our results the aerial survey data would need to be reanalyzed to include only the deeper waters in the northern half of Farmington Bay.

Although we have only reported bird densities from 2002-2003 surveys, those results are largely consistent with our observations made in other years in the course of traveling between our limnological sampling stations. For example, during a transect survey done in June 2012, birds were only observed in the southern 1.5 km (1 mile) of Farmington Bay where water depths were less than 0.3 m: no birds were observed along the entire rest of the transect to the northern end of the bay at the automobile causeway. On the north side of the causeway, however, eared grebes, Franklin gulls, other gulls, and phalaropes were very abundant (E. McCulley & W. Wurtsbaugh, unpublished data). During 2002-2003, and in other years, our sampling has primarily been restricted to the northern half of the bay where the water depth was greater than 0.5 m. Much of this area is underlain by a dead zone of anoxic, H_2S-rich water where there are no benthic invertebrates and where phytoplankton abundance is high and water transparency is consequently low. We suggest three hypotheses for the low density of birds in this northern, open-water area: (1) densities of large invertebrates are low and birds consequently forage in Gilbert Bay where *Artemia* and brine fly larvae are abundant; (2) sight-feeding birds (particularly eared grebes), cannot locate prey in the turbid water of Farmington Bay, and; (3) birds are avoiding the toxic cyanobacteria. More detailed work on the bird distributions in Farmington Bay will be necessary to test these hypotheses and resolve the discrepancy between our limited observations and those reported from aerial and shore-based surveys.

Odor problems

The odor problem can be broken into two different processes. First, people living along the east shore of the lake, and those driving to Antelope Island often experience highly-objectionable odors associated with the mud flats and shallow waters of Farmington Bay where phytoplankton can accumulate and decompose, and where hydrogen sulfide can be produced in the anoxic, interstitial water of the sediments. Arruda and Fromm (1989) found that odor problems in Kansas reservoirs were closely linked with eutrophication. Excess organic matter from eutrophication causes anoxia and the lowering of redox potentials which can lead to the production of hydrogen sulfide. Additionally, cyanobacteria produce objectionable musty odors (Wnorowski 1992) that are frequently a problem in drinking water supplies and when surface scums accumulate and die on the shorelines of lakes (Watson 2004). Musty odors were frequently described in our survey when respondents indicated moderate odor levels.

Secondly, large portions of the population of greater metropolitan Salt Lake City experience "lake stink" when wind events release hydrogen sulfide and/or other odor causing agents. The best hypothesis is that this occurs primarily from the entrainment of portions of the deep brine layer from Farmington Bay and the fringing sediments of the bay, because it is overlain by only a 1-m thick mixed layer. Consequently, it is easy for high winds to create turbulence that can mix hydrogen sulfide in the deep brine layer into the mixed layer and overlying air. The total anoxia we've observed in Farmington

Bay after wind events is consistent with this interpretation, whereas we have not observed mixed-layer anoxia in Gilbert Bay (Fig. 18). Since wave action and turbulence decays exponentially with depth (Wetzel 2001), and because the deep brine layer in Gilbert Bay does not begin until a depth of ~ 6 m, mixing forces in these deeper waters are only about 15% of those at a depth of 1 m (Wetzel 2001). Consequently, it is likely that more hydrogen sulfide is released from the deep brine layer of Farmington Bay than from Gilbert Bay. Additional hydrogen sulfide may be released from the margins of Farmington Bay, and perhaps Ogden Bay, when wave action disturbs the sediments that contain the gas in the interstitial water. Hydrogen sulfide in the interstitial water is 20-40 times more concentrated than in the deep brine layers of the lake (Bell and Wurtsbaugh 2007). The odors are not strictly a consequence of anthropogenic eutrophication and causeway construction, as in 1845 John Freemont described strong lake odors that he thought were derived from the scum around the lake (Morgan 2002). Any water body with sulfate—and the Great Salt Lake has ample—will produce hydrogen sulfide in the sediments, with the amount determined by the quantity of sedimenting organic matter that is available to drive the redox reactions that reduce sulfate. Additional studies and modeling will be necessary to understand the hydrodynamic processes that lead to "lake stink" events that influence metropolitan Salt Lake City, and if anthropogenic eutrophication has increased odors in the area.

Our odor survey suggested that most objectionable smells are primarily associated with Farmington Bay, and not Gilbert or Bear River Bays. Trentelman (2009; unpublished data) found a higher incidence of people reporting objectionable odors who lived in Davis County than in those living in Weber County, also suggesting that Farmington Bay is the primary source of odor. Regardless of the source, odor is an important factor influencing people's perception of the lake, and consequently the recreational use of the system. Brunson and Nicholson (1999), for example, found that 68% of Davis County respondents agreed with the statement that "the lake smells bad", and Trentelman (2009) found that 42% of Davis and Weber County residents listed odor as what they like least about living near the Great Salt Lake. However, responses from people who live, work, and/or recreate near Gilbert Bay, do not cite odor as a problem (our survey; Trentelman 2009). Lake-derived odors are difficult to quantify, and they are also an issue that falls between the regulatory authorities of the Division of Water Quality and the Division of Air Quality. Nevertheless, odor issues that may be related to nutrient loading and the deep brine layer(s) caused by the causeways should be addressed in order for the lake to be utilized by residents and tourists to its full extent.

Metal and metalloid concentrations in zooplankton

The primary metals in zooplankton that may pose a threat to birds feeding on them are mercury and selenium. Mercury levels were only high in Gilbert Bay *Artemia* with geometric mean concentrations that were 62% above threshold effects concentrations. Selenium concentrations in zooplankton were also usually above threshold effects concentrations, particularly in Farmington and Gilbert Bays. Additionally, arsenic concentrations of some *Artemia* samples in Gilbert Bay were above threshold effects concentrations, and overall levels were moderately high on other dates (**Fig. 21**). Selenium and arsenic concentrations warrant particular attention because a recent paleolimnological analysis of Gilbert Bay sediments suggests that these metalloids are increasing in the lake, whereas most other metals (including mercury) are decreasing (Wurtsbaugh 2012). Other metals occasionally exceeded threshold effects concentrations in one or more zooplankton sample, but overall, their levels do not appear to be a major threat to the bird community. It is also important to note that we observed few birds in the open waters of Farmington Bay where the zooplankton samples were collected, so foraging in the open waters could be limited. However, wading birds do appear to forage extensively in the shallow areas of Farmington Bay, but it is likely that they consume benthic invertebrates or the biofilm there. Benthic invertebrates have not been studied in Farmington Bay, but research on this community is needed to understand how eutrophication may influence these invertebrates, and whether they serve as a vector for transporting metals into birds.

