B.C. Lake Monitoring Network
Water Quality, Phytoplankton and Zooplankton Taxonomy
Summary Report for 2015-2020

Prepared for BC Ministry of Environment and Climate Change Strategy,
Environmental Sustainability Division

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Executive Summary

The British Columbia Ministry of Environment and Climate Change Strategy (ENV) conducts spring and fall lake monitoring at select sites across the province, through a program called the B.C. Lake Monitoring Network (BCLMN). Water chemistry was the focus of lakes monitoring for decades but in 2015 the BCLMN was establish and began the collection of taxonomic samples for phytoplankton and zooplankton. However, there has only been limited analytical assessment done of the accumulated taxonomic data to date because of limited funding and ENV staff time. Larratt Aquatic Consulting (LAC) was chosen to combine the taxonomy data, analyze it alongside available water chemistry data, and interpret the results for 19 lakes across British Columbia. This report summarizes those results with special focus on the taxonomic samples. In addition, a taxonomic reconciliation table was created to harmonize the taxonomy data from the different sites, correcting spelling errors and updating taxa to the latest accepted name. A master taxonomy table was created that provides information on each taxa such as its habitat, edibility, and whether it is an indicator taxa. Finally, the R-scripts used for statistical analyses are provided as part of this project.

The analyses in this report found many key messages in the BCLMN database, confirming the value of this program.

Summary of Findings:

Physical

- Spring and late-summer surface water temperature data demonstrated that the largest lakes had lower heat budgets than small, shallower lakes.
- Water clarity was excellent in the deep oligotrophic Adams and Chilliwack lakes and very poor in eutrophic Williams and Quamichan lakes.
- Lake depth affected nutrient cycling; deep lakes showed lower phosphorus and lower overall productivity.

Chemical

- Total phosphorus correlated strongly with chlorophyll-a indicating that phosphorus availability is a driving factor for phytoplankton production at most of the studied lakes.
- Orthophosphate accumulation in the hypolimnion was significant in Quamichan, Williams, Pennask, Puntzi, and Quiniscoe lakes.
- The ratio of bioavailable dissolved inorganic nitrogen to total dissolved phosphorus (DIN:TDP) is a key factor in determining which types of phytoplankton will proliferate. The 19 BC lakes ranged from highly phosphorus-limited Adams and Chilliwack lakes to strongly nitrogen-limited Quamichan Lake. Most lakes had ratios of less than 5:1 indicating that nitrogen was limiting productivity and pre-disposing those lakes to cyanobacteria.
- Hypolimnetic ammonia increased in Pennask Lake from 2015-2020 and may be related to extensive watershed deforestation following the Mountain Pine Beetle salvage logging. Increased ammonia has been noted in adjacent watersheds.
- There were no geographic patterns in TN or DIN distribution across British Columbia.
- Water quality objectives exist for Williams Lake, Lakelse Lake, and Columbia Lake and except for very high chlorophyll-a in Williams Lake, all objectives were met during most years from 2015-2020.

Biological - Phytoplankton

- Chlorophyll-a, a common photosynthetic pigment, varied by up to two orders of magnitude between the least productive (Chilliwack Lake) and most productive lake (Quamichan Lake). Chlorophyll-a tightly correlated with phosphorus concentrations.
- Total phytoplankton abundance was similar to chlorophyll-a, confirming its usefulness as a productivity metric, with Williams and Quamichan lakes having by far the highest productivity because of their very high phosphorus concentrations.
- High primary productivity was driven by intense cyanobacteria growth.
- Taxa that can cause aesthetic concerns were the dominant taxa at most sites but were likely to be a concern at: Quiniscoe, Pennask, Quamichan, and Williams lakes.
- Cyanobacteria blooms are a major concern for water industries as they represent high risk for human health and economic costs for drinking water treatment. Taxonomic data identified the lakes at highest risk of recurring toxic harmful algae blooms (HABs) as those dominated by taxa with toxin potential: Williams Lake (97%) Quamichan Lake (87%), Diana Lake (72%), Pennask Lake (65%) and Skaha Lake (63%).
- Lakes dominated by cyanobacteria were also the lakes with very low N:P ratios
- Overall phytoplankton diversity was low with the dominant five taxa accounting for most of the productivity, particularly at Williams Lake where the single cyanobacteria species accounted for nearly 80% of total abundance. Low phytoplankton diversity can affect lake resilience.
- Diatoms accounted for less than a quarter of total abundance at most lakes with chrysophytes and green algae both accounting for a larger percentage of total abundance.
- There were no statistically significant year-over-year phytoplankton trends because of the small sample size for each lake.
- Seasonal variation was consistent across the lakes with lower spring densities that contained high proportions of chrysophytes and diatoms, followed by higher densities in the summer samples that were dominated by cyanobacteria and green algae.
- Lakes prone to nuisance blooms such as Quamichan and Williams lakes had higher ratios of pollution tolerant : pollution sensitive taxa than oligotrophic lakes such as Chilliwack Lake.
- Phytoplankton community metrics tracked water chemistry and limnology factors including: lake depth (Adams), proximity to an urban area (Williams), strong internal nutrient loading (agricultural impacts (Quamichan), improved sewage treatment (Skaha)

Biological - Zooplankton

- Zooplankton abundance and diversity were variable between lakes but closely matched phytoplankton abundance and diversity. Zooplankton metrics were highest in Quiniscoe Lake, a productive alpine lake, and lowest in Chilliwack Lake, the lake with the lowest phytoplankton abundance.
- Zooplankton abundance correlated strongly with green algae abundance, likely because they are higher quality food while they correlated poorly to cyanobacteria abundance which is considered lower-quality food for zooplankton.
- Zooplankton species richness diversity was similar between most of the lakes with between 10-20 taxa per sample except for Ladyslipper and Glacier lakes that had very low diversity; these lakes also had very low phytoplankton diversity and abundance indicating overall low biological productivity.

- Copepod nauplii were the most abundant type of zooplankton, representing half of the observed zooplankton abundance across all sites.
- Zooplankton growth did not correlate to water chemistry but they are strong indicators of food web health, and the potential of a lake to support fisheries.

Summary table of physical, chemical, and biological data (Mean ± SD)

South >> North by Region

	Lizard Lake	Quamichan Lake	Cultus Lake	Chilliwack Lake	Ladyslipper Lake	Glacier Lake	Quiniscoe Lake	Skaha Lake	Pennask Lake	Sugar Lake	Adams Lake	Premier Lake	Columbia Lake	Williams Lake	Puntzi Lake	Fraser Lake	Moberly Lake	Lakelse Lake	Diana Lake
Temperature	15.2 ± 9	15.8 ± 9.3	19 ± 7	14.9 ± 5.9	10.4 ± 2.3	10.8 ± 0.8	11 ± 2.2	10.4 ± 9.4	13.6 ± 3.9	12.4 ± 7.8	11.7 ± 6.3	15.2 ± 6.1	15.4 ± 6.1	13.1 ± 7.2	13.1 ± 5.8	11.7 ± 5	10.4 ± 4	10.2 ± 1.3	15.3 ± 5.2
Secchi Depth	7.6 ± 1.1	1.4 ± 0.6	8.2 ± 3.5	12.3 ± 3.6	8.5 ± 0.8	5 ± 0	4.7 ± 0.8	6.4 ± 1.3	2.8 ± 0.7	8.5 ± 2.2	12.9 ± 3.4	10.8 ± 1.6	4 ± 0.5	1.2 ± 0.2	4.9 ± 2.3	2.9 ± 0.7	2.7 ± 1.8	2.7 ± 0.7	2.1 ± 0.8
Dissolved Oxygen	10.1 ± 1.7	11.1 ± 4.2	9.8 ± 1.8	9.3 ± 1	8.9 ± 0.7	8.7 ± 1	9 ± 0.5	11 ± 2.6	8.9 ± 0.9	9.8 ± 1	10.3 ± 1.2	9.4 ± 0.7	9.5 ± 1.1	10.4 ± 1.2	8.9 ± 0.9	10.5 ± 1.4	10.4 ± 1	13.2 ± 1.5	11.1 ± 2.7
Silica	2.39 ± 0.5	1.99 ± 1.96	3.17 ± 3.05	4.62 ± 1.79	8.81 ± 0.4	8.6 ± 0.98	8.86 ± 0.66	6.09 ± 0.76	10.22 ± 0.75	5.68 ± 0.98	6.14 ± 0.31	2.21 ± 0.43	5.57 ± 2.05	9.25 ± 6.34	0.43 ± 0.46	4.47 ± 1.08	2.99 ± 0.44	5.53 ± 0.8	1.4 ± 0.48
TN	0.146 ± 0.061	1.704 ± 0.899	0.145 ± 0.043	0.084 ± 0.026	0.064 ± 0.004	0.182 ± 0.004	0.252 ± 0.131	0.219 ± 0.02	0.65 ± 1.024	0.101 ± 0.039	0.13 ± 0.017	0.193 ± 0.022	0.22 ± 0.04	0.864 ± 0.298	0.679 ± 0.331	0.296 ± 0.017	0.313 ± 0.049	0.09 ± 0.029	0.148 ± 0.021
Ammonia	0.0094 ± 0.0132	0.5575 ± 0.8384	0.0033 ± 0.0018	0.0025 ± 0	0.0025 ± 0	0.0025 ± 0	0.0384 ± 0.0698	0.0025 ± 0	0.0091 ± 0.008	0.0036 ± 0.0024	0.0059 ± 0.0039	0.0036 ± 0.0024	0.0025 ± 0	0.0186 ± 0.0159	0.0447 ± 0.0905	0.0078 ± 0.0024	0.019 ± 0.0208	0.0038 ± 0.0031	0.0042 ± 0.0034
NO3+NO2	0.0123 ± 0.0171	0.1491 ± 0.1823	0.037 ± 0.06	0.0351 ± 0.0254	0 ± 0	0 ± 0	0 ± 0	0.0004 ± 0.0016	0.007 ± 0.0118	0.0406 ± 0.038	0.0659 ± 0.0353	0.0003 ± 0.001	0 ± 0	0.0408 ± 0.0596	0.0606 ± 0.0722	0.0039 ± 0.0061	0.097 ± 0.0366	0.02 ± 0.0229	0.011 ± 0.0092
TP	0.0058 ± 0.0037	0.3173 ± 0.1467	0.0038 ± 0.001	0.0015 ± 0.0009	0.0057 ± 0.0008	0.0486 ± 0.0395	0.0132 ± 0.0017	0.0068 ± 0.0025	0.0202 ± 0.0093	0.0017 ± 0.0011	0.0026 ± 0.0017	0.0035 ± 0.0019	0.0064 ± 0.0041	0.0418 ± 0.0347	0.0162 ± 0.018	0.0154 ± 0.0071	0.0078 ± 0.0084	0.0042 ± 0.002	0.0042 ± 0.0011
TDP	0.0023 ± 0.0014	0.2526 ± 0.1111	0.0021 ± 0.0006	0.001 ± 0	0.0018 ± 0.0011	0.0125 ± 0.002	0.0063 ± 0.0009	0.0033 ± 0.0011	0.0072 ± 0.0019	0.0016 ± 0.0011	0.0011 ± 0.0004	0.0026 ± 0.0013	0.0025 ± 0.0015	0.0153 ± 0.0152	0.0171 ± 0.0152	0.008 ± 0.0029	0.0032 ± 0.0026	0.0021 ± 0.0016	0.0024 ± 0.0009
Ortho P	0.0005 ± 0	0.25827 ± 0.24505	0.0005 ± 0	0.0005 ± 0	0.0005 ± 0	0.00455 ± 0.00445	0.01038 ± 0.01749	0.00068 ± 0.00061	0.0017 ± 0.00158	0.0007 ± 0.00045	0.00056 ± 0.00019	0.0007 ± 0.00041	0.0008 ± 0.00043	0.00997 ± 0.01256	0.00819 ± 0.01274	0.00257 ± 0.00169	0.00105 ± 0.0009	0.00083 ± 0.00082	0.0005 ± 0
Chl-a (mg/L)	0.00296 ± 0.00371	0.04212 ± 0.01736	0.00166 ± 0.00106	0.00057 ± 0.00027	0.00075 ± 0.00007	0.00088 ± 0.00037	0.00512 ± 0.00315	0.00361 ± 0.00318	0.00775 ± 0.00404	0.00139 ± 0.00135	0.0007 ± 0.00029	0.00088 ± 0.00068	0.00126 ± 0.00041	0.0142 ± 0.00683	0.00383 ± 0.00278	0.00382 ± 0.0012	0.00159 ± 0.00114	0.00153 ± 0.00063	0.00101 ± 0.00069
Phyto Abundance	940 ± 854	18744 ± 17528	246 ± 222	192 ± 274	225 ± 150	340 ± 293	2657 ± 2800	1172 ± 512	2138 ± 586	325 ± 267	210 ± 173	406 ± 229	458 ± 313	42457 ± 20022	1244 ± 493	1346 ± 964	571 ± 137	253 ± 139	1667 ± 1915
Phyto Species Richness	45 ± 11	31 ± 5	25 ± 5	24 ± 7	33 ± 4	37 ± 5	53 ± 11	46 ± 22	60 ± 6	40 ± 7	33 ± 13	23 ± 11	58 ± 20	20 ± 7	24 ± 10	56 ± 11	47 ± 4	52 ± 8	32 ± 4
Phyto Shannon-Weaver	2.1 ± 0.7	1.2 ± 0.4	1.9 ± 0.5	2 ± 0.7	2 ± 0.1	1.9 ± 0.1	1.9 ± 0.1	2 ± 0.5	1.6 ± 0.3	2 ± 0.7	1.9 ± 0.5	1.3 ± 0.4	2.4 ± 0.6	0.6 ± 0.5	0.8 ± 0.1	2.3 ± 0.3	1.7 ± 0.4	2.5 ± 0.5	1.4 ± 0.7
Zoops Abundance	16 ± 12	159 ± 108	19 ± 11	4 ± 2	23 ± 11	25 ± 26	809 ± 1047	26 ± 11	67 ± 63	11 ± 4	8 ± 4	54 ± 14	109 ± 83	186 ± 158	49 ± 37	45 ± 16	40 ± 52	29 ± 20	22 ± 13
Zoops Species Richness	15 ± 3	14 ± 4	14 ± 4	13 ± 0	6 ± 1	7 ± 2	14 ± 1	17 ± 2	18 ± 1	16 ± 2	12 ± 5	17 ± 1	13 ± 2	15 ± 3	19 ± 1	17 ± 1	15 ± 3	15 ± 3	16 ± 2
Zoops Shannon-Weaver	1.8 ± 0.5	1.5 ± 0.5	1.7 ± 0.4	1.6 ± 0.4	0.7 ± 0.2	0.3 ± 0	1.3 ± 0.8	1.9 ± 0.2	1.9 ± 0.3	1.3 ± 0.5	1.7 ± 0.5	2 ± 0.2	1.6 ± 0.3	0.8 ± 0.5	2 ± 0.4	1.7 ± 0.4	1.9 ± 0.3	1.8 ± 0.3	1.3 ± 0.4

Note: colour scale for each parameter is relative to that parameter with red cells having the poorest water quality and green cells having the highest water quality for a given parameter from a perspective of eutrophication and nutrient enrichment. A eutrophic, highly productive lake such as Quamichan Lake, will tend to have more orange/red cells than an oligotrophic lake that will be more green (Adams Lake). Colour scale does not reflect attainment of objectives

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Definitions

The following terms are defined as they are used in this report.

Term	Definition
Algae bloom	A superabundant growth of algae
Anoxic	Devoid of oxygen
Bioavailable	Available for use by plants or animals
Chlorophyll-a	Primary photosynthetic pigment in algae; used as a measure of photosynthetic activity
Cyanobacteria	Bacteria-like algae having cyanochrome as the main photosynthetic pigment
Diatoms	Algae that have hard, silica-based cell walls called frustules
Spring/Fall overturn	Point when lake becomes uniform density from surface to sediment and mixes, removing stratification
Eutrophic/hypereutrophic	Nutrient-rich, biologically productive water body
Harmful Algae Bloom	Algae bloom that produces negative impacts on human or wildlife health
Macronutrient	The major constituents of cells: nitrogen, phosphorus, carbon, sulphate, H
Micronutrient	Small amounts are required for growth; Si, Mn, Fe, Co, Zn, Cu, Mo etc.
Microflora	The sum of algae, bacteria, fungi, *Actinomycetes,* etc., in water or biofilms
Nutrient limitation	A nutrient will limit or control the potential growth of organisms e.g. P or N
Phytoplankton	Algae that float, drift or swim in water columns of reservoirs and lakes
Plankton	Those organisms that float or swim in water
Secchi depth	Depth where a 20 cm Secchi disk can be seen; measures water transparency
Thermocline	The lake zone of greatest change in water temperature with depth (> 1°C/m); it separates the surface water (epilimnion) from the cold hypolimnion below
Zooplankton	Minute animals that graze algae, bacteria and detritus in water bodies

Term	Definition
AFDM	Ash-free dry mass
Chl-a	Chlorophyll-a units µg/L
DO	Dissolved oxygen units mg/L
EMS	British Columbia Environmental Monitoring System (a database of water chemistry data)
ENV	British Columbia Ministry of Environment and Climate Change Strategy
HAB	Harmful algae bloom, typically of cyanobacteria
N	Nitrogen units mg/L as N
Ortho-P	Orthophosphate ≈ SRP monomeric inorganic phosphorus units mg/L as N
P	Phosphorus units mg/L as P
DIN	Dissolved inorganic nitrogen = ammonia + nitrate + nitrite units mg/L as N
TDN	Total dissolved nitrogen = ammonia + nitrate + nitrite + dissolved organic N units mg/L as N
TDP/DP	Total dissolved phosphorus units mg/L as P
TN	Total nitrogen: organic + dissolved units mg/L as N
TP	Total phosphorus: organic + dissolved units mg/L as P

Lake Classification by Trophic Status Indicators (Nordin, 1985)

Trophic Status	chlorophyll-a µg/L	Total P µg/L	Total N µg/L	Secchi disc m	primary production mg C/m²/day
Oligotrophic	0 – 2	1 – 10	<100	> 6	50- 300
Mesotrophic	2 – 5	10 – 20	100 – 500	3 – 6	250 – 1000
Eutrophic	>5	> 20	500-1000	< 3	>1000

Nutrient Balance Definitions for Microflora (Dissolved Inorganic N : Dissolved Inorganic P) (Nordin,1985)

Phosphorus Limitation	Co-Limitation of N and P	Nitrogen Limitation
>15 : 1	<15 : 1 – 5 : 1	5 : 1 or less

1.0 Introduction

1.1 Lake Sampling Program Overview

The British Columbia Ministry of Environment and Climate Change Strategy (ENV) monitors lakes throughout the province through the B.C. Lake Monitoring Network (BCLMN). As part of this program phytoplankton and zooplankton taxonomy samples were collected from 19 locations from 2015-2019. In addition to the taxonomy, water chemistry data were collected at all the sites and will be included in this report.