Fig. 25. Oil refineries and the Northwest Oil Drain that discharges into Farmington Bay.

The moderate metal concentrations in zooplankton from Farmington Bay was somewhat unexpected, given that drainage from EPA Superfund sites discharge into the bay via the NW Oil Drain and the Jordan River. Both the Jordan River and the Oil Drain contained significant amounts of heavy metals from industrial and mining activities (The Forrester Group 2001, EPA 2008). We should note that we did not sample zooplankton at southern ends of either Farmington Bay or Gilbert Bay where concentrations of metals are higher in the sediments and invertebrates (Sorensen et al. 1988, Waddell et al. 2009, Wurtsbaugh 2012). Additionally, the phenomenon of "bloom dilution" (Pickhardt et al. 2002, Chen and Folt 2005) could reduce mercury and/or other metal uptake by zooplankton in Farmington Bay. Bloom dilution occurs when a given amount of a metal contaminant in a lake is diluted into a large biomass of phytoplankton, thus decreasing its concentration in the food consumed by zooplankton. Wurtsbaugh and Jones (2012) suggested that bloom dilution explained low mercury concentrations in *Artemia* that were experimentally exposed to deep brine layer water from the Great Salt Lake.

It is difficult to compare the metal concentrations we measured with those reported by other groups studying the Great Salt Lake because different methods have been used to process the zooplankton samples (**Table 6**). Different investigators have reported mercury concentrations in *Artemia* that have varied almost 3-fold, and concentrations for selenium have varied 3-4 fold. Two sources of procedural variability may have influenced the reported results. The first source of variability is whether the concentrations are measured as wet or dry weight. Measurements expressed in wet weight are difficult to interpret because the amount of water removed from samples can vary appreciably, particularly when different types of organisms are in the samples (e.g. corixids vs. *Artemia*), as they differ with respect to cavities where water may remain. Consequently, most limnological analyses utilize dry weights (e.g. McCauley 1984, Watkins et al. No date). Dry weights of zooplankton are typically thought to be 10-15% of the blotted wet weight, but even this range can result in a 50% difference in the final estimate of contaminant content (**Table 6**). The second source of error is whether salt water is removed from the zooplankton sample prior to measurements. In freshwaters, this is not an issue, but in the hypersaline sections of Gilbert and Bear River Bays, the clinging "water" on the outside of the organisms contains significant salt that can contribute to the weight of the sample, thus resulting in an underestimate of the contaminant that is actually in the zooplankton. A potential example of the impact of this is from two *Artemia* samples collected by the US Fish and Wildlife Service. The data presented by Waddell et al. (2009) was for *Artemia* that did not have salts removed, and the resulting mercury estimate was 0.36 µg g^{-1} dw. In another set of samples that were processed by the Utah Division of Water Quality, the *Artemia* were first immersed in freshwater to remove salts, and the

Table 6. Mercury and selenium concentrations in adult *Artemia* from the Great Salt Lake measured by different research groups. Samples received several rinses to remove external salts, and some were first dried (DW) before metals analyses were conducted. Samples that were originally expressed in units of wet weight (Van Leeuwen et al., In review; Marden 2008) are compared here by assuming that either 10% or 15% of the *Artemia* tissue was dry weight (e.g. 90% or 85% water).

Metal	USU (this study)[1]	Waddell et al. (2009)[2]	Darnall (2008)[3]	Van Leeuwen et al. (in review)[4]		Marden (2008)[5]	
	dw	dw	dw	10% dw?	15% dw?	10% dw?	15% dw?
Mercury (µg g^{-1})	0.65	0.36	0.99	0.59	0.40		
Selenium (µg g^{-1})	7.18	2.64				11.80	7.87

[1]Rinsed with fresh water; dry weight

[2]No rinse; dry weight

[3]Immersed in fresh water; dry weight

[4]Rinse with fresh water; suction filteration; wet weight (converted to dry weight here using assumed percentages of 10% dry/wet and 15% dry/wet)

[5]No rinse; water removed via pipette (2006), or by suction filtration (2007); wet weight (converted to dry weight here using assumed percentages of 10% dry/wet and 15% dry/wet)

resulting mercury estimate was nearly three times higher (0.99 μg g^{-1}) (Darnall 2008; N. Darnall personal communication). These samples were, however, collected in different years, so it is difficult to attribute the change to either the methodology or year-to-year differences. Our samples were rinsed by squirting deionized water directed on to the zooplankton sample in the "bucket" of the zooplankton net. Our zooplankton collected from Gilbert Bay, and those collected in Bear River Bay when salinities were very high, had higher sodium content than zooplankton collected elsewhere (**Appendices 5-7**), suggesting that we were not entirely successful in removing all of the salts with our method. For future work it is recommended that samples of live zooplankton be immersed in fresh water for 30-60 seconds to remove salts, and then dried prior to analysis so that the amount of water can be standardized (i.e. zero).

We did not find large seasonal differences in the metals found in zooplankton, although mercury tended to be somewhat higher during midsummer. We did not, however, have adequate numbers of samples to determine if these differences were statistically different. Waddell et al. (2009) found higher concentrations of mercury in *Artemia* collected in the fall than those collected in the spring, and attributed the difference to bioaccumulation in the older shrimp. We also did not find particularly high concentrations of metals in samples dominated by predacious corixids, which could have potentially biomagnified the metals. However, for both metals of particular concern, mercury and selenium, biomagnification is not prominent in the invertebrates of the Great Salt Lake (Wurtsbaugh et al. 2011, Gardberg et al. In Prep.).

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Appendix 1. Great Salt Lake odor survey instructions for participants

Great Salt Lake Odor Survey - Resident

Wayne Wurtsbaugh
Department of Aquatic Watershed and Earth Sciences
Utah State University
435-797-2584

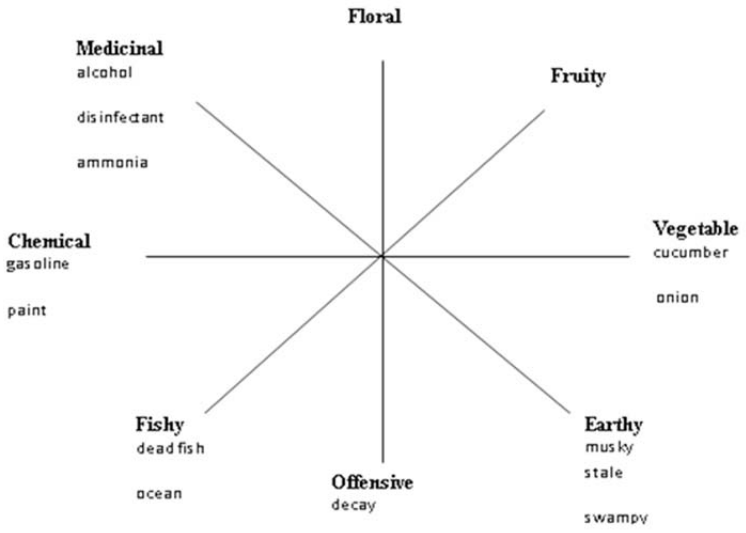
Please rate the odor level at your home as soon as you have a chance to step outside in the morning. Rate the general outside odor, ignoring any odors from temporary local sources at your home, such as flowers or nearby construction. If marked changes in odor intensity should occur during the day, please note these as well. Although daily records will be most valuable to our study, if you miss a day please skip it and resume recording the next day. Rate the odor level using the following 1-5 scale:

1	2	3	4	5
none	**mild**	**moderate**	**strong**	**unbearable**

Please use the odor wheel below to record the most accurate description of the odor, using the subcategories provided if applicable. Be sure to include the date and time with each entry, and note any special conditions in the comments section. If you leave your home during the day and notice a distinct odor somewhere else, please record the odor but note the change of location.

Thank you for your participation.

Odor Wheel



Recorder's name: _____

Location: _____

What would you consider the "normal" odor level in your location? _____

What would you consider the "normal" odor description in your location based on the odor wheel? _____

On average, how often do you notice strong, objectionable odors at your site (hourly, daily, X times/month, etc.)?

Appendix 1 (con't). Daily form for participants to fill in.

Great Salt Lake Odor Survey, page ___

Recorder's name: _____

Location: _____

Date	Time	Odor Level (1-5)	Odor Description (see odor wheel)	Comments or Notes (if any)

Appendix 2. Genera of phytoplankton (and protozoa) encountered in different stations in Bear River Bay, Farmington Bay and Gilbert Bay. Numbers show average cell densities/ml. However, because not all stations were sampled in all years and in all seasons, and because taxonomic classifications changed somewhat over the seven years, they should only be used to give rough approximations of densities.

		Mean Cell Density / ml												
		Bear River Bay		Farmington Bay							Gilbert Bay			
	Stations	24	26	0	1	2	3	4	5	6	14	15	18	2767
Division	Genus													
Chlorophyta	*Actinastrum*		727											
	Ankistrodesmus	61	228	3,376	1,643		274			1,095				33
	Carteria	27		8,739	4,429	26,039	7,759	936	9,363			250		
	Characium				548									
	Chlamydomonas		365	548	1,095		548			9,308			992	
	Chlorogonium									1,095				
	Coelastrum	730												
	Cosmarium	91												
	Dictyosphaerium	1,460	4,380		6,844									
	Dunaliella	17,980	365	42,503	80,079	233,537	106,220	34,568	229,074	912	59,289	47,590	64,641	33,403
	Geminella	8,517												
	Monoraphidium	831	183	1,369	540		684			548				
	Nannochloris	82,167	183		5,475		87,604			2,190				
	Oocystis	349	3,129	7,197	36,843	30,256	61,972	64,556	82,661	1,643	1,829	2,255	1,274	154
	Pediastrum	1,217		1,545	13,160	7,282	4,877	14,601						
	Pyramichlamys	1,156					548							
	Scenedesmus	303	730	4,153	10,937	33,070	23,029	28,879		3,650				24
	Schroederia						274							
	Spermatozopsis	58,276			37,255	105,819	16,349	15,474				691		
	Sphaerellopsis					1,488								
	Tetraedron	570		45	61									
	Treubaria				16,410		52,244		16,954				893	
	"Tiny Biflagellate"				15,533	992	11,187	366,241	125,155		48,034	63,120	45,611	
Chrysophyta	*Chromulina*	1,095	183										48,341	51,725
	Dinobryon		1,095											
Cryptophyta	*Cryptomonas*	1,300		409	517		91							
	Rhodomonas	27	183	1,091	421		593			2,190				
Cyanobacteria	*Anabaena*	1,444												
	Aphanocapsa			16,426	3,635		10,084							
	Aphanothece	15,412		76,653	8,200,360		8,459,553							88,699
	Chroococcus	547			545		3,650			17,740				66
	Limnothrix						164,257							
	Merismopedia									6,570				
	Microcoleus	482		2,311	18,989	18,187	14,320	26,157	42,067		27,639	17,843	12,625	
	Nodularia			91,554	237,907	168,102	232,630	165,836			1,190	739	1,766	5,376
	Pseudanabaena	8,804	2,190	14,601	3,494		15,540							
	Pseudoanabaena	787		252	364	4,280	7,522	941	16,615		2,282	7,709		
	Romeria			91,010										
	Spirulina				564	464	1,344	774			364	149	243	
	Synechococcus	35,918	16,426	21,353	133,924		21,901			1,643			4,106	670
	Synechocystis	47,430	38,327	83,680	161,137		217,436			312,636			45,554	34,268
Diatom	*Amphora*	234		43,486	2,545	1,722	981		807		170	202	331	
	Asterionella		1,095											
	Chaetoceros			92,002	10,284		411							
	Chaetocerous			6,554	26,581	11,792	16,378	5,630	32,961		706	538	213	
	Cyclotella	325	2,738	400	2,924	5,088	1,787	1,434	5,159	182	639	471	156	
	Cylindrotheca	319												
	Donkinia			364										
	Fragilaria									1,095				
	Navicula	1,580		709	1,302	1,002	1,341	3,888	337	1,095	224	73	206	38
	Navicula											50		
	Nitzchia			20,755	9,673	21,675	9,541	7,237	6,129		224	193	407	
	Nitzschia	21,711	365	409	18,365		39,011			5,475				55
	Phaedactylum						19,116							
	Phaeodactylum			13,141										
	Rhopalodia	27												
	Synedra	234		31,259	44,539	26,909	11,300	82,656						
	"Clear oval diatom"				14,898	18,636	17,581	17,480	32,672		334	1,976	262	
Euglenophyta	*Phacus*									548				
Miscellaneous		7,513	32,851	136,166	23,720		33,688			11,498			3,237	12,675
Protozoa	*Euplotes*				804	672	1,814	732						
	Unknown ciliates			10,588	2,239			819						
Pyrrophyta	"Chrysophytes"	3,680		594,795	464,278	616,322	562,491	420,165	867,703		58,353	64,540	71,434	
	Amphidinium		183											
	Cryptomonas	162,376		25,713	60,781	59,040	56,044	40,284			675	393	177	
	Glenodinium	262		252	5,992	2,297	1,819	2,707	1,664		1,750	11	9,848	
	Gymnodinium		183				365						342	
	Peridinium			730	365		593							
Xanthophyta	*Monodus*												342	
Total Algal Genera	67	38	21	36	43	23	44	22	15	19	16	19	23	14

Appendix 3. Algal and cyanobacterial taxa that were present in each bay that were ≥ 0.01% of mean cell densities during the 2009 study.