Lake sampling focused on three primary categories at each site: physical parameters, water chemistry, and biological activity.

- Physical parameters including temperature profiles were taken at each site on each date and Secchi depth, a measure of water clarity, was also recorded for each site.

- In addition, dissolved oxygen profiles were taken and a range of parameters were chemically analyzed from samples taken in the epilimnion and the hypolimnion. Chemistry included a broad range of parameters but this report focuses on the major nutrients in their various forms.

- Biological sampling included generic parameters such as chlorophyll-a concentration, as well as detailed taxonomic classification of phytoplankton (algae) and zooplankton.

1.2 Data Analysis Study Overview

The results from the BCLMN were analyzed and interpreted to provide context and insight into the environmental conditions at 19 lakes that are spread across the province (Figure 1, Appendix 3). The sites were selected to represent a diverse range of habitat found in British Columbia and two sites were included for each geographic region.

This study contained four primary components:

- The taxonomic reconciliation table: Changes in labs and taxonomists over the years have resulted in a variety of different taxonomic names for the same organisms. We created a list that matches the existing ID name to ITIS number and currently accepted taxonomic name.
- Master taxonomy table: Taxonomic lists are useful but do not provide insight into the important characteristics of each species. The master taxonomy table aligns the corrected name from the taxonomic reconciliation table for each taxa observed at the 19 sites from 2015 - 2020 with a series of informative variables such as habitat preference, size, usefulness as food for larger organisms, etc.
- Summary report: This report was prepared using the Okanagan Lake Collaborative summary report as a template. It discusses the physical, chemical, and biological conditions in the 19 studied lakes. We focused on the taxonomic data as it had not been analyzed in depth prior to this report. The 2015-2020 time frame was used throughout this report as those were the years with taxonomic data. The entire water chemistry dataset was considered but only discussed if there were long-term trends. The report concludes by ranking the lakes against each other for a suite of parameters designed to

provide insight on aquatic health. The R scripts developed to generate this report were provided to ENV to aid in future analyses.

- Analysis of taxonomic levels: The current monitoring program utilizes a highest possible taxonomic resolution approach with diatoms identified to sub-species when possible. While having these data available is potentially valuable, we reviewed whether there could be a benefit to reducing taxonomic identification to genus level and passing the cost savings to other aspects of the program such as increased number of samples.

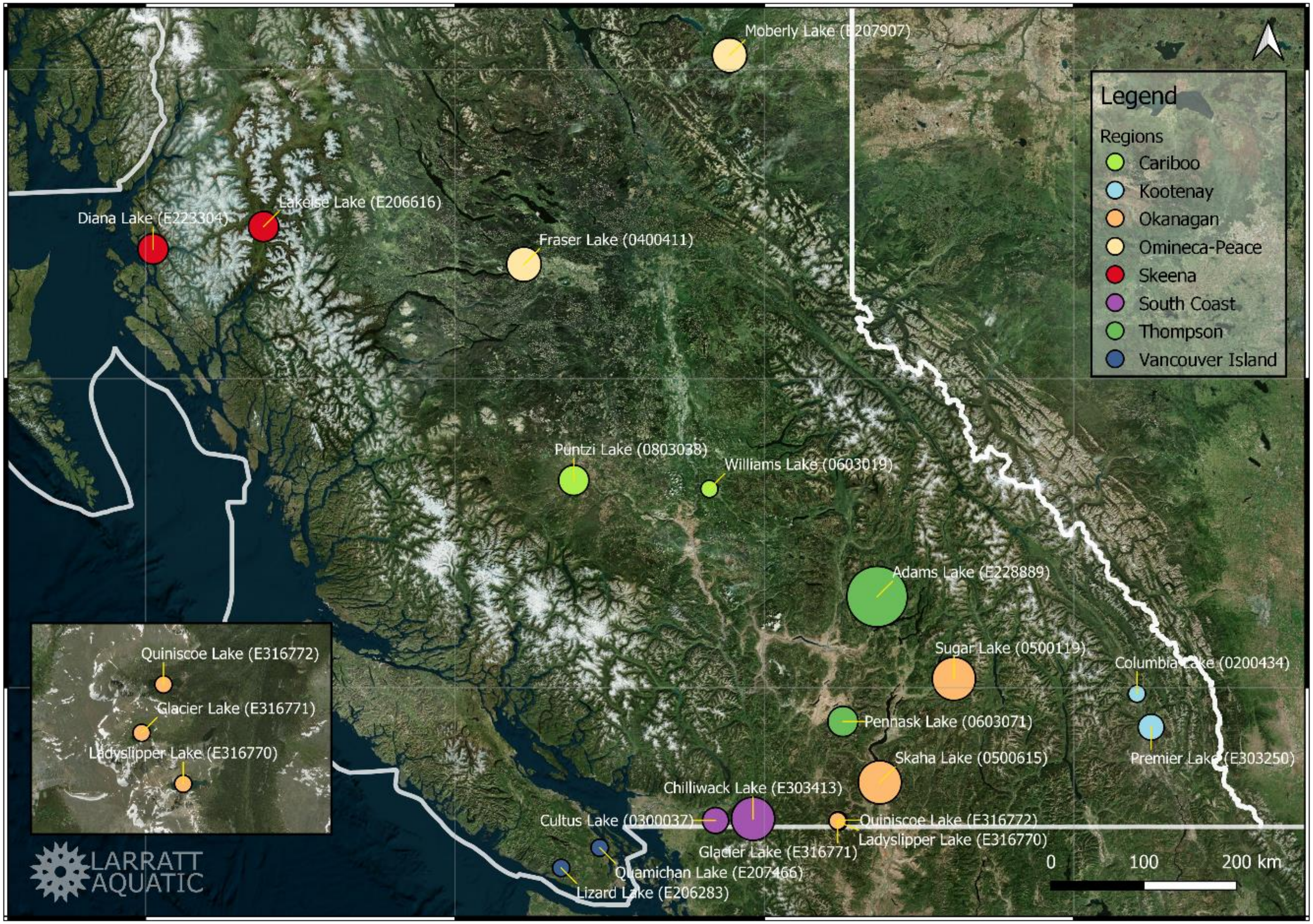

Figure 1: Map of sampling locations within British Columbia

Note: Size of bubbles approximates to size and depth of lake with larger/deeper lakes = larger bubbles

Table 1: Site Information

Region	Lake	EMS Site Name	Longitude	Latitude	EMS ID	Sample Site Depth (m)	Max Depth (m)	Elevation (m)	Surface Area (km^2)
Thompson	Adams	ADAMS LAKE, OFF BRENNAN CR	-119.6347	51.1472	E228889	397	457	408	131.08
South Coast	Chilliwack	CHILLIWACK LAKE NEAR CENTRE OF THE NORTH 1/2 OF LAKE	-121.436211	49.076764	E303413	114	114	621	11.82
Kootenay	Columbia	COLUMBIA LAKE, MIDLAKE NORTH	-115.8625	50.2533	0200434	5	5	810	25.1
South Coast	Cultus	CULTUS LAKE AT CENTRE	-121.9814	49.0608	0300037	41	42	46	6.31
Skeena	Diana	DIANA LAKE	-130.1467	54.2083	E223304	15	32	70	2.6
Omineca-Peace	Fraser	FRASER L NEAR MIDDLE 3 KM E LOT 3229	-124.7625	54.0778	0400411	28	31	676	53.85
Okanagan (Cathedral)	Glacier	Glacier Lk @ Deepest Point	-120.207504	49.056184	E316771	5	5	2192	0.08
Okanagan (Cathedral)	Ladyslipper	Ladyslipper Lk @ Deepest Point	-120.196561	49.047398	E316770	20	20	2219	0.11
Skeena	Lakelse	LAKELSE LAKE DEEP STATION	-128.5429	54.3984	E206616	30	30	76	13.68
Vancouver Island	Lizard	LIZARD LAKE DEEPEST POINT	-124.2219	48.6067	E206283	15	16	65	0.08
Omineca-Peace	Moberly	MOBERLY LAKE DEEP STN.	-121.7767	55.8222	E207907	44	44	697	28.51
Thompson	Pennask	PENNASK LK NEAR CENTER	-120.1308	49.9944	0603071	25	25	1421	9.42
Kootenay	Premier	PREMIER LAKE (DEEPEST POINT)	-115.656101	49.941192	E303250	35	35	877	2.03
Cariboo	Puntzi	PUNTZI LAKE AT CENTRE	-124.0392	52.1947	0803038	35	44	955	16.88
Vancouver Island	Quamichan	QUAMICHAN LAKE, CENTRE	-123.6625	48.8003	E207466	7	8	25	2.88
Okanagan (Cathedral)	Quiniscoe	Quiniscoe Lk @ Deepest Point	-120.201754	49.064548	E316772	12	12	2061	0.11
Okanagan	Skaha	SKAHA L OPP. GILLIES	-119.5951	49.4225	0500615	54.1	57	339	19.59
Okanagan	Sugar	SUGAR L @ SITKUM CR.	-118.5197	50.39145	0500119	85.1	85	606	21.3
Cariboo	Williams	WILLIAMS LAKE AT CENTER	-122.0708	52.1183	0603019	18	24	571	6.92

2.0 Results & Discussion

2.1 Physical

2.1.1 Temperature

Water temperature was collected at each site via field readings during the spring and fall sampling trips. The largest lakes, because of their great thermal mass had cooler peak surface water temperatures compared to shallow lakes (see Fall in Figure 2) while coastal lakes were on average warmer than interior lakes because of the moderating influence of the Pacific Ocean on winter temperatures Coastal lakes that do not freeze will therefore have warmer spring temperature measurements with the noted exception of Lizard and Quamichan Lakes because they were sampled in February compared to April-May for most other sites.

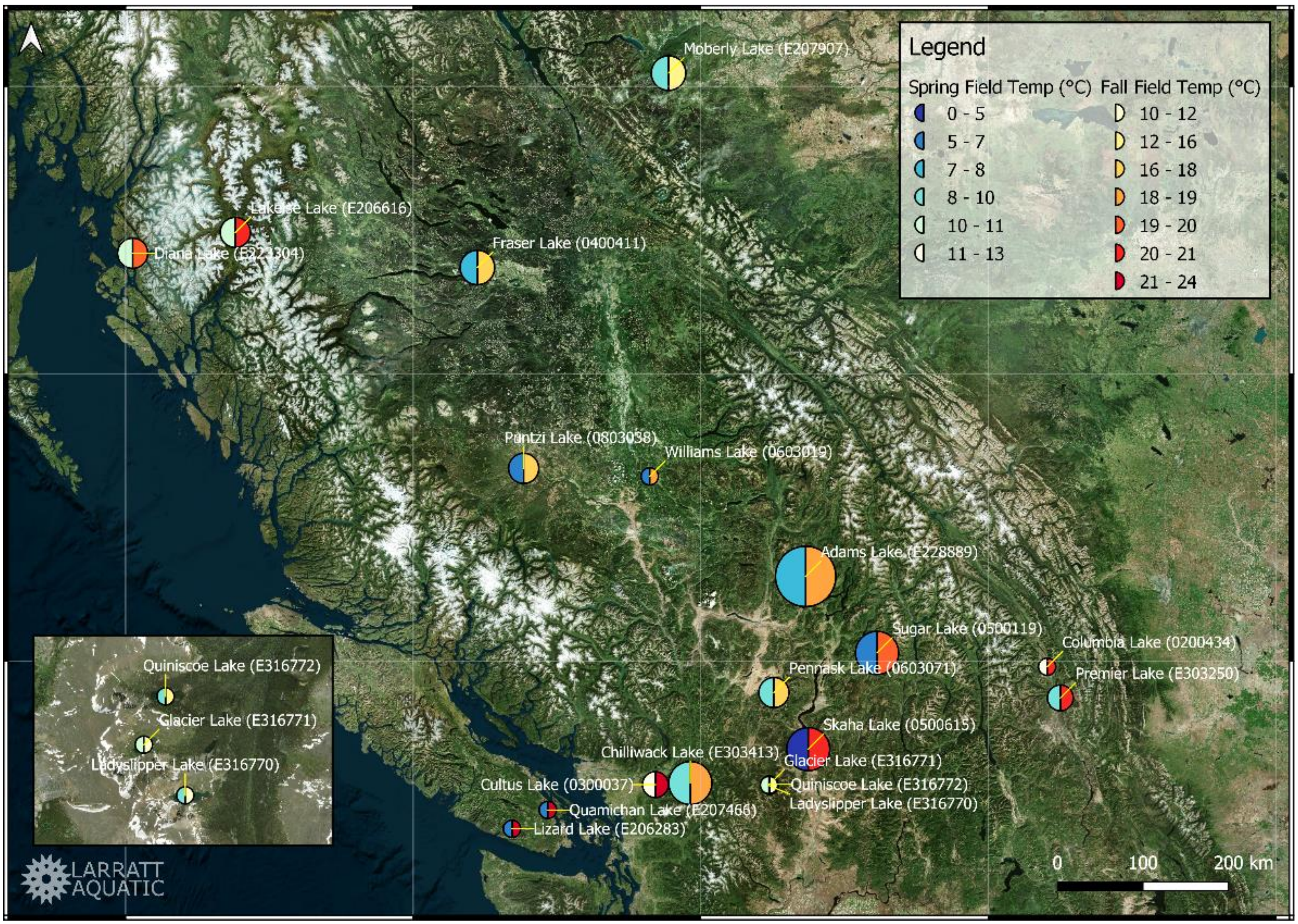

Figure 2: Mean epilimnion water temperature at sample locations, 2015-2020

Note: Size of bubbles approximates to size and depth of lake with larger/deeper lakes = larger bubbles

Source: EMS

2.1.2 Water Clarity and Secchi Depth

Secchi depth is a standard measure of water clarity used in lakes throughout the world. There was a general south to north decrease in water clarity with the northern sites in Skeena and Omineca-Peace regions having consistently lower Secchi depths than the sites in the southern interior regions during the spring and late-summer samples (Figure 3). There were no significant increasing or decreasing trends in Secchi data from 2015-2020 (Mann-Kendall trend tests). Very deep lakes such as Adams Lake (457 m) and Chilliwack Lake (114 m) had the highest Secchi depth because nutrient cycling is slow and nutrients settle into the deep hypolimnion/sediments (Figure 7) where they cannot fuel algae blooms (Figure 12, Figure 14). Secchi depth and algae productivity are often inversely correlated with Pearson's R values as low as -0.96 for Moberly Lake. Most of the lakes had higher or similar water clarity in the fall compared to the spring because of consumption of nutrients by spring phytoplankton production. However, those lakes that were dominated by cyanobacteria such as Williams and Quamichan lakes (see Figure 22) had higher water clarity in the spring when the cool water temperature restricts cyanobacterial growth.