Division	Genus and species (if known)	Bear River Bay	Farmington Bay	Gilbert Bay	Grand Total
Bacillariophyta (Diatoms)					
	Amphora		x		x
	Asterionella	x			x
	Chaetoceros		x		x
	Cyclotella	x	x		x
	Cylindrotheca	x			x
	Donkinia		x		x
	Fragilaria		x		x
	Navicula	x	x	x	x
	Nitzschia sp.	x	x	x	x
	N. closterium			x	x
	N. palea	x			x
	N. subacicularis	x			x
	Phaeodactylum		x		x
	Rhopalodia	x			x
Chlorophyta (Green algae)					
	Actinastrum	x			x
	Ankistrodesmus sp.	x	x	x	x
	A. falcatus	x	x		x
	Carteria	x			x
	Characium		x		x
	Chlamydomonas	x	x	x	x
	Chlorogonium		x		x
	Coelastrum pseudomicroporum	x			x
	Cosmarium	x			x
	Dictyosphaerium	x	x		x
	Dunaliella salina	x	x	x	x
	D. viridis	x	x	x	x
	Geminella	x			x
	Monoraphidium	x	x		x
	Nannochloris	x	x		x
	Oocystis lacustris	x			x
	O. parva		x	x	x
	Pediastrum sp.	x	x		x
	P. boryanum	x			x
	Pyramichlamys	x			x
	Scenedesmus sp.	x	x	x	x
	S. bijuga				
	S. quadricauda		x		x
	S. subspicatus		x		x
	Schroederia				
	Tetraedron caudatum	x			x
Chrysophyta (Golden-brown algae)					
	Chromulina lunaris	x		x	x
	Dinobryon	x			x
Cryptophyta (Cryptomonads)		x	x		x
	Cryptomonas sp.	x	x		x
	C. erosa	x			x
	Rhodomonas minuta	x	x		x
Cyanobacteria (Blue-green algae)					
	Anabaena	x			x
	Aphanocapsa		x		x
	Aphanothece sp.	x	x	x	x
	A. halophytica		x		x
	Chroococcus sp.		x	x	x
	C. minimus	x			x
	C. minutus	x			x
	Limnothrix redekei		x		x
	Merismopedia		x		x
	Nodularia spumigena		x	x	x
	Pseudanabaena	x	x		x
	Romeria		x		x
	Synechococcus	x	x	x	x
	Synechocystis	x	x	x	x
Euglenophyta (Flagellate protozoa)					
	Phacus		x		x
Pyrrhophyta (Dinoflagellates)					
	Amphidinium	x			x
	Gymnodinium	x		x	x
	Peridinium		x		x
Xanthophyta (Yellow-green algae)					
	Monodus clavata			x	x

Appendix 4a. Algal biovolumes (million μm^3 ml^{-1}) measured in Farmington Bay of the Great Salt Lake in 2002 and 2003.

Farmington Bay		Division									
Date	Station	*Chlorophyta*	*Chrysophyta*	*Cryptophyta*	*Cyanobacteria*	*Diatom*	*Euglenophyta*	*Pyrrophyta*	*Miscellaneous*	*Protozoa*	*Grand Total*
12-Aug-02	1	115.893			2.335	18.052		18.549			154.83
	2	70.877			10.353	20.254		18.844			120.33
	3	69.438			8.299	14.478		13.384			105.60
	4	48.074			7.740	12.579		14.032			82.43
	5	59.987			22.699	27.683		14.208			124.58
20-Oct-02	1	63.686			4.208	3.247		54.919			126.06
	2	272.533			8.954	0.043		18.179			299.71
	3	102.611			2.717	2.420		28.759			136.51
	4	34.586			2.945	1.465		14.776			53.77
	5	81.016			1.838			9.170			92.02
23-Nov-02	1	45.083			2.518	0.898		2.590			51.09
	3	34.827			0.479			2.072			37.38
	5	75.369			2.579	1.955		10.280			90.18
8-Jan-03	1	37.281				0.671		1.139			39.09
	3	17.574			0.322	0.075		3.024			20.99
26-Feb-03	1	35.569			0.790	8.418		0.678			45.46
	3	0.281			0.524	13.045		8.151			22.00
	5	24.717			0.871	10.941		2.963			39.49
31-Mar-03	1	9.215				19.139		1.437			29.79
	3	9.610			0.078	9.591		0.724			20.00
	5	5.403			0.007	9.303		0.128			14.84
1-May-03	1	2.140			0.239	6.527		0.347			9.25
	3	7.678			0.792	11.373		0.489			20.33
	5	1.140				11.706		1.253			14.10
15-May-03	1	0.046				0.045		0.001			0.09
	3	0.247			0.132	0.152					0.53
	5	0.655				0.095		0.011			0.76
5-Jun-03	1	35.596				3.738		0.515			39.85
	3	63.178				14.503		1.496			79.18
	5	29.723				11.051		0.656			41.43
26-Jun-03	1	47.955				10.097		0.737			58.79
	3	34.180				0.879		1.654			36.71
	5	3.714				10.788		0.185			14.69
25-Jul-03	1	14.153			0.053	15.305		1.154			30.67
	3	31.017				7.205		2.643			40.87
28-Aug-03	1	227.465						3.640			231.11
	2	70.700				2.161		16.741			89.60
	3	66.974			0.663	4.507		9.929			82.07
26-Sep-03	0	19.829			0.560	5.178		10.573			36.14
28-Oct-03	1	29.381			0.667	14.165		2.339			46.55
	2	41.192			0.911	19.247		0.541			61.89
	3	10.269			0.547	10.148		2.572			23.54
23-Nov-03	0	16.923				34.896		0.457			52.28
12-Dec-03	1	9.328				6.331		0.733			16.39

Appendix 4a (con't). Algal biovolumes (million μm^3 ml^{-1}) measured in Farmington Bay of the Great Salt Lake in 2005.

Farmington Bay		Division									
Date	Station	*Chlorophyta*	*Chrysophyta*	*Cryptophyta*	*Cyanobacteria*	*Diatom*	*Euglenophyta*	*Pyrrophyta*	*Miscellaneous*	*Protozoa*	*Grand Total*
3-May-05	1	7.819			114.303	0.408					122.53
	2	6.013			15.140	0.538		0.025			21.72
	4	8.303			0.021	0.079		1.058		0.530	9.99
17-May-05	1	8.327			88.275	0.559		0.037		7.218	104.42
	2	8.110			34.949	0.852		0.195		7.349	51.46
	3	11.190			35.543			0.078		23.885	70.70
1-Jun-05	1	17.101			5.257	1.675		2.923			26.96
	3	19.813			7.302	0.534		0.936			28.59
	4	30.986			8.040	1.351		0.468		2.094	42.94
15-Jun-05	1	3.855			9.467	0.993		0.649			14.96
	2	6.359			5.996	4.176		0.016			16.55
	4	14.937			13.235	2.903		1.689			32.76
27-Jun-05	1	15.941			3.278	65.542		0.571		5.741	91.07
	2	17.830			15.711	23.464		2.224			59.23
	4	36.889			1.410	71.055		0.345			109.70
13-Jul-05	1	0.118			39.049	0.390		0.347			39.90
	2	0.660			44.516	0.815		1.139			47.13
	4	3.872			32.490	1.841		1.304			39.51
27-Jul-05	1	1.139			21.703	5.277		1.489		1.273	30.88
	2	2.249			31.854	0.973		0.096			35.17
	4	5.792			28.497	2.091		2.920			39.30
8-Aug-05	3	0.699			47.850	1.758		0.964		5.603	56.87
	4	0.607			34.998	1.935		1.952		4.016	43.51
9-Aug-05	1	0.066			28.771	0.992		0.504			30.33
25-Aug-05	1	0.150			29.215	15.566		1.627		1.661	48.22
	2	0.403			37.786	3.897		2.137		1.109	45.33
	3	0.265			54.043	4.256		2.483		2.386	63.43
10-Sep-05	1	0.511			15.988	5.094		5.248		1.028	27.87
12-Sep-05	2	3.109			10.999	13.126		6.587		2.263	36.08
13-Sep-05	1	5.979			25.448	0.725		4.425		3.075	39.65
	3	6.046			36.441	6.684		7.219		4.518	60.91
2-Oct-05	0	0.116			12.782	6.229		0.660		11.635	31.42
6-Oct-05	2	2.687			12.039	36.243		0.597			51.57
20-Oct-05	1	0.988			12.062	81.489		1.671		1.879	98.09
21-Oct-05	1	0.016			7.477	6.866		0.410		5.684	20.45
22-Oct-05	2	1.259			3.996	15.418		0.673			21.35
	3	3.006			9.290	8.194		0.653			21.14
13-Nov-05	1	0.514			7.825	1.983		9.954			20.28
	2	1.211			12.244	32.316		0.763			46.53
	3	11.200			37.162	0.115		0.534			49.01

Appendix 4a (con't). Algal biovolumes (million μm^3 ml^{-1}) measured in Farmington Bay of the Great Salt Lake in 2009.

Farmington Bay		Division									
Date	Station	*Chlorophyta*	*Chrysophyta*	*Cryptophyta*	*Cyanobacteria*	*Diatom*	*Euglenophyta*	*Pyrrophyta*	*Miscellaneous*	*Protozoa*	*Grand Total*
15-Apr-09	0	1.765			0.081	8.087		0.063	2.296		12.29
21-May-09	1	0.291		0.005	134.607	0.141			0.033		135.08
	3	1.453			0.064	0.261			0.373		2.15
1-Jun-09	0	0.447		0.058	56.000	0.014			0.009		56.53
8-Jun-09	1	11.697		0.109	38.723	0.804		0.073	0.074		51.48
24-Jun-09	1	1.806		0.009	218.441	4.545					224.80
14-Jul-09	1	0.533		0.003	91.450				0.042		92.03
	3	2.699		0.027	41.277			0.015	0.127		44.15
27-Jul-09	1	0.042		0.003	77.912	0.015			0.156		78.13
	3	0.589		0.018	54.797			0.070	0.241		55.71
17-Aug-09	1	0.698		0.028	151.996	4.007			0.478		157.21
	3	2.084			282.095	5.953		0.143	0.181		290.46
	6	0.782		0.055	0.280	0.830	0.288		0.094		2.33
11-Sep-09	1	0.266		0.028	359.354	0.543			0.118		360.31
	3	1.234			46.656	0.610			0.178		48.68
7-Oct-09	1	0.183			59.413	9.344			0.133		69.07
15-Oct-09	0	1.159			22.649	0.742			0.306		24.86

Appendix 4b. Algal biovolumes (million μm^3 ml^{-1}) measured in Bear River Bay of the Great Salt Lake in 2002, 2005 and 2009.

Bear River Bay		Division									
Date	Station	*Chlorophyta*	*Chrysophyta*	*Cryptophyta*	*Cyanobacteria*	*Diatom*	*Euglenophyta*	*Pyrrophyta*	*Miscellaneous*	*Protozoa*	*Grand Total*
19-Aug-02	9	4.233			0.078	4.075		0.343			8.73
	10	0.116				0.497		0.021			0.63
2-Jun-05	24	0.243			0.058	0.125		1.447			1.87
28-Jun-05	24	0.353			0.039	5.684		1.225			7.30
20-May-09	24	0.014		0.001	0.017	0.029			0.044		0.10
	26	0.157	0.077	0.004	0.023	0.207		0.068	0.120		0.66
10-Jun-09	24	1.096	0.003	0.024	0.068	0.600			0.028		1.82
9-Jul-09	24	0.091	0.005		0.025	0.022			0.050		0.19
30-Jul-09	24	0.941	0.282	0.098	0.046	7.226					8.59
9-Sep-09	24	2.398	0.037		0.175	0.698					3.31

Appendix 4c. Algal biovolumes (million μm^3 ml^{-1}) measured in Gilbert Bay of the Great Salt Lake in 2002 and 2003.