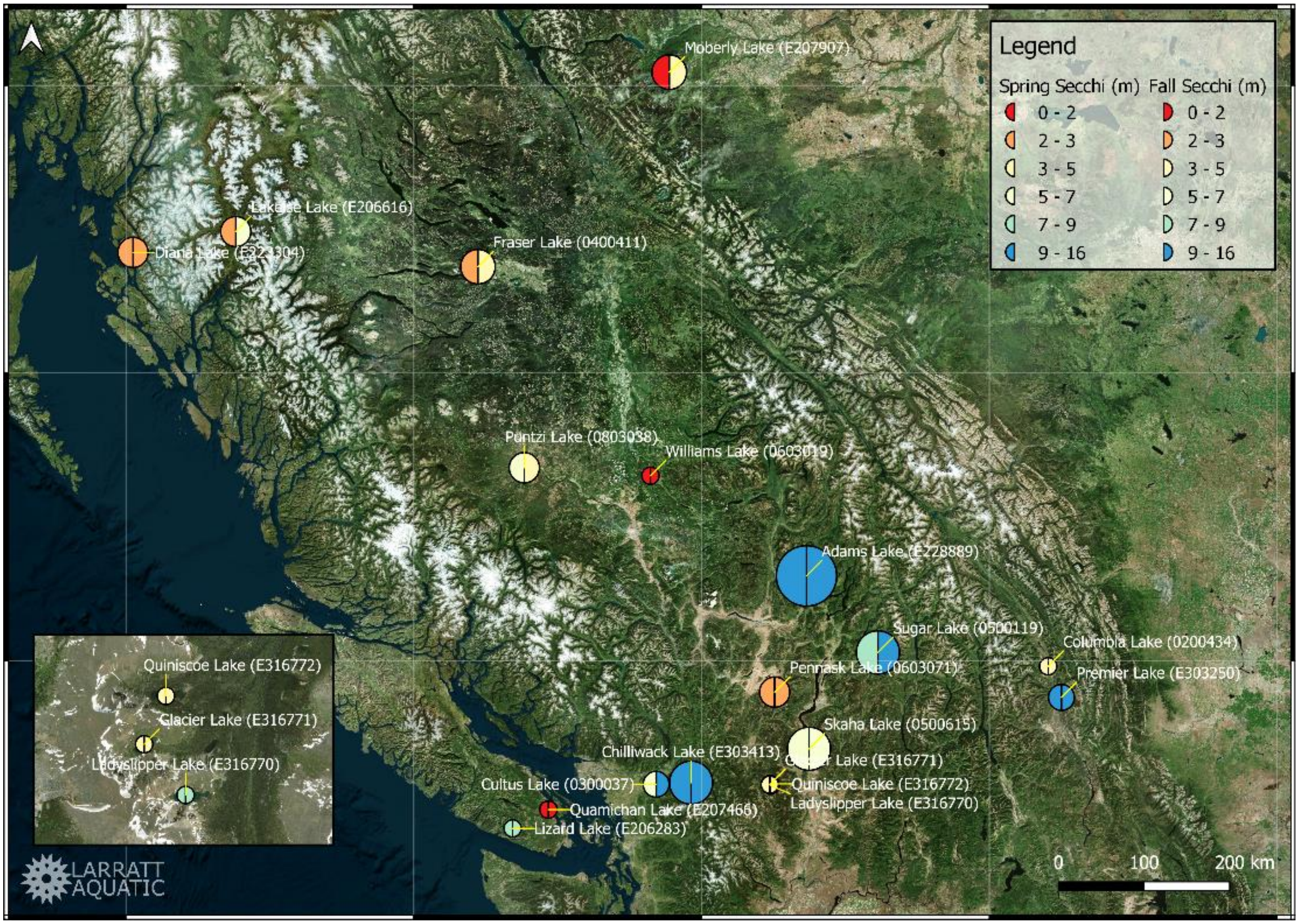

Figure 3: Secchi depth at various sample sites, 2015-2020

Note: Size of bubbles relates to size and depth of lake with larger/deeper lakes = larger bubbles

Source: EMS

2.2 Chemistry

Chemistry sampling focused on dissolved oxygen, nitrogen and phosphorus (the most important aquatic nutrients), and silica; these parameters were chosen as they are most important for phytoplankton which serves as the base of the food chain. Increasing nutrient trends frequently result from human activities such as wastewater effluent disposal, riparian degradation, agriculture, fertilizer use, storm water, etc. These human-caused impacts are gradual and are easiest to detect as year-over-year trends.

2.2.1 Dissolved Oxygen

Dissolved oxygen (DO) is essential for all aquatic animals. Low DO will stress fish and possibly preclude them from certain portions of the water column. Anoxic conditions can occur in the bottom water along substrates when hypolimnetic DO is very low but not necessarily fully anoxic (≤2 mg/L) and this has a profound impact on water chemistry through the mobilization of nutrients and metals from the sediment. Anoxic conditions were not recorded at any site in the EMS data because only surface DO is recorded in EMS but Quamichan Lake on Vancouver Island is known to experience low oxygen (Figure 4; Preikshot 2019). Quamichan is a broad shallow lake (max depth 8 m) that is surrounded by farmland and is highly eutrophic (Figure 8) with organic sediment that exert significant oxygen demand on the water column. Quamichan only weakly stratifies each summer but bottom water still becomes hypoxic or fully anoxic each year because of the intense sediment oxygen demand. Based on their water chemistry[1], other lakes that likely experience episodes of low hypolimnetic dissolved oxygen are Williams, Puntzi, Pennask, Fraser, and Quiniscoe lakes (Figure 9).

Quamichan Lake also experienced very high dissolved oxygen concentrations during frequent algae blooms (Figure 12). Algal photosynthesis can super-saturate the water column during the daylight hours. Very high dissolved oxygen occurred at other lakes that experienced algal blooms such as Skaha Lake, Lakesle Lake, and Diana Lake.

There were no significant trends in dissolved oxygen concentration data from 2015-2020 at any of the sites.

[1] Orthophosphate and manganese are released from the sediment under anoxic conditions and are markers of nutrient recycling via anaerobic nutrient release from sediment.

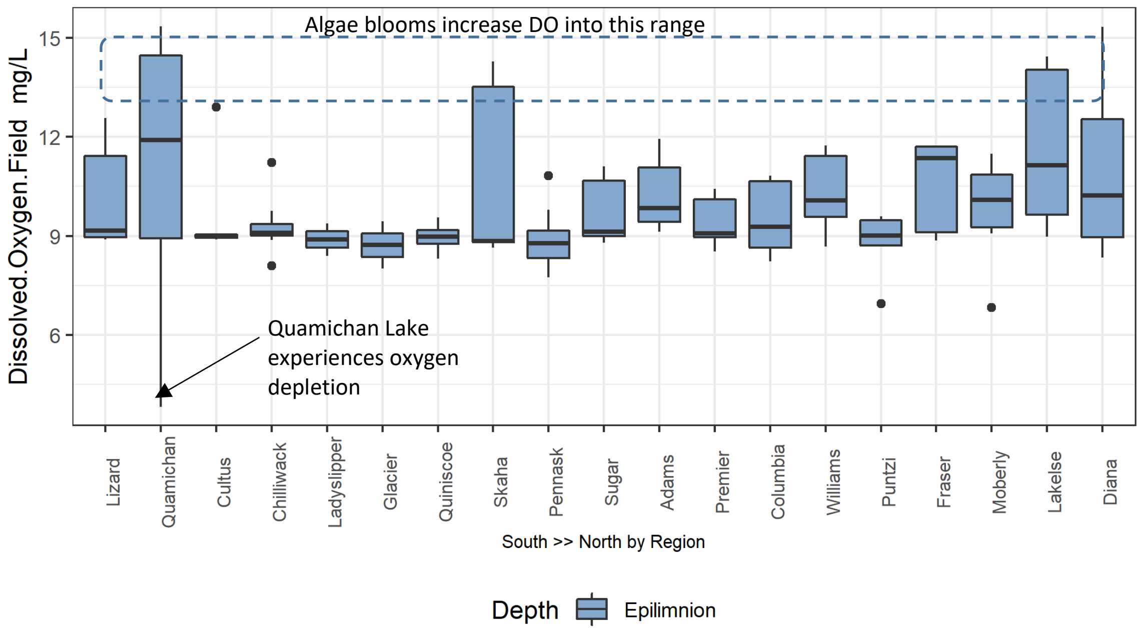

Figure 4: Surface dissolved oxygen data from select lakes across British Columbia, 2015-2020
Source: EMS
Note: Most sites have only surface DO measurements recorded in EMS and this is reflected in the absence of hypolimnion boxplots above

2.2.2 Silica

Diatom algae use silica as a structural building block for their cell walls, and their growth can be restricted at silica low concentrations. The warm, dry Southern Interior had the highest dissolved silica concentrations, while the wetter coastal and Kootenay regions had lower silica concentrations (Figure 5). Williams Lake and Pennask Lake had the highest silica concentrations averaging 11.59 ± 5.16 mg/L and 10.95 ± 1.29 mg/L respectively from 2015-2020 while Diana Lake had very low silica averaging only 1.45 ± 0.40 mg/L during 2015-2020. Silica concentrations did not measurably affect phytoplankton community composition. Lakes with higher silica content did not correlate to greater diatom abundance (Pearson's R=-0.01), indicating that other factors such as nutrient ratios and nutrient limitation were more important drivers of phytoplankton abundance and community composition (Figure 5, Figure 22). No significant trends in silica content occurred at any lake site from 2015-2020 (Mann-Kendall trend tests).

Diatoms are essential to lake health because of their high nutritional value (see Master Taxonomy Table). They require about the same amounts of nitrogen and silica for growth. There is evidence that nitrogen:silica ratios above 3:1 lessen the growth rate of diatoms (Flynn and Martin-Jezequel 2000); fortunately, all lakes studied had average N:SiO_2 ratios of <2:1.

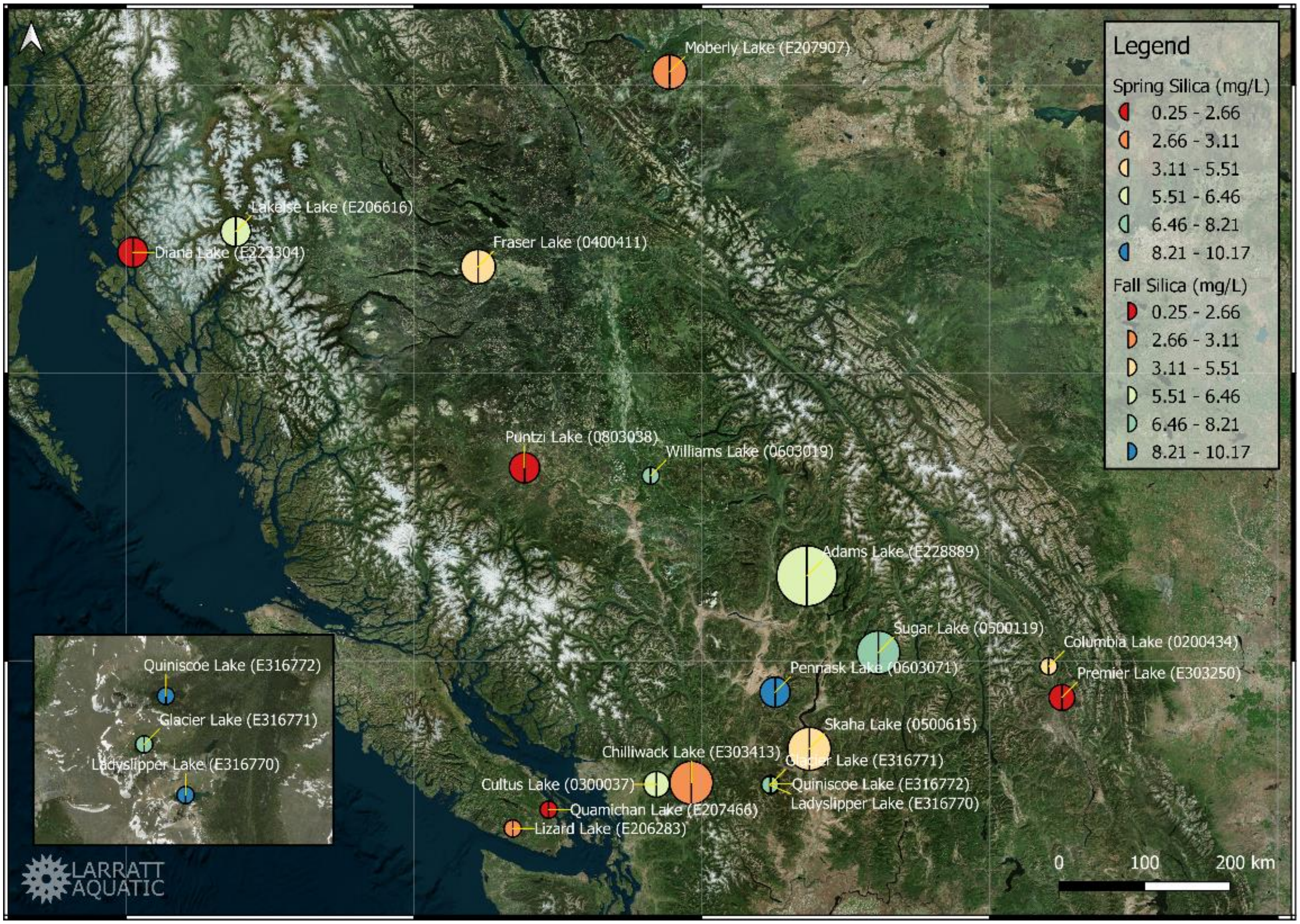

Figure 5: Average silica concentration in lakes across British Columbia, 2015-2020
Note: Size of bubbles relates to size and depth of lake with larger/deeper lakes = larger bubbles
Source: EMS

2.2.3 Nitrogen and Phosphorus

Nitrogen and phosphorus are the most important nutrients in most aquatic environments and are key drivers of plankton dynamics in B.C. lakes. Nutrient limitation occurs when an essential element is in relatively short supply. Consequently, algae production is limited by the availability of that nutrient despite the potential abundance of other nutrients.

Nitrogen

Total nitrogen (TN) concentrations for most lakes averaged <0.5 mg/L during 2015-2020 but three lakes stood out with significantly higher TN. These included two lakes in the Cariboo (Williams Lake [0.904 ± 0.220 mg/L as N], and Puntzi Lake [0.791 ± 0.268 mg/L as N]), and one lake on Vancouver Island (Quamichan Lake [1.70 ± 0.90 mg/L as N])(Figure 6). Also of note were significant increasing trends in TN in the hypolimnion of Skaha Lake (Mann-Kendall, $p=0.01$) and in the epilimnion of Premier Lake (Mann-Kendall, $p=0.02$).

TN includes the organic fraction already incorporated into algae and bacteria, which correlated strongly with chlorophyll-a (Pearson's R = 0.94). Conversely, dissolved inorganic nitrogen (DIN = NH_3 + NO_3 + NO_2) represents the nitrogen that is readily available to algae in the water column. Average DIN ranged from 0.016 ± 0.042 mg/L as N in the epilimnion of Moberly Lake to 0.078 ± 0.038 mg/L as N in the epilimnion of Adams Lake. Note that in Adams Lake, there was relatively high DIN but low algal productivity due to very low phosphorus concentrations and strong phosphorus limitation (Figure 8). TN was particularly high in Quamichan Lake because of the very high cyanobacterial biomass there (TN measures nitrogen in algae cells as well as in the water column). DIN was higher in the hypolimnion in all 19 study lakes where there are fewer growing algae using this available form of nitrogen (Figure 7). There was an apparent increase in hypolimnetic ammonia in Pennask Lake from 2015-2020 but the sample size was too small for statistical significance; this trend may be related to extensive watershed deforestation following the Mountain Pine Beetle infestation. There were no obvious geographic patterns in TN or DIN distribution across the study lakes.

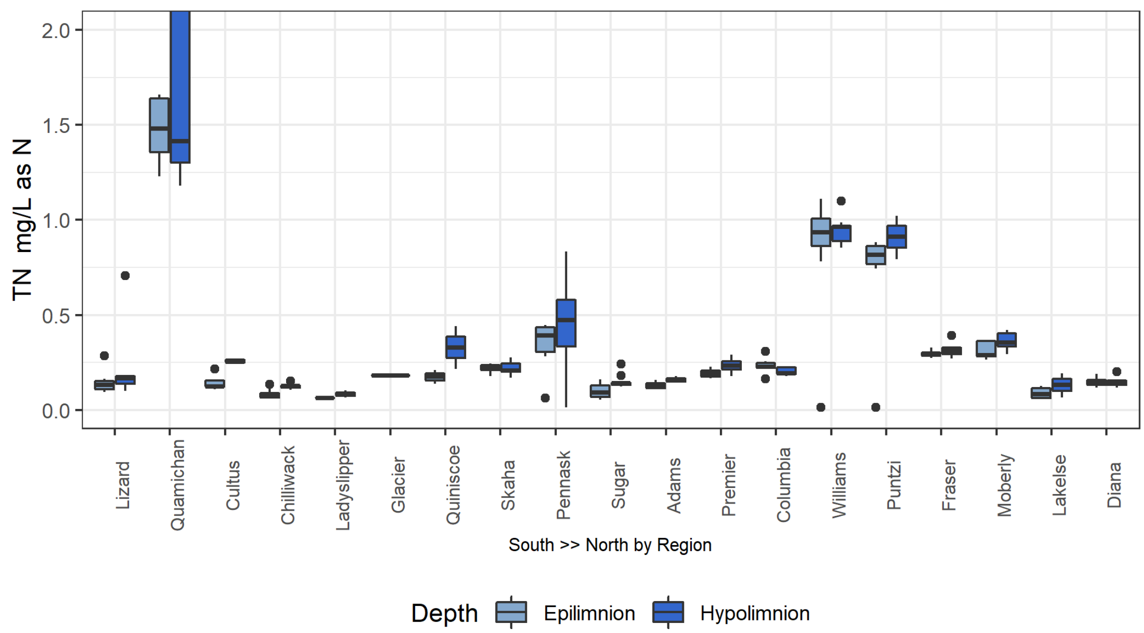

Figure 6: Average total nitrogen in select British Columbia lakes during 2015-2020

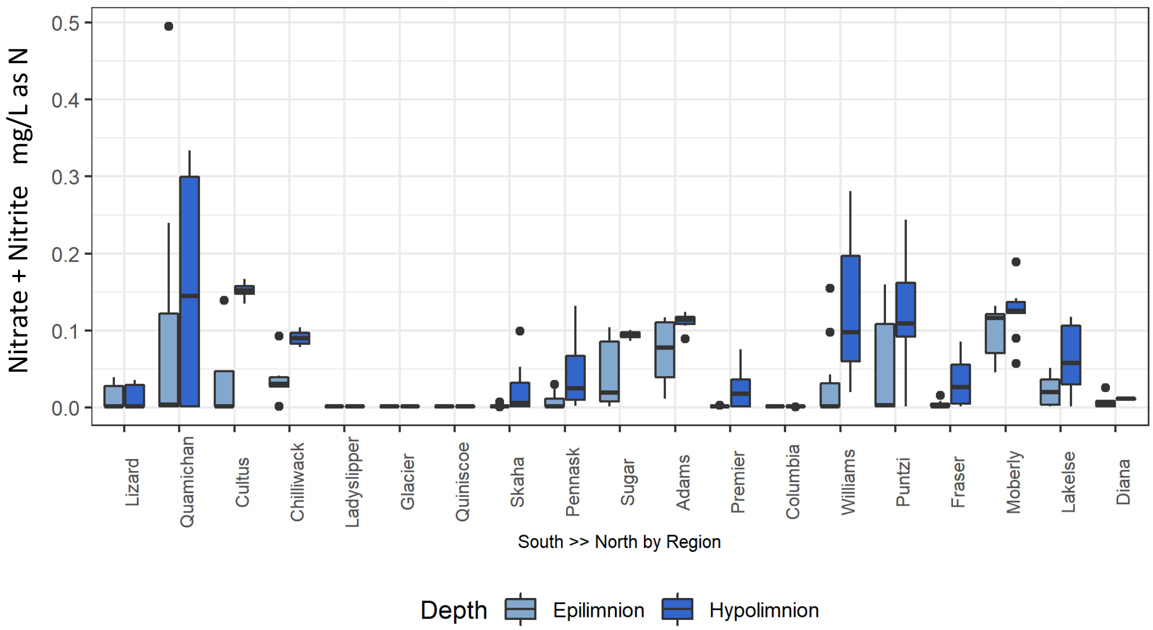

Figure 7: Nitrate + nitrite concentration in select lakes across British Columbia, 2015-2020.
Note: that nitrate + nitrite was higher in the hypolimnion of all 19 study lakes.