Gilbert Bay		Division									
Date	Station	*Chlorophyta*	*Chrysophyta*	*Cryptophyta*	*Cyanobacteria*	*Diatom*	*Euglenophyta*	*Pyrrophyta*	*Miscellaneous*	*Protozoa*	*Grand Total*
20-Aug-02	13	2.573			0.100	1.621		0.443			4.74
21-Aug-02	14	1.161			0.011	2.182		0.714			4.07
	15	5.692			0.015	0.100		0.345			6.15
22-Oct-02	13	1.027				0.289		0.048			1.37
	16	9.541				0.093		0.089			9.72
25-Oct-02	14	0.419				0.723		0.039			1.18
	15	0.188			0.000	0.245		0.047			0.48
23-Nov-02	14	15.693			0.143	0.713		0.300			16.85
	15	28.457			0.409	0.244		0.579			29.69
	18	18.269						0.093			18.36
8-Jan-03	14	5.664			1.201			0.096			6.96
	15	6.575			0.089			1.413			8.08
	18	4.420			0.075	0.165		2.753			7.41
26-Feb-03	14	7.893			0.141	0.068		1.543			9.64
	15	4.412			0.272	0.083		0.332			5.10
	18	0.000			0.027	0.943		0.000			0.97
31-Mar-03	14	4.867			0.026	1.303		0.000			6.20
	15	10.161			0.454	0.070		0.526			11.21
	18	11.883			0.525	0.866		1.731			15.01
1-May-03	14	11.111			1.525	0.083		0.386			13.10
	18	16.942				0.591		0.896			18.43
15-May-03	14	13.650			0.113	4.241		0.474			18.48
	15	8.970			0.008			0.344			9.32
	18	9.583			0.043			1.417			11.04
5-Jun-03	14	0.391			0.192	0.300		0.099			0.98
	18	0.592			0.578	0.069		0.278			1.52
26-Jun-03	14	0.847			0.123	0.086		0.095			1.15
	15	1.171			0.326	0.634		0.068			2.20
25-Jul-03	14	0.294			0.312	0.352		0.168			1.13
28-Aug-03	14	1.512			0.005	1.636		0.282			3.43
	15	2.691				0.300		0.458			3.45
	18	6.885				0.122		0.083			7.09
26-Sep-03	14	0.040				0.540		0.015			0.59
28-Oct-03	14	3.045			0.016	0.052		0.086			3.20
	15	0.841						0.046			0.89
	18	0.849				0.086		0.021			0.96

Appendix 4c (con't). Algal biovolumes (million μm^3 ml^{-1}) measured in Gilbert Bay of the Great Salt Lake in 2005 and 2009.

Gilbert Bay		Division									
Date	Station	Chlorophyta	Chrysophyta	Cryptophyta	Cyanobacteria	Diatom	Euglenophyta	Pyrrophyta	Miscellaneous	Protozoa	Grand Total
3-May-05	14	0.970				0.056		0.083			1.11
	15	0.762				0.003		0.088			0.85
	18	1.171				0.030		0.040			1.24
27-Jun-05	14	0.878				0.033		0.058			0.97
	15	1.883				0.014		0.014			1.91
	18	1.072				0.082		0.014			1.17
27-Jul-05	14	1.614				0.100		0.078			1.79
	15	0.130			0.082						0.21
9-Aug-05	14	0.176				0.403		0.002			0.58
	18	0.129				0.097		0.002			0.23
13-Sep-05	14	0.919			0.271	0.180		0.014			1.39
	15	0.896			0.076	0.038		0.019			1.03
	18	0.591			0.557	0.018		0.018			1.18
21-Oct-05	14	1.576				0.069		0.080			1.73
	15	0.491						0.007			0.50
	18	0.960				0.190		0.011			1.16
13-Nov-05	18	0.459				0.389		0.003			0.85
21-May-09	18	1.178	0.476		0.014	0.069		0.007	0.016		1.77
	2767	0.225	0.020		0.006				0.013		0.26
8-Jun-09	2767	0.022	0.020		0.162	0.005			0.020		0.23
24-Jun-09	18	0.010	0.008		0.011				0.000		0.03
	2767	0.019	0.009		0.062	0.005			0.004		0.10
14-Jul-09	2767	0.057	0.040		0.002				0.014		0.11
27-Jul-09	18	0.145	0.905		0.002						1.05
	2767	0.012	0.151		0.103				0.005		0.27
13-Aug-09	2767	0.344	0.939		0.012						1.30
11-Sep-09	18	0.131	1.695		0.011				0.003		1.84
	2767	0.182	1.224		0.004						1.41
7-Oct-09	18	0.844	2.333		0.028				0.014		3.22
	2767	3.520	0.689		9.714	0.012			0.336		14.27

Appendix 5. Taxonomic composition and metal concentrations (µg g^{-1} dry weight) of zooplankton collected in Gilbert Bay in 2009. Concentrations shown in blue italic font were below levels of detection and are reported here as half way between the detection limit and zero.

	Gilbert Bay													
	21-May	8-Jun	8-Jun	24-Jun	24-Jun	14-Jul	27-Jul	27-Jul	13-Aug	13-Aug	11-Sep	11-Sep	7-Oct	7-Oct
Station	18	18	2767	18	2767	2767	18	2767	18	2767	18	2767	18	2767
Zooplankton Composition (%)														
Artemia	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Corixids	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cladocera	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Metal	Metal Concentration (*u* g g^{-1}; ppm)													
Ag	*0.005*	*0.005*	*0.005*	*0.005*	*0.005*	*0.005*	*0.005*	*0.005*	*0.005*	*0.005*	*0.005*	*0.005*	*0.005*	0.030
Al	259	443	426	238	575	344	69	17	93	67	130	64	164	1,335
As	19.8	33.5	25.1	25.1	26.9	32.0	19.7	15.4	15.5	15.9	20.0	20.5	19.6	15.8
B	21.1	32.0	32.5	31.5	38.2	45.7	16.0	13.3	15.2	19.4	22.0	30.5	41.0	25.3
Ba	6.9	11.6	10.0	5.9	12.4	8.9	2.2	0.6	4.0	2.6	3.8	11.2	5.1	5.8
Be	0.020	0.040	0.030	0.020	0.070	0.040	*0.005*	*0.005*	*0.005*	0.010	0.010	*0.005*	0.010	0.020
Ca	2,743	4,160	3,960	1,687	6,675	3,116	970	599	1,455	1,493	1,710	1,370	283	3,346
Cd	0.17	0.50	0.48	0.42	0.71	0.49	0.36	0.32	0.29	0.30	0.23	0.28	0.19	0.35
Co	0.46	0.62	0.60	0.42	0.65	0.59	0.21	0.17	0.28	0.24	0.39	0.56	0.35	0.45
Cr	1.21	1.50	2.45	1.08	2.00	1.20	0.78	0.94	0.81	0.91	0.89	4.20	1.91	1.68
Cu	15.0	25.2	20.2	15.2	16.8	16.2	10.1	7.4	9.4	9.7	12.9	15.5	12.5	70.5
Fe	601	957	838	600	1155	742	272	164	291	251	333	261	375	362
Hg	0.16	0.54	0.61	0.64	0.76	1.00	1.04	0.94	0.77	0.75	0.68	0.74	0.72	0.45
K	9,853	10,338	10,224	9,602	10,942	9,234	10,535	11,602	10,104	9,968	11,304	10,929	12,003	10,427
Li	24.74	40.34	30.67	37.07	38.33	33.29	48.46	45.75	21.11	30.66	35.44	25.73	50.50	18.03
Mg	3,394	4,194	4,280	5,123	5,842	4,524	2,549	1,920	2,415	2,887	3,358	4,223	7,721	3,875
Mn	32.1	52.9	61.0	27.8	45.1	75.2	11.0	6.9	17.2	18.1	18.3	25.2	31.4	33.8
Mo	0.31	0.57	0.55	1.03	0.75	0.54	0.25	0.18	0.25	0.27	0.33	0.32	0.33	0.27
Na	33,031	55,628	50,940	62,266	58,339	40,575	81,175	71,780	29,496	47,574	49,093	36,183	76,649	26,603
Ni	1.69	1.94	2.04	1.49	1.81	2.14	0.68	0.36	0.56	0.50	1.13	2.14	0.70	0.91
P	8,480	7,613	7,119	5,593	7,301	6,221	5,867	6,846	7,794	7,717	8,488	8,193	6,988	9,580
Pb	1.07	2.17	2.02	0.81	3.49	1.55	0.30	0.16	0.64	0.47	0.65	0.83	0.60	1.03
Sb	0.11	0.12	0.11	0.10	0.12	0.14	0.04	0.03	0.05	0.05	0.08	0.11	0.09	0.16
Se	6.88	10.76	9.52	8.34	9.93	7.37	5.72	5.94	5.15	5.30	8.14	8.96	5.50	6.06
Si	378	433	374	316	249	287	245	187	304	306	329	284	350	326
Sn	0.070	0.090	0.060	0.060	0.080	0.100	0.500	0.010	0.030	0.030	0.060	0.480	0.040	0.270
Sr	19.8	26.7	28.4	12.7	35.1	25.7	5.1	2.9	9.7	11.3	13.7	19.0	22.0	19.0
Tl	0.02	0.01	0.01	0.01	0.01	0.01	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	0.03
V	0.90	1.31	1.49	0.82	1.78	1.12	0.33	0.27	0.40	0.41	0.56	0.38	0.87	0.77
Zn	100.0	127.5	105.1	78.4	92.8	76.7	75.4	63.0	74.2	78.3	80.5	98.9	75.3	93.0

Appendix 6. Taxonomic composition and metal concentrations (µg g^{-1} dry weight) of zooplankton collected in Farmington Bay in 2009. Concentrations shown in blue italic font were below levels of detection and are reported here as half way between the detection limit and zero.

	Farmington Bay														
	21-May	21-May	8-Jun	8-Jun	24-Jun	14-Jul	14-Jul	14-Jul	27-Jul	17-Aug	17-Aug	11-Sep	11-Sep	7-Oct	7-Oct-09
Station	1	3	1	2	1	1	2	3	1	1	3	1	3	2	1
Zooplankton Composition (%)															
Artemia	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0
Corixids	10	0	0	0	20	10	20	10	30	20	90	100	80	0	10
Cladocera	90	100	20	90	80	90	90	90	70	0	10	0	20	90	60
Other	0	0	40	10	0	0	0	0	0	90	0	0	0	10	30
Metal	Metal Concentration ($\mu g\ g^{-1}$; ppm)														
Ag	0.030	0.150	0.100	0.070	0.010	0.040	0.030	*0.005*	0.200	0.070	0.160	0.580	0.230	0.050	0.060
Al	29	645	20	43	21	23	28	42	9	22	42	1	17	29	22
As	12.1	12.6	15.6	14.8	13.2	16.8	13.3	12.1	8.0	15.0	7.8	2.0	4.4	12.3	14.9
B	13.9	24.7	20.1	16.2	12.3	19.4	18.8	15.3	18.1	20.7	14.5	3.9	9.7	13.6	7.0
Ba	15.6	40.3	4.0	12.9	8.1	14.3	10.1	7.6	9.8	5.7	22.6	14.6	13.5	2.2	1.6
Be	*0.005*	0.050	*0.005*	0.010	*0.005*	*0.005*	*0.005*	*0.005*	*0.005*	*0.005*	0.010	*0.005*	*0.005*	*0.005*	*0.005*
Ca	25,000	54,285	4,874	25,017	7,758	14,500	18,174	12,600	2,434	1,717	6,954	1,995	5,370	1,348	1,100
Cd	1.40	1.12	1.19	1.74	1.76	6.39	5.42	4.85	6.83	1.35	1.97	2.07	1.61	1.19	0.83
Co	0.25	0.62	0.21	0.22	0.14	0.18	0.19	0.16	0.16	0.20	0.24	0.07	0.21	0.20	0.18
Cr	1.38	2.74	1.52	0.92	1.36	0.83	1.35	0.83	2.43	0.64	5.51	0.54	0.67	0.68	1.44
Cu	10.9	21.9	9.7	10.2	13.9	11.1	15.9	12.3	34.7	13.9	21.6	65.8	47.7	11.2	10.5
Fe	265	1356	130	265	102	145	171	170	81	101	151	45	124	150	105
Hg	0.13	0.18	0.20	0.17	0.15	0.24	0.25	0.22	0.39	0.19	0.12	0.57	0.30	0.18	0.16
K	11,537	8,429	9,578	8,816	9,324	8,052	9,537	9,046	7,230	10,329	9,415	10,058	10,106	8,765	8,716
Li	9.40	8.34	17.69	7.99	10.28	13.49	13.77	12.05	13.96	19.00	10.78	2.85	5.13	8.46	5.77
Mg	2,878	6,035	2,725	2,936	2,151	4,032	3,641	2,623	3,134	1,852	2,197	1,517	1,835	1,671	1,436
Mn	15.7	87.6	10.2	14.7	6.4	6.4	13.8	8.6	6.1	6.2	12.1	8.1	10.4	8.7	7.6
Mo	0.70	0.66	0.56	0.55	0.49	0.62	7.30	0.54	0.87	0.56	0.52	1.05	0.73	0.56	0.56
Na	19,016	8,777	39,813	16,430	20,629	29,537	25,005	21,035	25,935	31,294	16,330	5,699	9,104	14,196	10,507
Ni	1.78	1.75	0.78	0.58	2.54	0.41	0.54	0.38	0.86	0.40	0.55	0.21	0.32	0.56	0.96
P	14,668	17,092	11,077	14,619	11,638	12,766	14,607	12,974	10,052	10,382	11,456	10,969	11,188	11,163	9,239
Pb	0.90	9.07	0.40	1.02	0.50	0.63	1.08	1.36	0.39	0.81	1.20	0.15	0.48	1.09	1.10
Sb	0.04	0.11	0.03	0.07	0.03	0.03	0.19	0.06	0.04	0.04	0.05	0.02	0.05	0.05	0.06
Se	10.25	5.68	11.29	10.33	7.59	7.71	8.24	8.18	10.22	7.38	7.25	4.56	4.63	7.23	6.76
Si	266	287	254	264	240	249	274	231	183	243	258	135	245	362	320
Sn	0.030	0.200	0.020	0.030	0.010	0.020	0.030	0.010	0.010	0.020	0.150	0.010	0.010	0.020	0.030
Sr	178.2	363.8	34.2	148.5	56.1	92.0	110.7	80.3	30.2	22.6	95.0	49.9	127.8	15.9	9.7
Tl	0.01	0.04	*0.01*	0.01	*0.01*	0.01	0.01	0.01	*0.01*	*0.01*	0.01	*0.01*	*0.01*	0.01	*0.01*
V	0.49	2.38	0.50	0.38	0.41	0.28	0.47	0.36	0.72	0.28	0.56	0.10	0.31	0.48	0.60
Zn	86.1	96.1	76.4	83.2	102.1	76.2	93.7	89.6	133.5	100.0	114.5	223.9	165.9	81.1	80.9