Phosphorus

Total phosphorus (TP) is a key nutrient for most freshwater systems and is often the limiting nutrient for algal growth in many B.C. lakes. It is a measure of all forms of phosphorus, including those that may not be bioavailable. Total phosphorus ranged from very low in large deep lakes such as Sugar Lake (0.0016 ± 0.009 mg/L as P from 2015-2020) and Adams Lake (0.0024 ± 0.0015 mg/L as P from 2015-2020), to very high in the shallow hypereutrophic Quamichan Lake (0.317 ± 0.145 mg/L as P from 2015-2020). In fact, TP concentrations in Quamichan Lake were the highest of all study lakes and averaged 200 times more TP than Sugar Lake (Figure 8). Quamichan Lake is broad and shallow with a watershed heavily impacted by urban development and agriculture that have caused a long history of nutrient enrichment (Preikshot, 2019). For example, TP averaged 0.556 ± 0.630 mg/L as P during 1988, the earliest Quamichan data in EMS. Average TP correlated strongly with chlorophyll-a at each site (Pearson's R = 0.96). There were also increasing TP trends observed for Moberly and Puntzi lakes during 2015-2020, but when the time span was expanded to include data from all available years in the EMS database, the trends were revealed as short-term, and likely a result of climatic variation and large recent forest fires.

Dissolved phosphorus (TDP) measures the more bioavailable forms of phosphorus and is a good indicator of potential impacts to aquatic food chains. TDP was stable across all sites[2] from 2015-2020 and was lowest in the large deep lakes such as Sugar Lake (<0.002 mg/L as P) to the eutrophic Quamichan Lake (0.557 ± 0.838 mg/L as P from 2015-2020). Orthophosphate is a subset of dissolved phosphorus and is associated with anoxic release from sediments and internal nutrient recycling. Lakes with elevated hypolimnetic orthophosphate included Quamichan Lake, Williams Lake, Puntzi Lake, Pennask Lake, Fraser Lake, and Quiniscoe Lake (Figure 9). With the exception

[2] An apparent increase in TP and TDP was noted in the Hypolimnion of Pennask Lake but the sample size was too small to ascribe statistical significance. It is likely that this is related to reduced watershed resilience caused by extensive logging and the 2017-2018 freshets.

of the alpine Quiniscoe Lake, these are all productive lakes prone to nuisance cyanobacteria blooms (Figure 26), likely a consequence of their internal recycling and elevated orthophosphate.

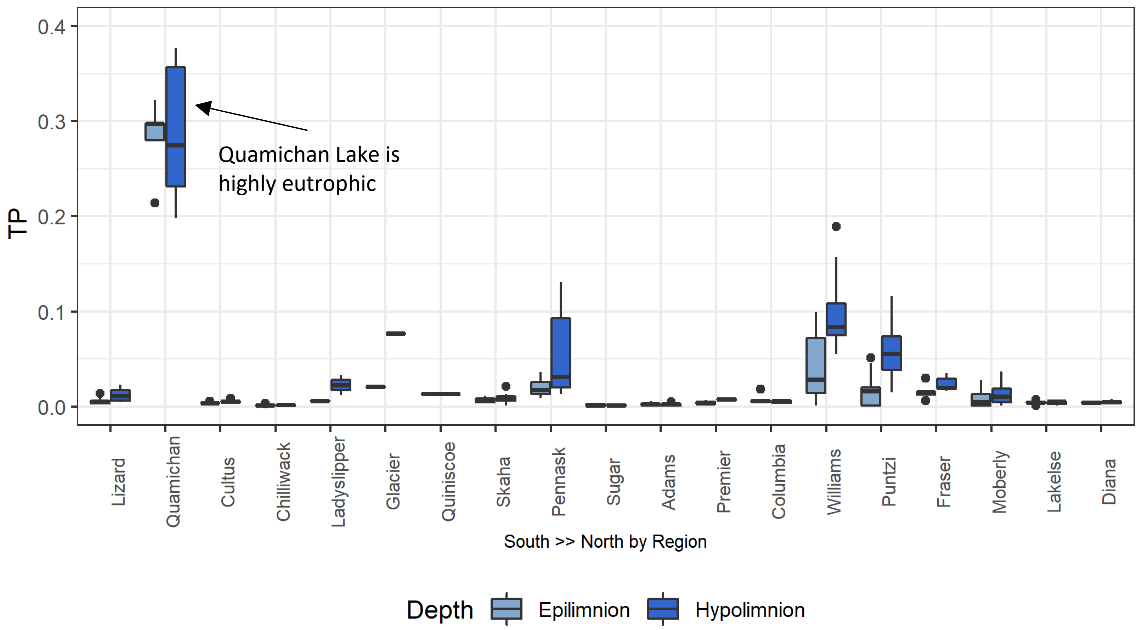

Figure 8: Total phosphorus in select lakes across British Columbia from 2015-2020
Source: EMS

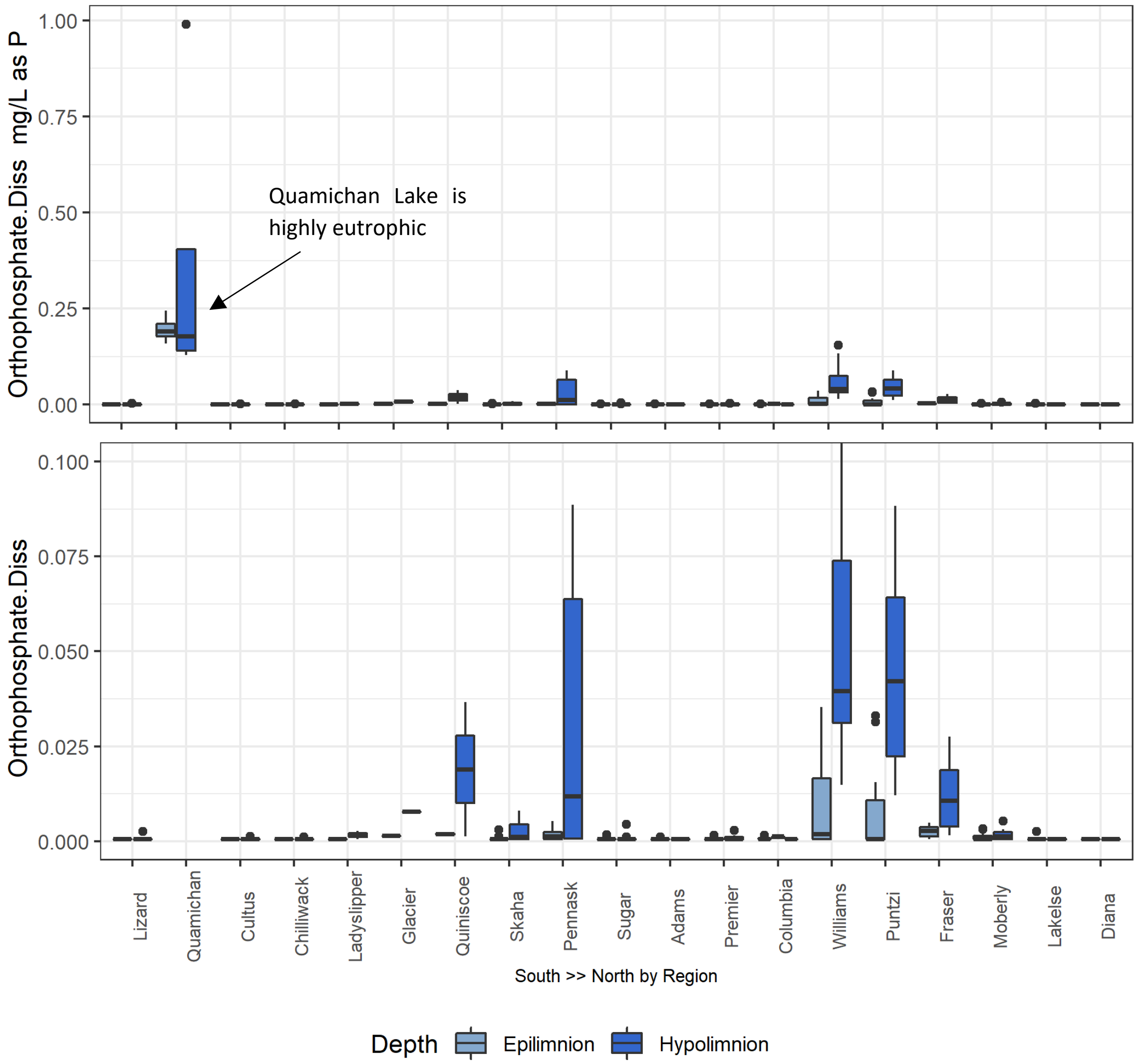

Figure 9: Orthophosphate in select lakes across British Columbia, 2015-2020

Notes: -arrows indicate lakes with suspected internal nutrient recycling
- These two plots contain the same data and are shifted on the y-axis to reveal the range of data (top) and to focus on sites with lower orthophosphate concentrations (bottom)

Source = EMS

N:P Ratio

The ratio of nitrogen to phosphorus is a key factor in determining which types of phytoplankton will proliferate within a lake. Many species of cyanobacteria can fix atmospheric nitrogen and are therefore limited primarily by available phosphorus. These algae are more likely to bloom when phosphorus is abundant relative to nitrogen (Table 2).

Table 2: Nitrogen vs phosphorus limitation ratios and their impacts on phytoplankton community composition

Ratio (N:P)	Limitation Status	Effect on Phytoplankton
>15 : 1	Phosphorus Limitation	Favours green algae and diatoms. Lower risk of cyanobacteria blooms.
<15 : 1 – 5 : 1	Co-Limitation of N and P	Favours mixed community with increased risk of cyanobacteria blooms
<5 : 1	Nitrogen Limitation	Favours cyanobacteria with higher risk of nuisance blooms.

The deepest lakes in this study had very high DIN:TDP ratios because of their low phosphorus concentrations (Figure 10). In general, these lakes should have relatively low densities of cyanobacteria. Of the 19 lakes analyzed in this report, 13 had DIN:TDP ratios of <5:1 indicating strong nitrogen limitation; these lakes were therefore frequently dominated by cyanobacteria and may experience nuisance blooms (Figure 22, Figure 16). From 2015-2020, Sugar Lake had a DIN:TDP ratio of 65:1 and had very low cyanobacteria populations (0.3% of total abundance, Figure 22) while at the other end of the spectrum, Quamichan Lake had a ratio of only 1.3:1 and has frequent and intense cyanobacteria blooms (87% of total abundance, Figure 22).

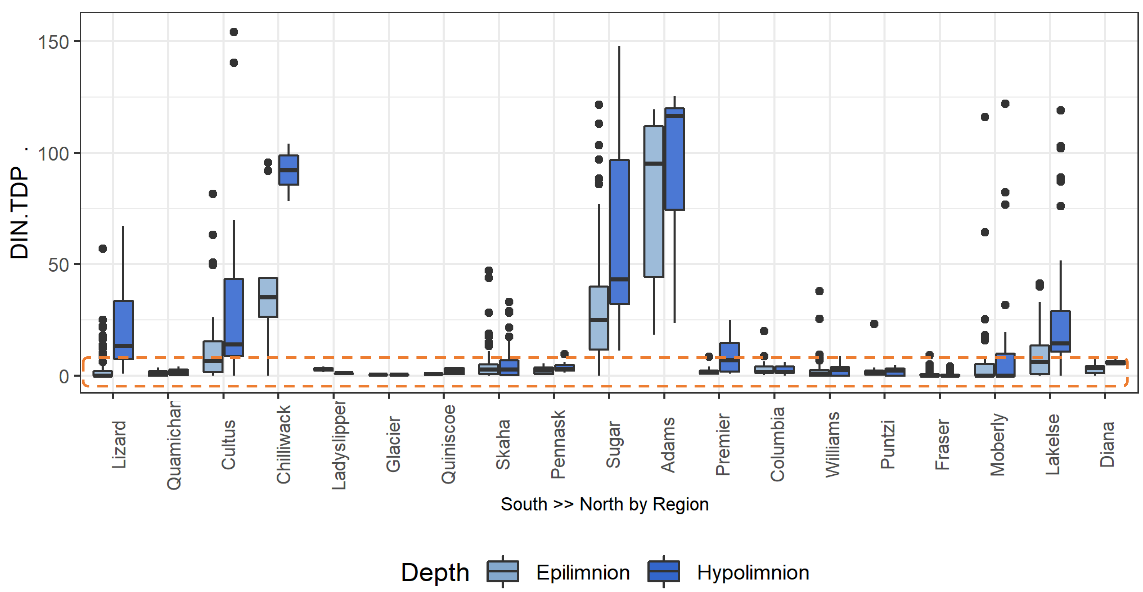

Figure 10: Dissolved inorganic nitrogen to total dissolved phosphorus ratio at select sites across British Columbia, 2015-2020

Note: Dashed orange box = phosphorus limitation and predisposition towards cyanobacteria dominance of phytoplankton

Source: EMS

2.2.4 Statistical Comparison of Water Chemistry Variability

Non-metric multidimensional scaling (NMDS) analysis is a statistical method used to collapse variation in many dimensions (e.g. sample parameters) into 2-dimensions for plotting. This is valuable for interpretating the variation between sites across many variables. NMDS uses rank ordering and is therefore versatile when analyzing data that vary over orders of magnitude and different units such as orthophosphate and conductivity. Figure 11 displays the results of the NDMS analysis on the 19 lakes included in this study. The coloured points represent the scaled values for each parameter in each sample and tend to cluster because of their inherent similarity. The lake sites are plotted as black diamonds and are placed on the graph in proximity to the parameters that best differentiate each lake; they were grouped using dashed grey lines for ease of readability. The plot tells us that:

- Premier Lake, Columbia Lake, and Skaha Lake have relatively high water-hardness and therefore cluster around the sulphate and hardness data points.
- Diana Lake and Lizard Lake are very close to the ocean and have a greater chloride influence and low water hardness and therefore plot separate from the hardness group and near chloride.
- Quamichan Lake is eutrophic and is plotted next to orthophosphate and ammonia, both of which are abundant and fuel its intense algae blooms
- The deepest lakes form a cluster around nitrate because it accumulates in their hypolimnions where it cannot be used by algae, thus lowering their overall productivity
- The central area of the plot shows the lakes with high phytoplankton productivity where chlorophyll-a and organic nitrogen (a proxy measure for biological material in the water column) dominate the analyses.
- Quamichan Lake, Pennask Lake, Williams Lake, Puntzi Lake, Fraser Lake, and Quiniscoe Lake exhibit internal nutrient loading and group together.
- The sub-alpine Glacier and Ladyslipper lakes had distinct water chemistry profiles and stood alone compared to the other lakes.

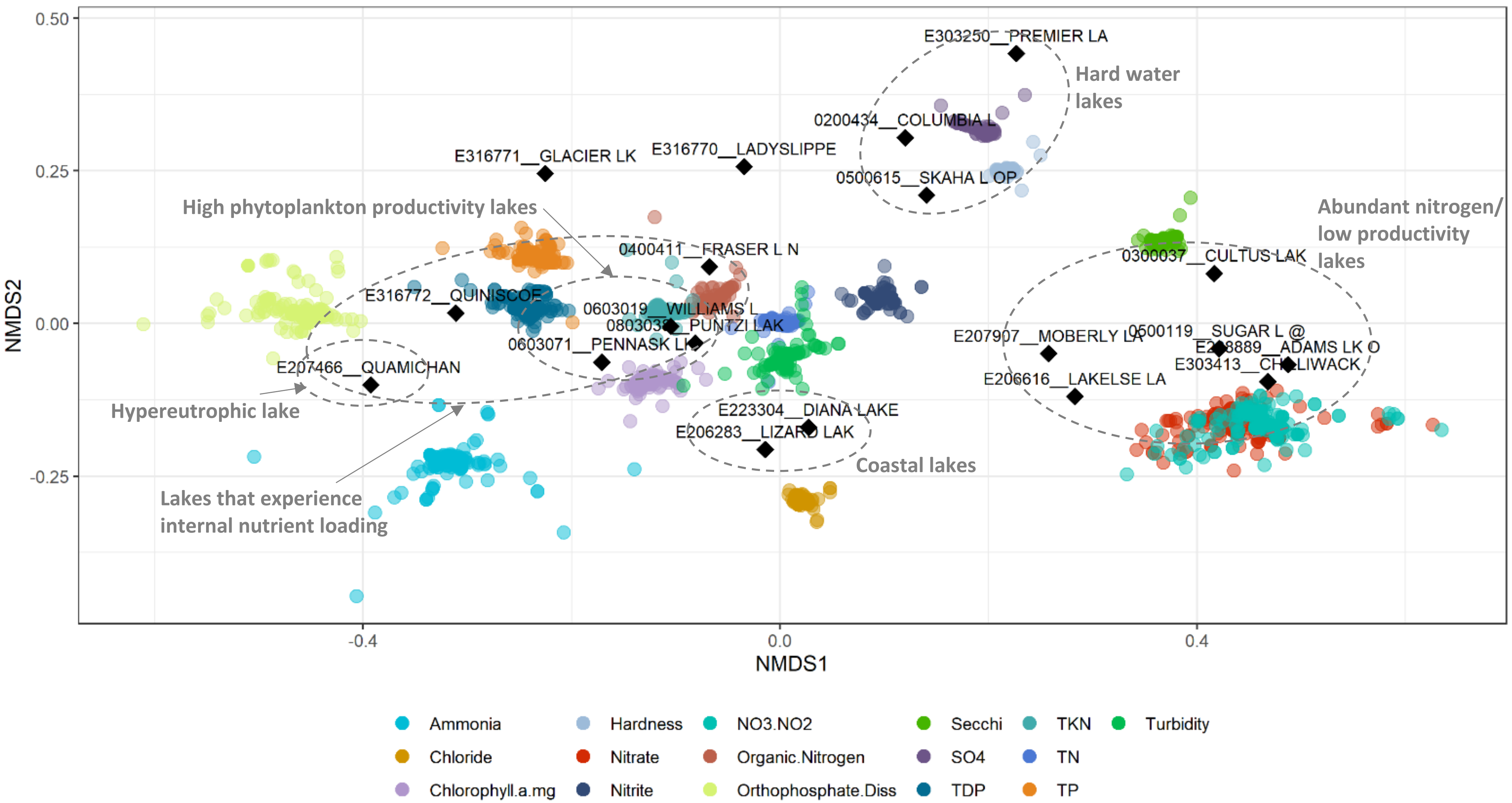

Figure 11: NMDS results for select water chemistry parameters at 19 study sites across British Columbia, 2015-2020

2.3 Biology

2.3.1 Phytoplankton

Phytoplankton (algae) represents the combination of freely floating aquatic photosynthetic microorganisms. There are several different taxonomic groups that share little in common beyond photosynthesis. Taxonomic identification of phytoplankton provides valuable data about the health and nature of an aquatic environment and can serve as a tool to detect subtle changes in the lake ecosystems over time.

Chlorophyll-a

Chlorophyll-a is a photosynthetic pigment found in most freshwater algae species and is simple to test for, making it an ideal measurement of algae productivity. Unsurprisingly, given its very high nutrient concentrations, Quamichan Lake had the highest chlorophyll-a concentrations with an average of 42 ± 17 µg/L during 2015-2020 and a maximum of 81.6 µg/L on Feb 26, 2020 (Figure 12). Quamichan Lake has a long history of nuisance algae blooms with a toxic cyanobacteria bloom in 2016 (North Cowichan, 2018; Preikshot, 2019; Figure 23). Other productive lakes included Williams Lake (14 ± 7 µg/L from 2015-2020), Pennask Lake (8 ± 4 µg/L), and Skaha Lake (4 ± 3 µg/L).

Unusually, Quiniscoe Lake, a sub-alpine lake located in Cathedral Provincial Park, also had high chlorophyll-a averaging 5 ± 3 µg/L during 2019-2020 while nearby Ladyslipper and Glacier Lakes were unproductive averaging 0.7 µg/L and 0.8 µg/L respectively during 2019. The cause for this unusually high productivity in a sub-alpine situation is likely related to Quiniscoe's watershed being forested (nearby Glacier and Ladyslipper lakes were above the treeline) and the release of orthophosphate from the sediment by anaerobic bacteria, causing internal nutrient recycling in Quiniscoe Lake (Figure 9). A nearby campground and private lodge may also provide additional nutrients.

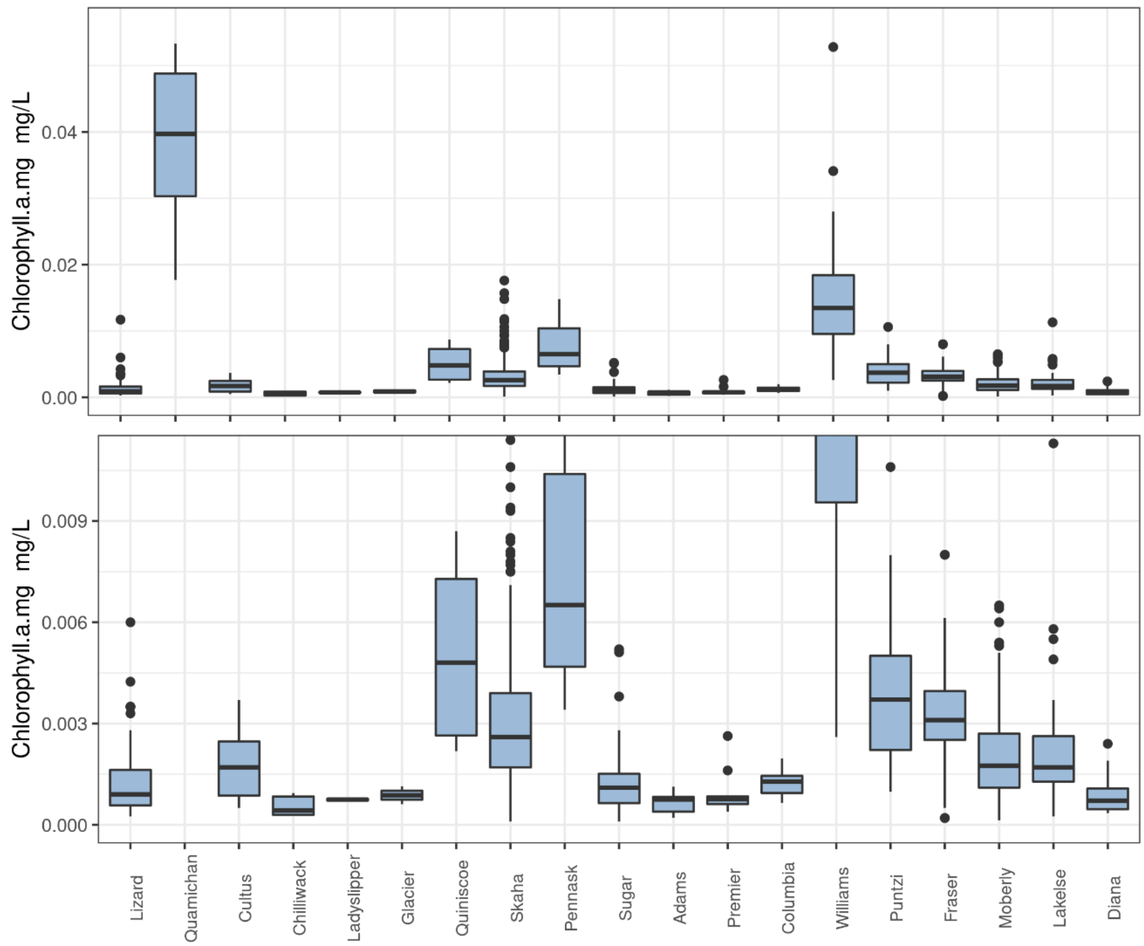

Figure 12: Chlorophyll-a concentrations in select lakes across British Columbia, 2015-2020
Note: These two plots contain the same data and are shifted on the y-axis to reveal the range of data (top) and to focus on sites with lower chlorophyll-a concentrations (bottom)
Source: EMS

A significant increasing trend in chlorophyll-a occurred in Diana Lake (Mann-Kendall, p=0.02) but data exists only for 2016-2020, meaning that the trend could be driven by short-term climate variability. Skaha Lake showed a decreasing trend in chlorophyll-a from 1990-2000 (p=0.01) after nutrient removal was added to Okanagan valley municipal wastewater treatment plants (Figure 13). This was followed by an increasing trend over the past 10 years (p=0.04, 2010-2020), likely related to impacts from population growth, increased urban and agricultural development, and overall watershed degradation throughout the Okanagan.

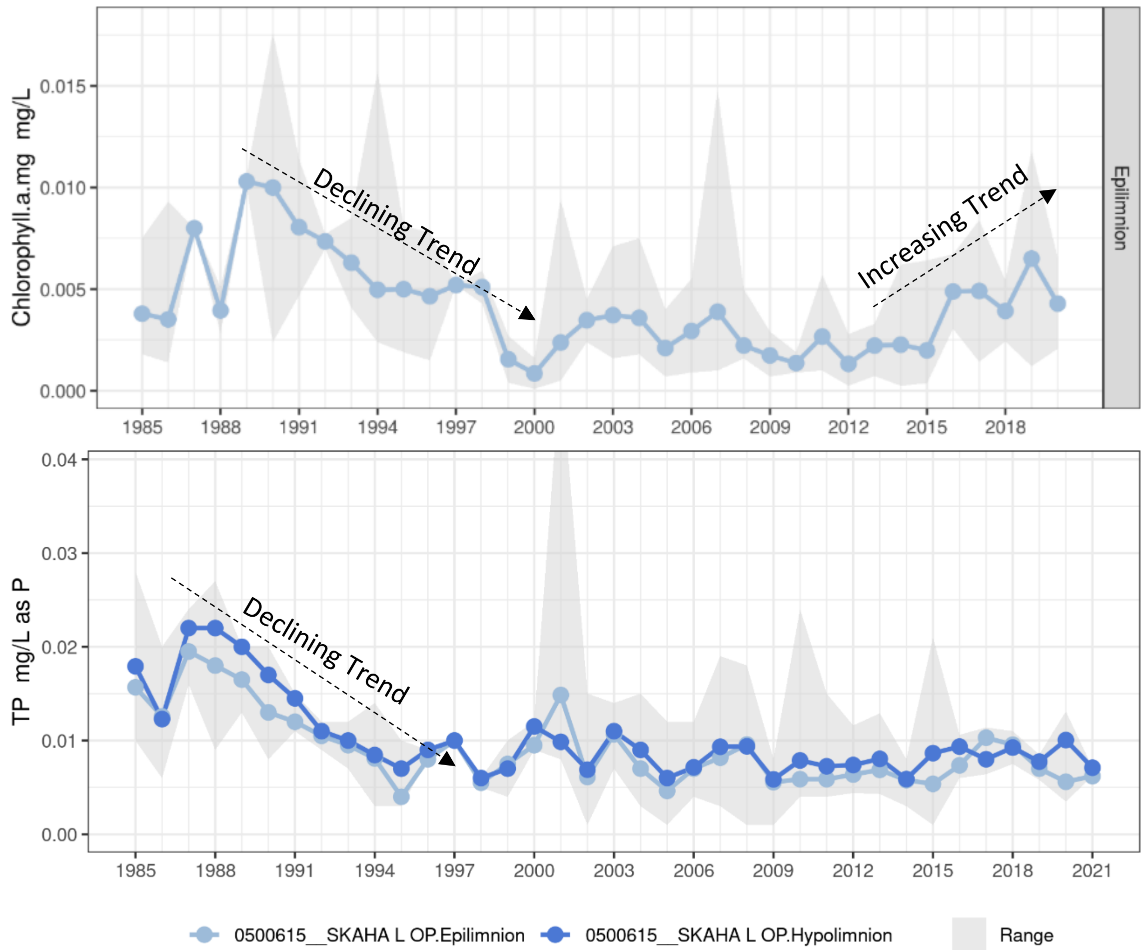

Figure 13: Chlorophyll-a and total phosphorus concentrations in Skaha Lake, 1985 - 2020

Abundance

Phytoplankton taxonomy samples were collected at each site on the spring and late-summer sample trips from 2015-2019 and analyzed by Fraser Environmental Services in Burnaby. The sample data was cleaned using the Taxonomic Reconciliation Table produced for this project such that taxa identified were aligned with latest ITIS (Interagency Taxonomic Identification System) taxonomy information.

Total abundance was calculated for each sample and plotted in Figure 14 (also see

Appendix 3: Phytoplankton and Zooplankton Abundance Graphs). Williams Lake and Quamichan Lake had far higher densities than the rest of the lakes averaging 42,457 ± 20,022 cells/mL and 18,744± 17,528 cells/mL respectively from 2015-2019 (Figure 14, Figure 23). Both lakes had high chlorophyll-a (Figure 12) and high nutrient concentrations (Figure 8). Other lakes with high phytoplankton densities included the sub-alpine Quiniscoe Lake (2657 ± 2800 cells/mL), and Pennask Lake in the Thompson region (2138 ± 586 cells/mL) (Figure 15). Both lakes also experience internal nutrient loading (Figure 9).

Total abundance correlated moderately to chlorophyll-a (Pearson's R=0.61 across all sites). Chlorophyll-a is not the primary photosynthetic pigment in cyanobacteria and this can reduce the strength of the correlation.

The most productive lakes experienced internal nutrient loading during most years, both a trigger for and consequence of their high productivity. Some of these lakes were also impacted by human activities with Quamichan, Williams, and Skaha lakes affected by urbanization and agriculture while Pennask Lake's watershed has been heavily logged in recent years.

No statistically significant increasing or decreasing trends emerged from the taxonomy data because the sample size was too small with fewer than 7 data points per site per taxonomic group[3].

Similarly, no geographic patterns in total abundance data emerged. Highly productive lakes were found in all regions and at both high and low elevations (Figure 15).

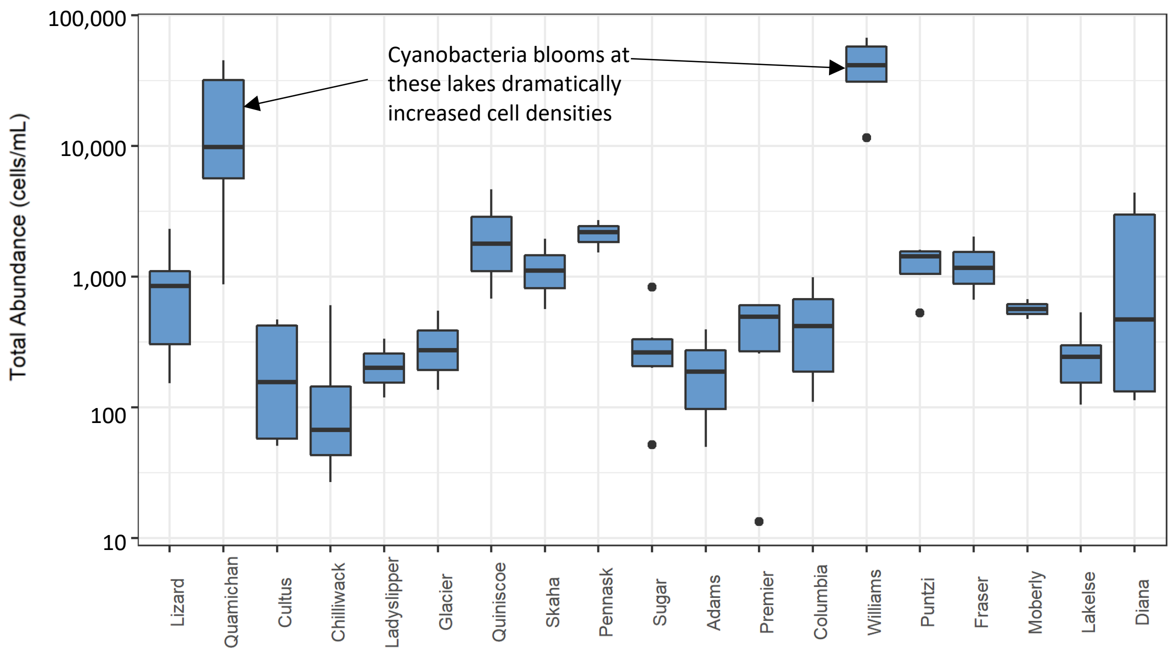

Figure 14: Total abundance of phytoplankton in cells/mL at select site in British Columbia, 2015-2019

Note: y-axis scale is log-based because of large variation between sites

[3] Mann-Kendall non-parametric trend test requires at least 8 data points to calculate statistical significance.