Appendix 7. Taxonomic composition and metal concentrations (µg g^{-1} dry weight) of zooplankton collected in Bear River Bay in 2009. Concentrations shown in blue italic font were below levels of detection and are reported here as half way between the detection limit and zero.

	Bear River Bay									
	20-May	20-May	10-Jun	19-Jun	19-Jun	24-Jun	9-Jul	30-Jul	21-Aug	9-sep-099
Station	24	25	24	24	25	24	25	25	24	24
Zooplankton Composition (%)										
Artemia	0	0	0	0	0	0	0	0	0	0
Corixids	100	100	100	20	100	100	100	100	60	100
Cladocera	0	0	0	0	0	0	0	0	0	0
Other	0	0	0	80	0	0	0	0	40	0
Metal	Metal Concentration (ug g^{-1}; ppm)									
Ag	*0.005*	0.010	*0.005*	*0.005*	0.030	*0.005*	*0.005*	0.010	0.070	*0.005*
Al	95	103	73	5,536	1,721	101	213	1,029	944	244
As	1.4	1.8	1.3	12.6	5.4	2.6	3.2	3.3	4.8	7.7
B	2.8	2.1	9.3	69.8	28.4	7.8	9.7	19.9	143.5	134.0
Ba	9.4	9.8	5.6	113.2	75.5	9.0	15.9	43.9	58.8	92.7
Be	0.040	0.010	0.010	0.570	0.150	0.010	0.020	0.110	0.060	0.010
Ca	5,812	7,619	1,529	101,437	59,681	2,116	23,475	55,924	25,163	39,922
Cd	1.05	1.57	2.86	0.57	1.19	1.69	1.40	3.18	0.83	0.22
Co	0.67	0.58	0.29	3.20	1.32	0.39	0.31	1.09	0.56	0.20
Cr	0.48	0.58	1.55	7.88	2.59	0.54	0.62	1.81	1.88	0.97
Cu	28.2	21.4	31.5	11.0	18.7	17.5	16.2	33.4	25.3	7.0
Fe	272	220	109	8526	2613	248	429	1777	997	460
Hg	0.28	0.31	0.26	0.06	0.17	0.19	0.13	0.15	0.25	0.10
K	9,527	10,886	9,437	5,677	6,500	10,761	6,439	6,871	8,852	9,150
Li	1.24	1.70	7.29	38.63	14.17	5.57	2.97	9.81	31.66	76.83
Mg	1,328	1,496	2,189	29,424	7,422	2,033	2,134	4,942	12,747	44,445
Mn	26.0	37.4	15.4	245.9	97.6	18.6	18.2	67.7	125.3	279.7
Mo	0.86	1.00	0.52	0.23	0.53	0.66	0.60	0.54	1.61	0.51
Na	4,408	5,243	10,110	2,339	3,070	6,451	4,062	3,880	17,556	40,075
Ni	0.48	0.74	0.29	8.32	3.53	0.34	0.80	2.20	3.69	1.08
P	10,572	11,557	8,990	4,829	6,760	10,000	6,340	7,206	7,759	6,933
Pb	0.61	0.53	0.29	10.63	7.16	0.51	0.79	3.26	3.36	3.58
Sb	0.04	0.06	0.02	0.04	0.08	0.02	0.03	0.04	0.22	0.12
Se	2.71	6.67	3.92	1.81	3.46	5.66	4.12	5.02	2.69	1.60
Si	539	335	369	527	360	416	324	301	347	276
Sn	0.110	0.030	*0.005*	0.100	0.030	0.010	0.050	0.010	0.080	0.340
Sr	43.2	44.3	10.1	433.8	539.0	13.6	94.5	239.9	242.3	298.6
Tl	0.01	0.01	0.01	0.10	0.05	*0.01*	0.01	0.03	0.02	0.01
V	0.29	0.28	0.52	10.18	4.50	0.34	0.64	2.38	2.19	0.62
Zn	150.1	118.9	125.2	63.9	94.5	124.5	84.8	122.5	98.7	170.7