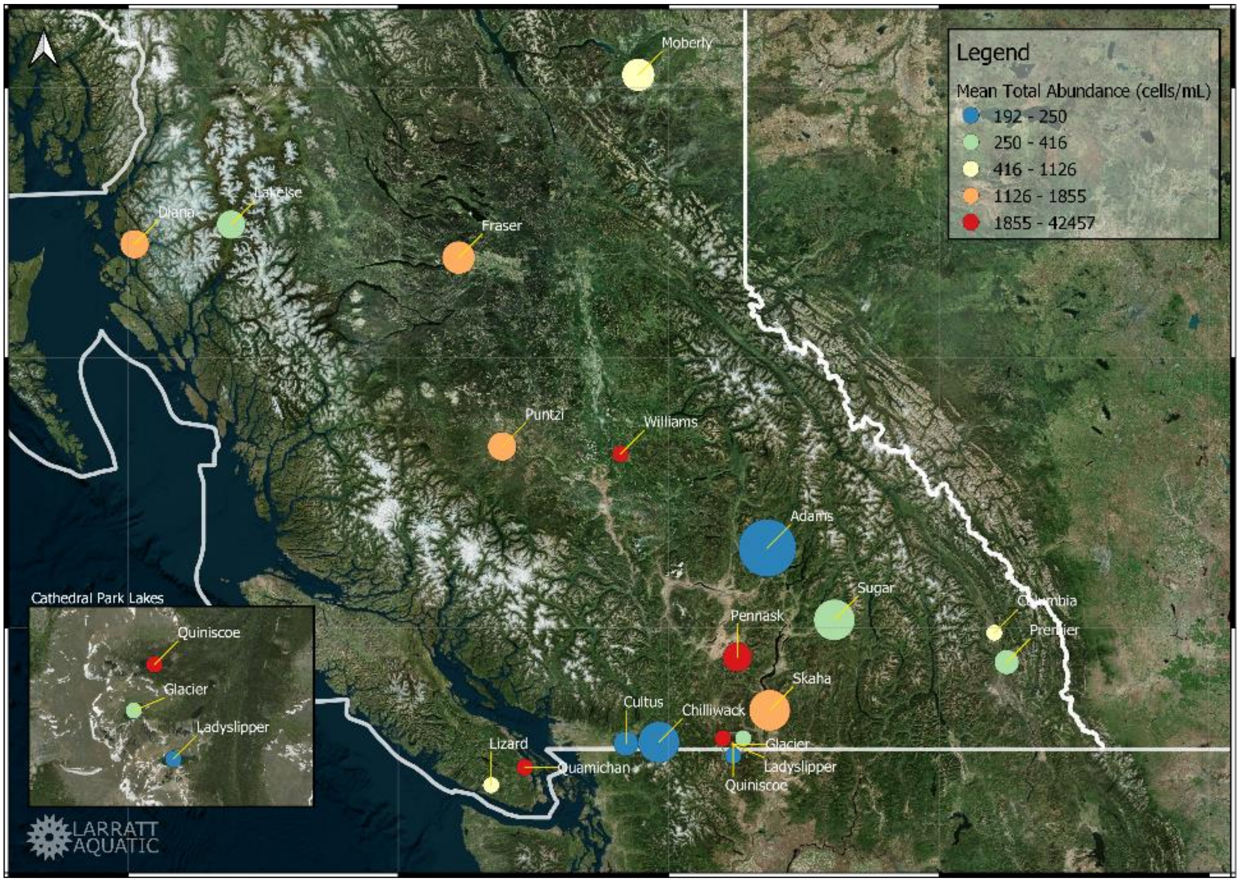

Figure 15: Mean total abundance of phytoplankton in cells/mL at select site in British Columbia, 2015-2019

Note: Size of bubbles relates to size and depth of lake with larger/deeper lakes = larger bubbles

Comparison of High-Level Taxonomic Groups

Taxonomy data can be combined or divided into various taxonomic resolutions. The most common approaches were explored in this report. Using high-level taxonomic groups (Phylum or Division) is the broadest type of analysis. This approach can provide useful information with the fewest number of groups and therefore the largest number of data points within each group. It is possible to break up these high-level groups into class, genus, or species but this significantly increases the number of dimensions of analysis, necessitating more complicated statistical approaches to assess variation in community composition and these analyses were done later in this report (Figure 28).

Most lakes were dominated numerically by cyanobacteria with Williams Lake and Quamichan Lake having both the highest total abundance and experiencing nuisance cyanobacteria blooms in recent years (Preikshot, 2019; Lamb-Yorski, 2020; Figure 16, Figure 22, Figure 23). Williams Lake reached a maximum density of 50,125 cells/mL of the cyanobacteria *Oscillatoria tenuis* in a bloom during April 2017 and up to 46,636 cells/mL during another bloom in September 2019 (Figure 16). Quamichan Lake also had cyanobacteria blooms that reached toxic densities (Preikshot, 2019) with maximum concentrations of over 30,000 cells/mL during 2016[4] and 2017 (Figure 16, Figure 17, Figure 22, Figure 23).

[4] Several cases of pet deaths were reported during the 2016 bloom on Quamichan Lake (Preikshot, 2016).

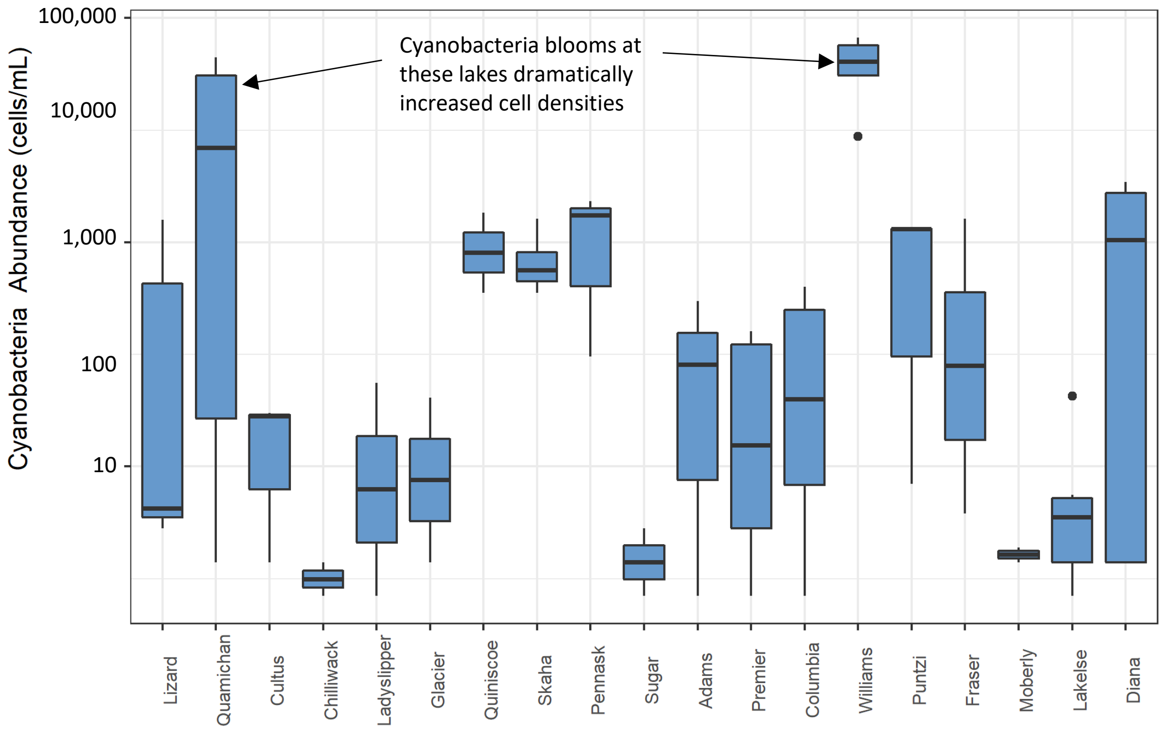

Figure 16: Cyanobacteria abundance of phytoplankton in cells/mL at study lakes in British Columbia, 2015-2019

Note: y-axis scale is log-based because of large variation between sites

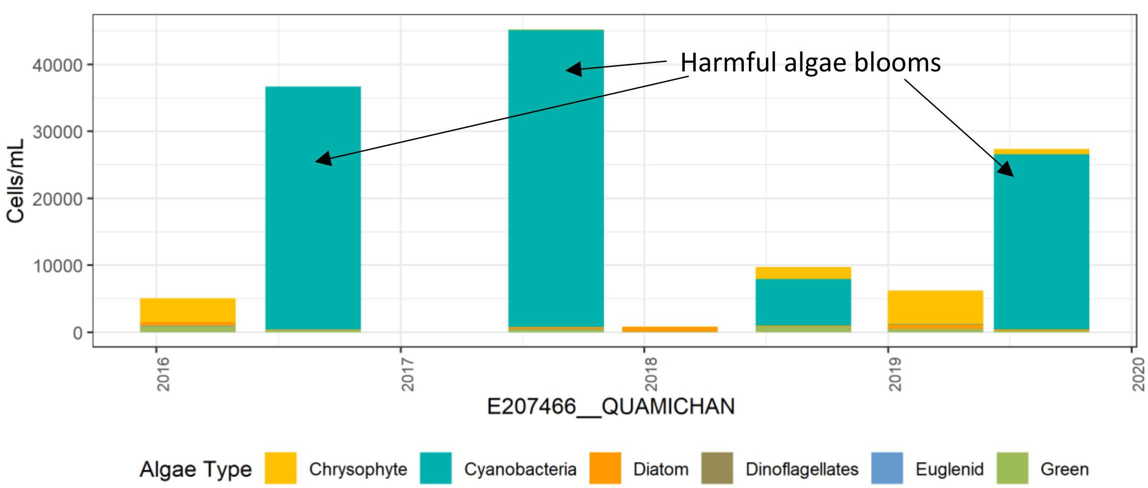

Figure 17: Phytoplankton abundance by high level taxonomic group at Quamichan Lake, 2016-2019

Diatoms are a diverse group of phytoplankton characterized by silica cell walls (frustules) that surround each cell. The size and shape of the frustule is unique to each species, although differences between closely related taxa can be very subtle. Eutrophic Quamichan Lake had the highest diatom density averaging 375 ± 270 cells/mL from 2019. Most planktonic diatom cells are orders of magnitude larger than cyanobacteria cells and despite their lower abundance, they often represent the largest component of the algal biovolume in most lakes[5] (Figure 18). Diatoms rarely composed more than one quarter of phytoplankton abundance with only Lakelse Lake and Moberly having a high proportion of diatoms (Figure 22).

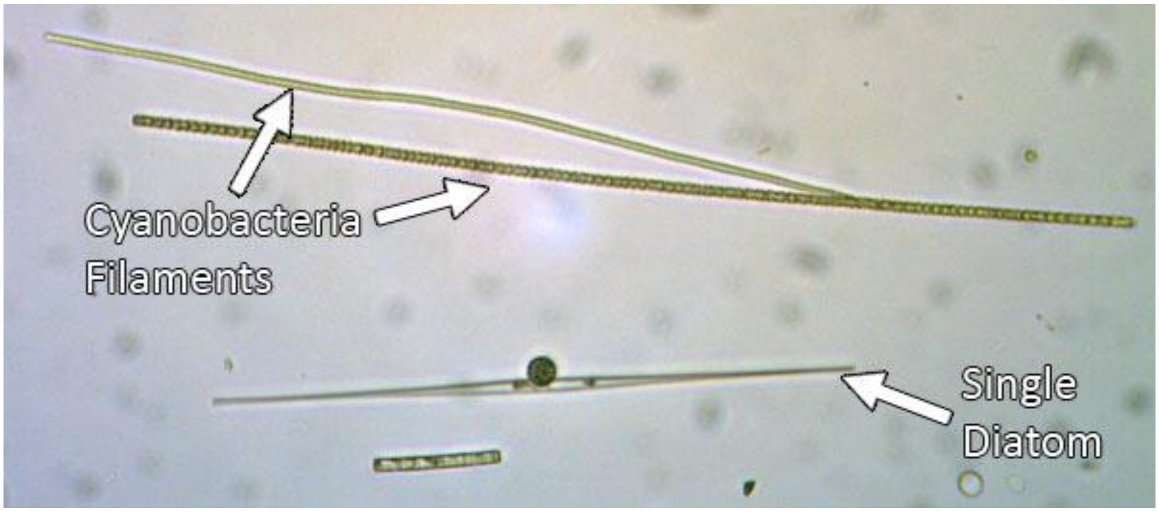

Figure 18: Microscope image of algae at 200x magnification from Okanagan Lake

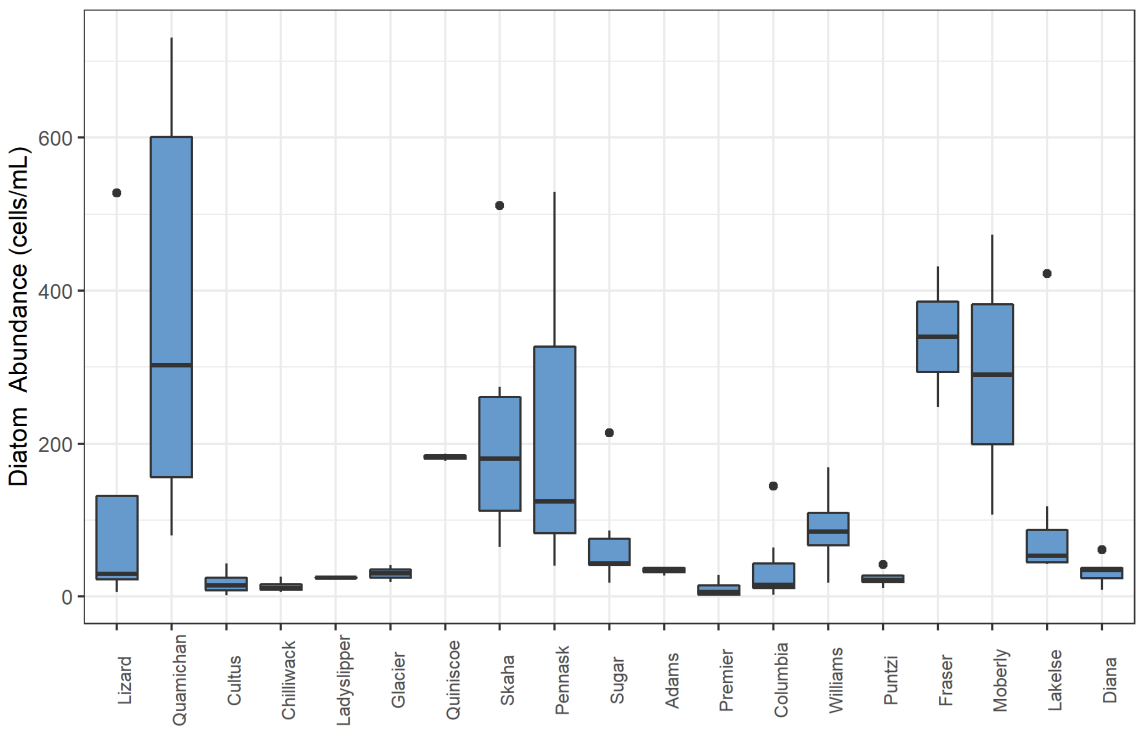

Figure 19: Diatom abundance of phytoplankton in cells/mL at study lakes in British Columbia, 2015-2019

[5] Note that biovolume per taxa was not calculated for any samples in this study, but will be measured from 2020 onwards.

The sub-alpine lakes in Cathedral Provincial Park (Quiniscoe, Glacier, Ladyslipper), Kootenay region lakes (Columbia, Premier), and Chilliwack Lake in the South Coast region were all dominated by green algae (Figure 22). Quiniscoe Lake had the highest abundance of green algae, averaging 1286 ± 1718 cells/mL during 2019[6] (Figure 20). The particular species of green algae that was most numerous in Quiniscoe Lake was *Spondylosium planum* and it is a common desmid in high elevation lakes in the interior of British Columbia.

Lakelse Lake, Moberly Lake, and Sugar Lake had higher proportions of chrysophyte algae but overall abundance was low (Figure 21, Figure 23). Chrysophytes can photosynthesize but are also able to feed upon organic particulates such as bacteria and therefore tend to be most numerous in river dominated lakes and lakes with high bacterial loading. In high densities, chrysophytes can generate a fishy or musty taste and odor in the water. Despite several lakes having higher relative proportions of chrysophytes, the eutrophic Quamichan Lake had the highest total chrysophyte abundance averaging 1624 ± 1982 cells/mL from 2015-2019.

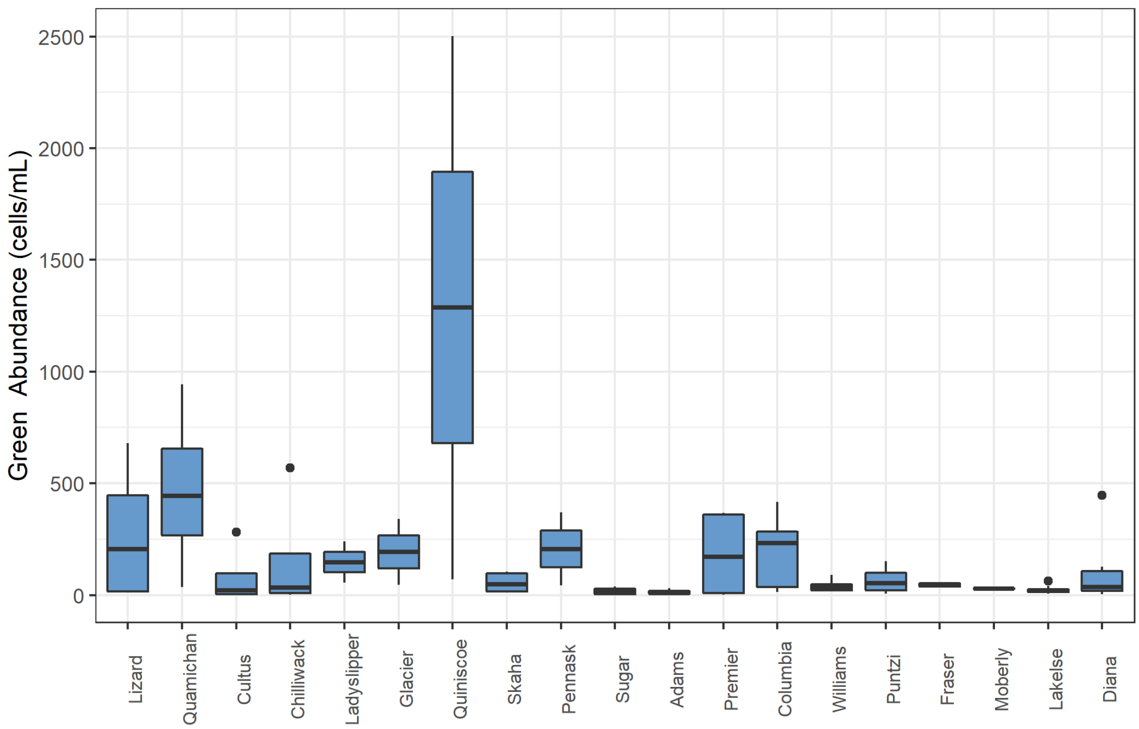

Figure 20: Green algae abundance in study lakes across British Columbia, 2015-2019

[6] Taxonomic data for Quiniscoe Lake was collected only during 2019

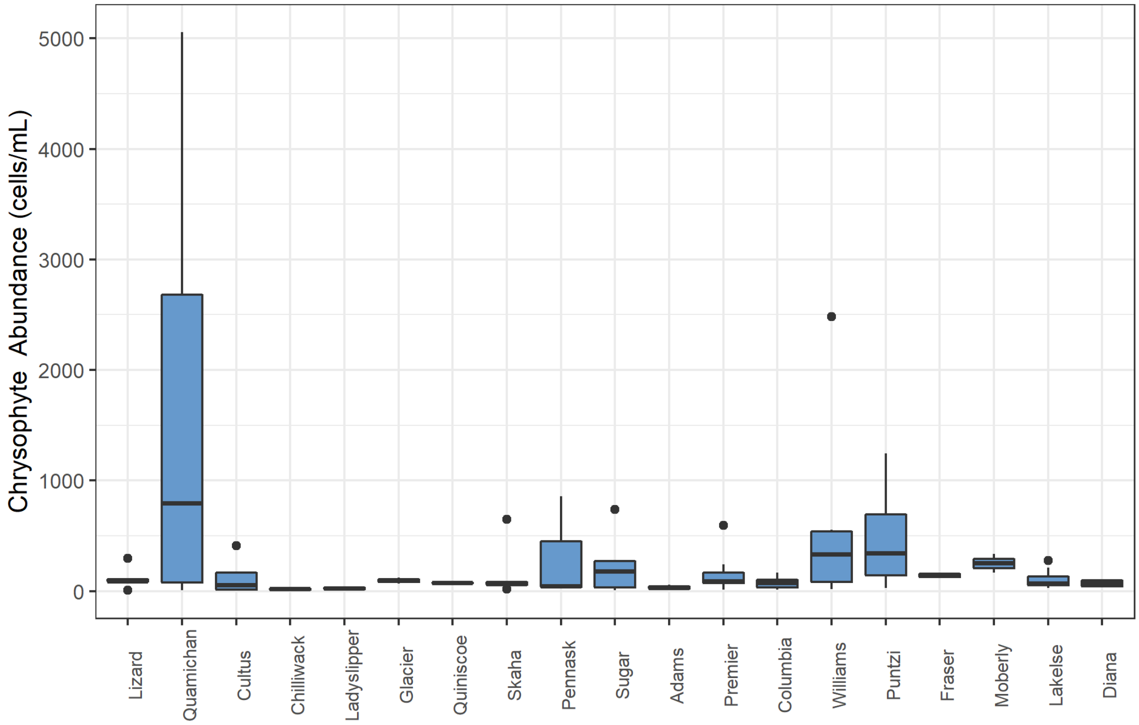

Figure 21: Chrysophyte abundance in study lakes across British Columbia, 2015-2019

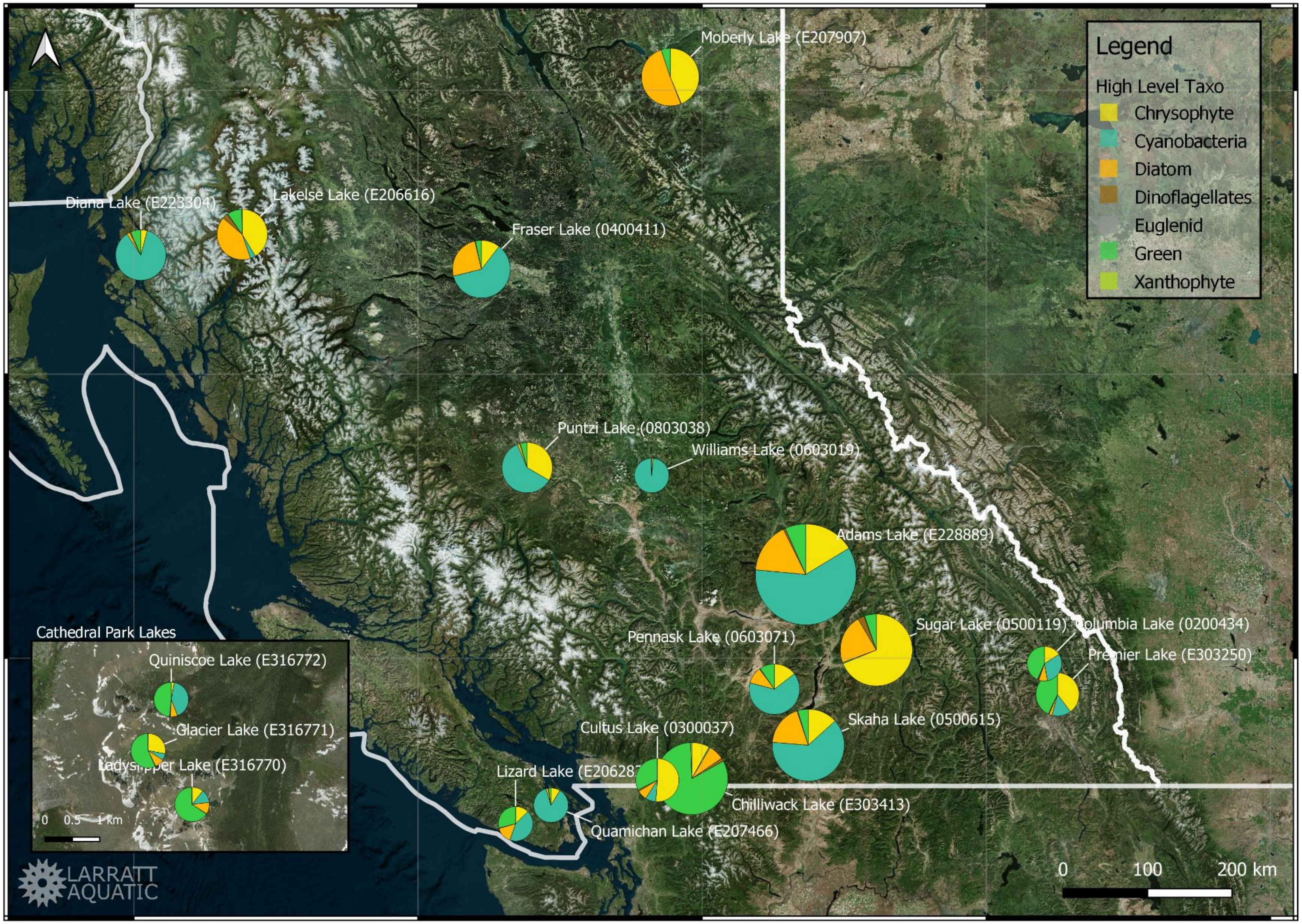

Figure 22: Map of mean high-level taxonomic results for each lake plotted as percent abundance pie-chart scaled by lake size, 2015-2019

Note: Size of bubbles relates to size and depth of lake with larger/deeper lakes = larger bubbles

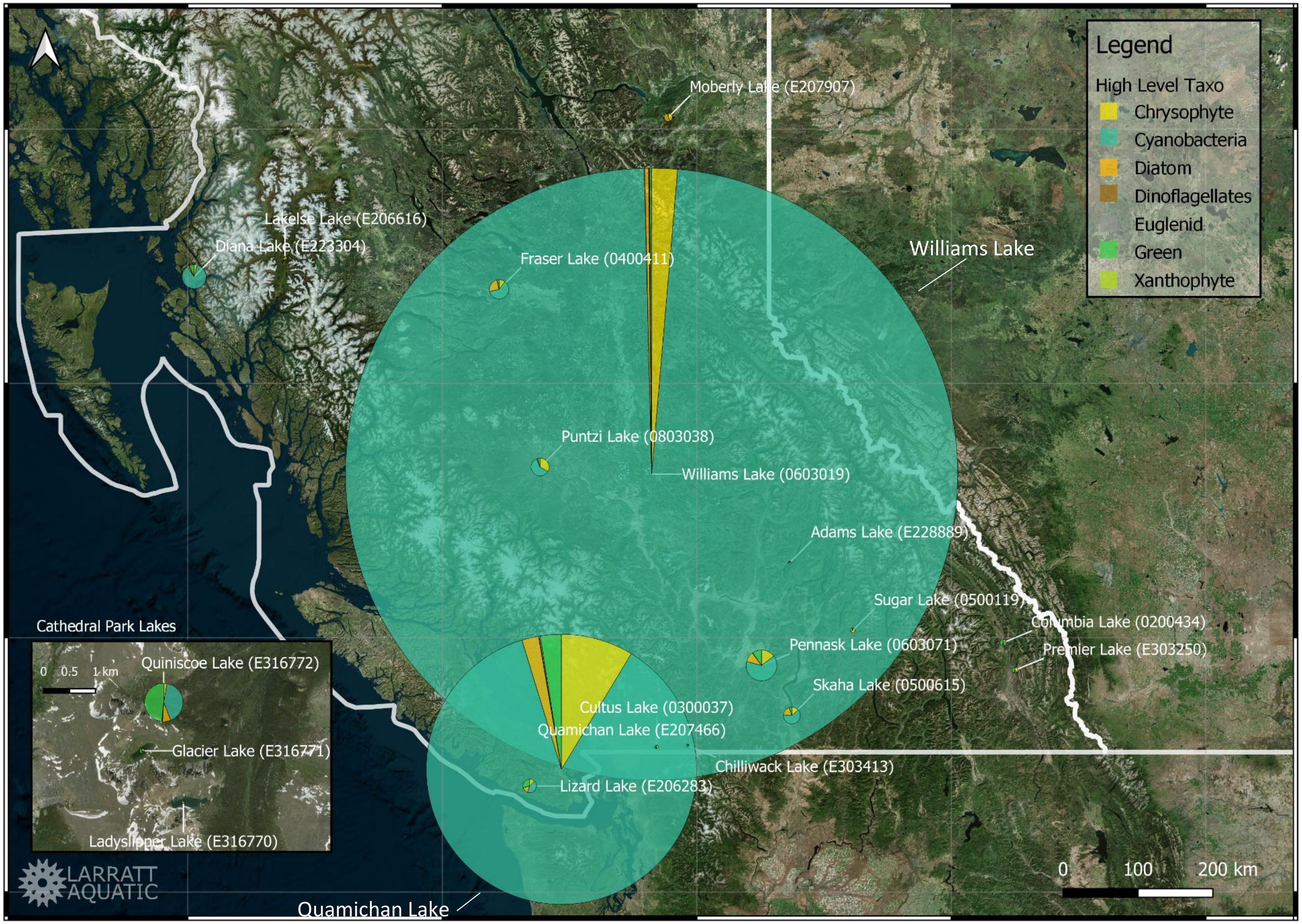

Figure 23: Map of mean high-level taxonomic results for each lake plotted as percent abundance pie-chart scaled by abundance, 2015-2019

Note: Size of bubbles relates to phytoplankton abundance; higher abundance = larger bubbles; production in some lakes was so low that they are barely visible in this plot compared to the cyanobacteria bloom forming Quamichan and Williams lakes. This plot serves to contrast the range of productivity amongst the selected lakes and displays the same data as Figure 22

Seasonal Variation

Phytoplankton abundance and community composition changed seasonally at most of the study lakes. Spring samples had lower overall densities with higher proportions of diatoms and chrysophytes, compared to the late-summer samples which had higher overall densities and higher proportions of green algae and cyanobacteria (Figure 24, Appendix 3). This is a common pattern in British Columbia that occurs because cyanobacteria prefer warmer water and proliferate in the summer, while spring freshet inflows carry high bacterial loads that feed chrysophyte algae.

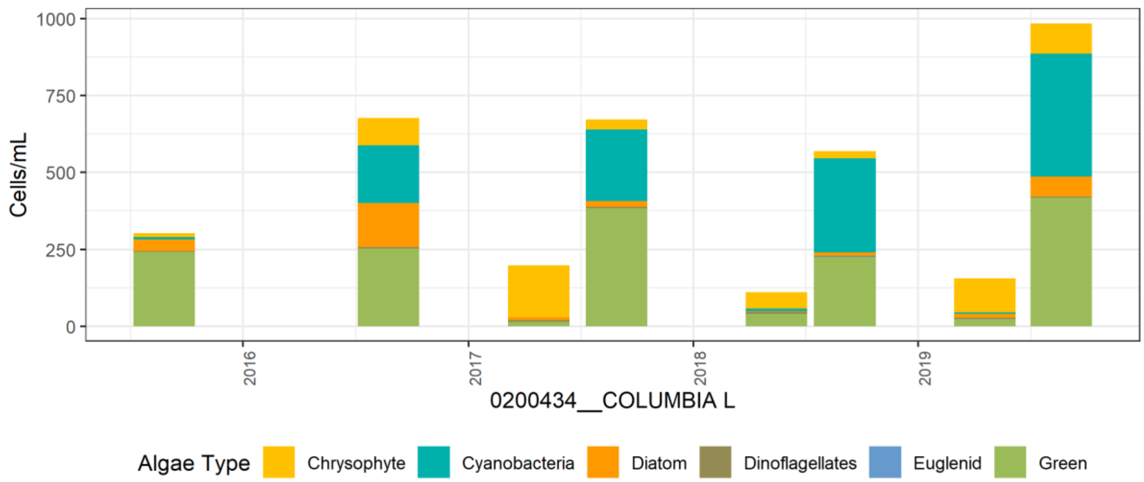

Figure 24: Phytoplankton abundance by high level groups for each sample at Columbia Lake, 2015-2019

Species Diversity

In ecology, species diversity is often used as a measure for ecosystem health with the assumption that a healthier system will have a greater number of taxa present and that abundance will be more evenly distributed between those taxa. Monocultures where one taxon totally dominates are considered signs of an unhealthy ecosystem.

The species richness index, the number of unique taxa per sample, varied between sites but all sites averaged more than 20 taxa identified in each sample with the highest diversity in Pennask Lake (60 ± 6 taxa/sample) and Columbia Lake (58 ± 20 taxa/sample) (Figure 25). Despite the relatively high species richness, most sites scored moderate or poor on the Shannon-Weaver Diversity Index because at each site, a small number of taxa dominated the total abundance (Figure 25, Table 3). For example, Williams Lake had the lowest Shannon-Weaver score at only 0.57 because 79% of total abundance was from a single species (*Oscillatoria tenuis*). Columbia Lake had the lowest percent of total abundance from the dominant five taxa (52%) and the second highest mean Shannon-Weaver index of 2.4.

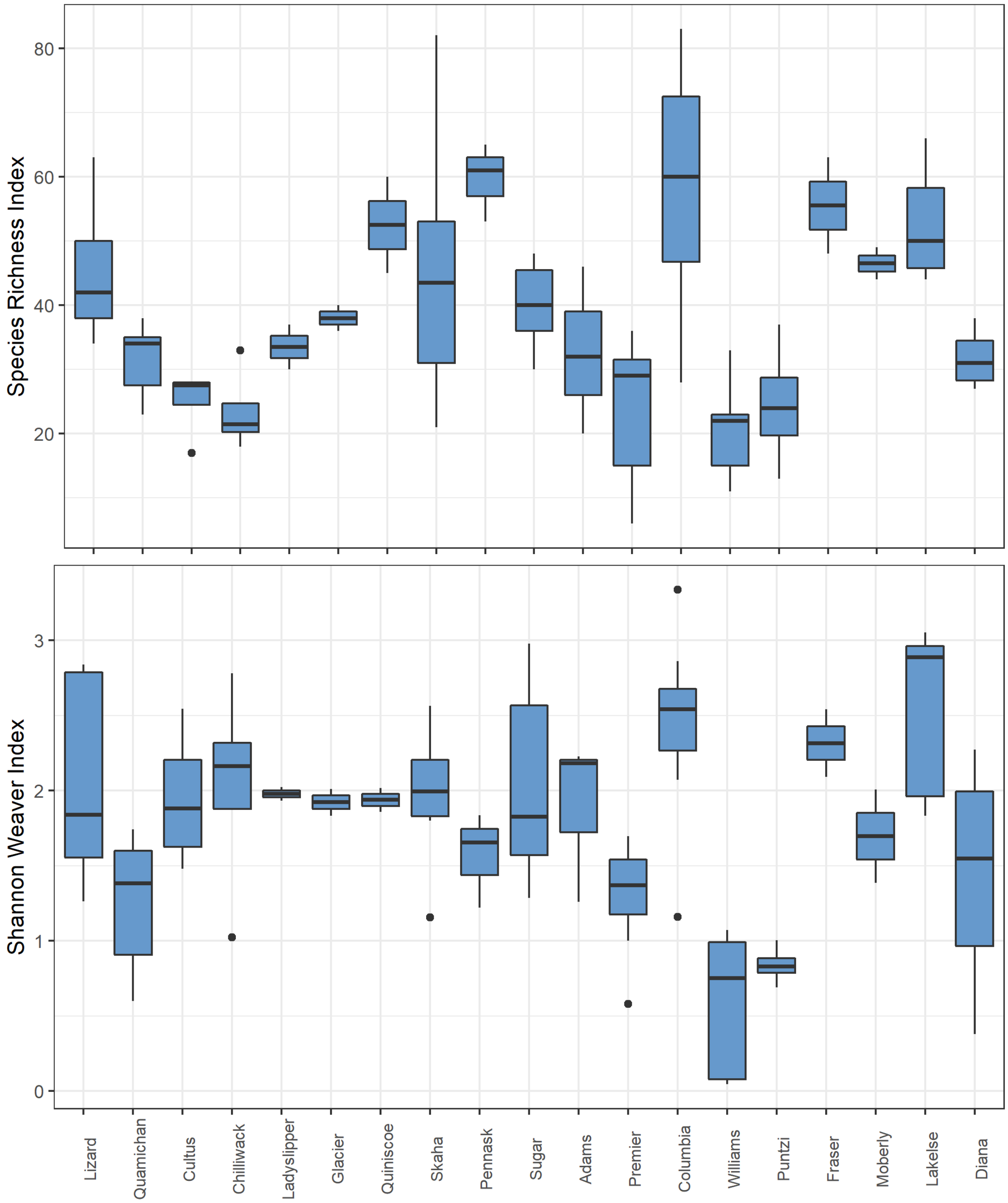

Figure 25: Species Richness Index (top) and Shannon Weaver Diversity Index (bottom) from samples collected at study lakes across British Columbia during 2015-2019

Table 3: Percent of phytoplankton total abundance that was from the five most abundant taxa at each lake

Site	Percent of total abundance that was dominant 5 taxa
0200434__COLUMBIA L	51.7%
0300037__CULTUS LAK	68.6%
0400411__FRASER L N	64.9%
0500119__SUGAR L @	77.9%
0500615__SKAHA L OP	63.7%
0603019__WILLIAMS L	97.6%
0603071__PENNASK LK	78.0%
0803038__PUNTZI LAK	87.9%
E206283__LIZARD LAK	61.1%
E206616__LAKELSE LA	62.9%
E207466__QUAMICHAN	89.1%
E207907__MOBERLY LA	84.7%
E223304__DIANA LAKE	93.6%
E228889__ADAMS LK O	73.9%
E303250__PREMIER LA	82.9%
E303413__CHILLIWACK	84.6%
E316770__LADYSLIPPE	73.4%
E316771__GLACIER LK	86.9%
E316772__QUINISCOE	85.2%
Mean	**77%**
SD	**12%**
Max	**98%**
Min	**52%**

Note: Colour scale is relative with green being most diverse and red being least diverse based on abundance of top 5 taxa

Community Composition

While higher diversity is considered preferable as a general rule, the individual taxa within each lake phytoplankton community can lead to very different ecological outcomes. For example, a lake that had only 20 diatom taxa (healthier, good base of food web) would be very different from one that was populated with only 20 cyanobacteria taxa (nutrient-enriched, poor base of food web) or one with only 20 flagellated chrysophyte algae (bacterially enriched, moderate base of food web).

The ten dominant (most abundant) cyanobacteria taxa represented 87% of the total abundance observed across all lakes, led by the very high densities of *Oscillatoria tenuis* at Williams Lake and *Anacystis aeruginosa* at Quamichan Lake (Table 4). The most abundant species at each site averaged 41.2 ± 16.0% of the total abundance at that lake and ranged from a low of 22% at Fraser Lake (*Aphanizomenon spp.*) to 79% at Williams Lake (*Oscillatoria tenuis*).

Table 4: Percent abundance of ten dominant phytoplankton taxa per high level group

	Lowest Taxo Level	Percent of Total Abundance	Percent of High Level Abundance
Chrysophyte	*Chroomonas acuta*	2.2%	41.3%
	Cryptomonas ovata	1.7%	32.2%
	Dinobryon sertularia	0.6%	10.8%
	Dinobryon divergens	0.2%	4.0%
	Ochromonas spp.	0.2%	3.3%
	Chrysophyta spp.	0.1%	2.4%
	Kephyrion spp.	0.1%	2.0%
	Cryptomonas spp.	0.1%	1.5%
	Dinobryon spp.	0.1%	1.3%
	Dinobryon bavaricum	0.0%	0.5%
Cyanobacteria	*Oscillatoria tenuis*	48.8%	54.7%
	Anacystis aeruginosa	15.6%	17.5%
	Aphanizomenon spp.	6.6%	7.4%
	Aphanizomenon flosaquae	4.0%	4.5%
	Coelosphaerium naegelianum	3.7%	4.1%
	Lyngbya limnetica	3.5%	4.0%
	Merismopedia tenuissima	1.9%	2.1%
	Limnothrix redekei	1.1%	1.2%
	Anabaena affinis	0.9%	1.0%
	Anabaena circinalis	0.7%	0.8%
Diatom	*Aulacoseira italica*	0.5%	22.4%
	Asterionella formosa	0.3%	15.6%
	Stephanodiscus niagarae	0.3%	15.3%
	Fragilaria crotonensis	0.1%	5.2%
	Cyclotella glomerata	0.1%	4.4%
	Tabellaria fenestrata	0.1%	3.6%
	Melosira sp.	0.1%	3.3%
	Achnanthidium microcephalum	0.1%	2.5%
	Tabellaria flocculosa	0.0%	1.9%
	Navicula spp.	0.0%	1.7%
Green	*Gloeocystis ampla*	0.3%	11.7%
	Spondylosium planum	0.3%	11.0%
	Sphaerocystis schroeteri	0.3%	10.1%
	Pediastrum boryanum	0.3%	8.8%
	Schroederia setigera	0.2%	7.0%
	Botryococcus braunii	0.2%	6.9%
	Crucigenia retangularis	0.2%	5.8%
	Elakatothrix gelatinosa	0.1%	4.5%
	Oocystis lacustris	0.1%	4.1%
	Oocystis borgei	0.1%	2.4%

Notes: Orange shading indicates taxa typically associated with toxic blooms | These data represent the combined values across all lakes

Table 5: Percent abundance of the most common species in each lake

Lake Site	Taxonomic Name	% abundance	Taste & Odor Taxa	Toxin Producing Taxa
0200434__COLUMBIA L	*Aphanocapsa elachista*	23.4%	Y	Y
0300037__CULTUS LAK	*Chroomonas acuta*	35.3%	Y	
0400411__FRASER L N	*Aphanizomenon sp.*	22.2%	Y	Y
0500119__SUGAR L @	*Dinobryon sertularia*	55.8%	Y	
0500615__SKAHA L OP	*Oscillatoria tenuis*	29.5%	Y	Y
0603019__WILLIAMS L	*Oscillatoria tenuis*	78.8%	Y	Y
0603071__PENNASK LK	*Aphanizomenon flosaquae*	34.1%	Y	Y
0803038__PUNTZI LAK	*Dinobryon sertularia*	28.7%	Y	
E206283__LIZARD LAK	*Merismopedia tenuissima*	34.6%	Y	Y
E206616__LAKELSE LA	*Chroomonas acuta*	27.2%	Y	
E207466__QUAMICHAN	*Anacystis aeruginosa*	57.6%	Y	Y
E207907__MOBERLY LA	*Aulacoseira italica*	40.2%		
E223304__DIANA LAKE	*Merismopedia tenuissima*	72.3%	Y	Y
E228889__ADAMS LK O	*Aphanocapsa elachista*	46.9%	Y	Y
E303250__PREMIER LA	*Gloeocystis ampla*	37.3%		
E303413__CHILLIWACK	*Sphaerocystis schroeteri*	54.2%		
E316770__LADYSLIPPE	*Sphaerocystis schroeteri*	36.2%		
E316771__GLACIER LK	*Crucigenia retangularis*	27.3%		
E316772__QUINISCOE	*Anabaena affinis*	41.1%	Y	Y

Legend:

Diatom	Chrysophyte	Cyanobacteria	Green

Note: Toxin producing taxa are those that are capable of producing toxins, it is not well understood what specific conditions trigger production and release of toxins into the environment

High phytoplankton densities are often associated with impaired aesthetics such as taste and odor concerns. Taxa that can cause aesthetic concerns were the dominant taxa at most sites but were likely only a potential concern at: Quiniscoe Lake, Pennask Lake, Quamichan Lake, and Williams Lake where abundance of those taxa were also high (Figure 15).

The bloom forming cyanobacteria found in the genera *Anabaena (Dolichospermum)*, *Anacystis*, and *Aphanizomenon* are particularly problematic because they can form toxic harmful algae blooms (HABs). Lakes with high percent abundances of this group of cyanobacteria included: Puntzi Lake (28%), Fraser Lake (32%), Quiniscoe Lake (41%), Pennask Lake (63%) and Quamichan Lake (72%; Figure 26). These are all lakes that experience anoxia-related nutrient release from sediments causing internal nutrient loading (Figure 9).
The broader taxonomic orders Nostocales and Chroococcales contain these and other common cyanobacteria that are known to produce toxins under certain conditions. These orders represented most of the phytoplankton abundance at Skaha Lake (63%), Pennask Lake (65%), Diana Lake (72%), Quamichan Lake (87%), and Williams Lake (97%). Adams Lake and Fraser Lake also had greater than 50% of total abundance represented by these orders but overall abundance was too low to be of concern.

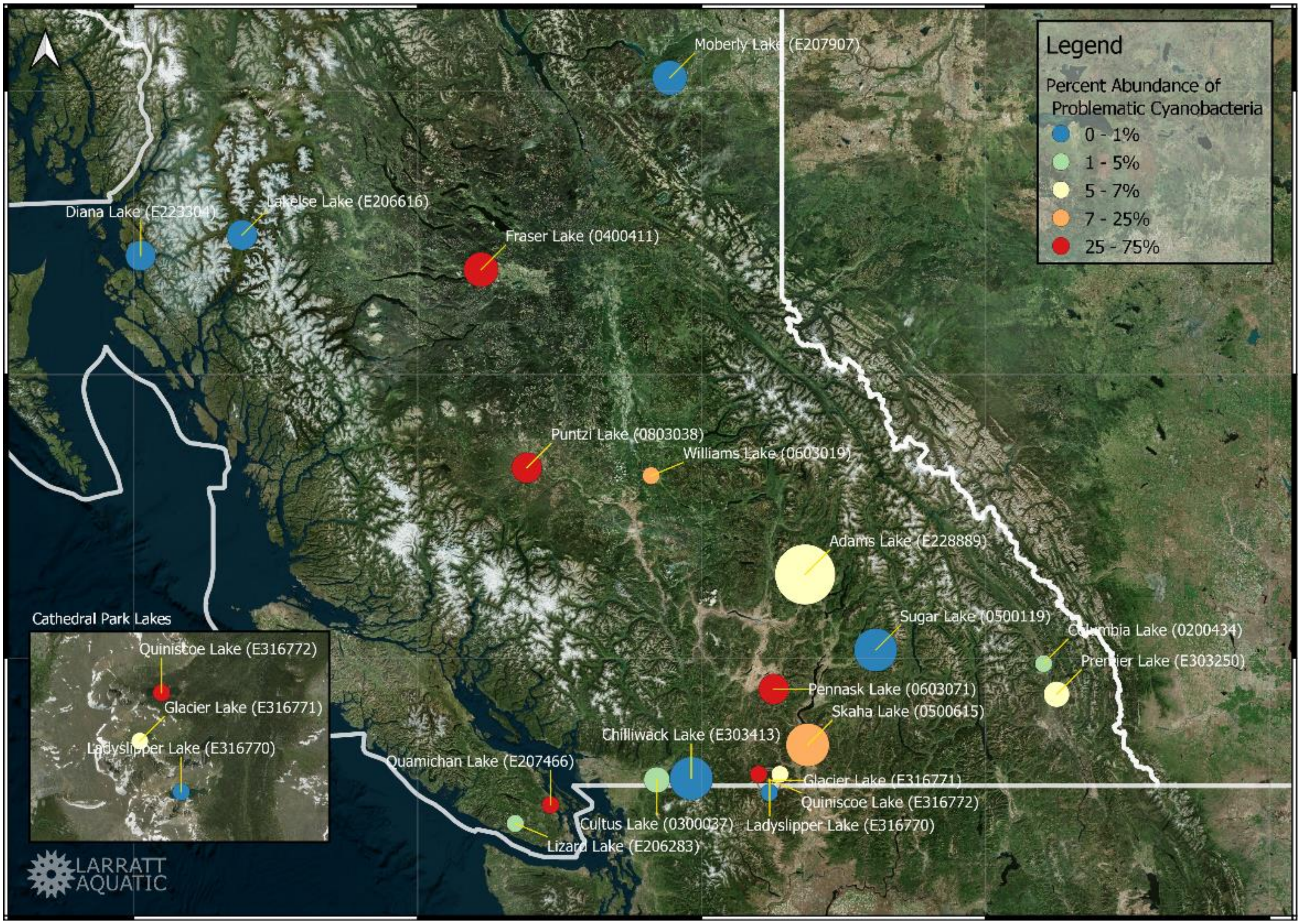

Figure 26: Percent of total abundance from cyanobacteria genera *Anabaena*, *Anacystis,* and *Aphanizomenon,* 2015-2019

Notes: -Size of bubbles relates to size and depth of lake with larger/deeper lakes = larger bubbles
-Sites with red circles were the same sites that likely exhibited internal nutrient loading based on water chemistry(Figure 9)

Diatoms were far less numerous than cyanobacteria because of their larger cell size, representing <2% of total abundance across all lakes. *Aulacoseira italica* was the most numerous diatom at Moberly Lake (40.2% of abundance), Fraser Lake (7.8%), Skaha Lake (4.7%), Pennask Lake (4.6%), and Cultus Lake (3.7%). *Asterionella formosa* was the most abundant diatom in Lakesle Lake (18.5%), Lizard Lake (10.6%), Adams Lake (5.7%), and Diana Lake (0.9%). Generalist species that can inhabit a broad range of environmental conditions were the most numerous types of diatoms at all lakes.

The most common chrysophyte was *Chroomonas acuta* representing 2.2% of total abundance across all lakes. *Chroomonas acuta* was the most numerous chrysophyte species at Moberly Lake (35.9%), Lakelse Lake (27.2%), Glacier Lake (25.1%), Adams Lake (8.7%), Lizard Lake (5.4%), and Chilliwack Lake (3.3%). *Chroomonas acuta* is considered a pollution sensitive indicator species and its presence indicates lower nutrient concentrations. Other common chrysophyte taxa included *Cryptomonas ovata* and *Dinobyron spp.*, both generalist taxa common to British Columbia.

The relative abundance of pollution tolerant taxa and pollution sensitive taxa can be used as a metric for environmental health. This can be assessed as a ratio of the pollution sensitive to tolerant taxa at a given site. Figure 27 compares the ratios of tolerant to sensitive taxa at each lake; a large blue bar indicates a high percentage of total abundance composed of taxa that indicate eutrophication and pollution while a large grey bar indicates the opposite, a high proportion of abundance composed of pollution sensitive species. Unsurprisingly then, Williams Lake and Quamichan Lake, the lakes with the poorest water quality, had the largest blue bars while Cultus Lake, Moberly Lake, Glacier Lake, and Lakelse Lake were dominated by sensitive species indicating good water quality.

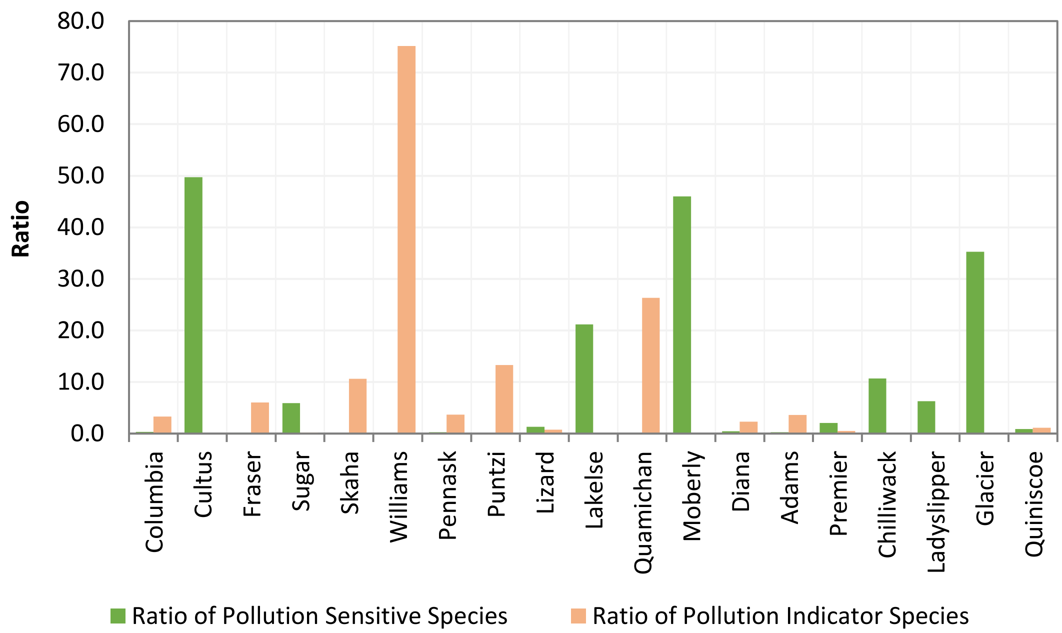

Figure 27: Comparison of percent of total abundance composed of pollution indicator taxa and pollution sensitive taxa, 2015-2019

Note: categorization is based upon the indicator/generalist column in the Master Taxonomy Table created for this project. Size of bars do not indicate actual abundance but relative abundance between these groupings; large numbers = relatively more of that type of algae.

Non-metric multidimensional scaling (NMDS) analysis was conducted on the taxonomic data as it was on the chemistry data. These analyses compare how the phytoplankton community composition in each lake plot relative to one another. The x-axis effectively represents abundance with the most productive lakes lying on the left side of the plot while the least productive lakes were on the right side. Lakes clustered together based on shared characteristics that affected their phytoplankton community composition (Figure 28).

- The highly eutrophic cyanobacteria bloom dominated Williams and Quamichan lakes stood on their own far from the rest of the lakes.
- Hardness appeared to play an important role in community composition and lakes with higher hardness such as Columbia and Puntzi lakes grouped together.

- Deep oligotrophic lakes were very unproductive and clustered on the far right-side of the graph.
- Lakes with lower proportions of cyanobacteria overlapped with the hardness and oligotrophic groups on the low productivity end of the spectrum confirming the abundance data with 87% of total abundance as cyanobacteria across all lakes.
- Coastal Lakes formed only a loose group because of elevated cyanobacteria concentrations in Diana Lake.

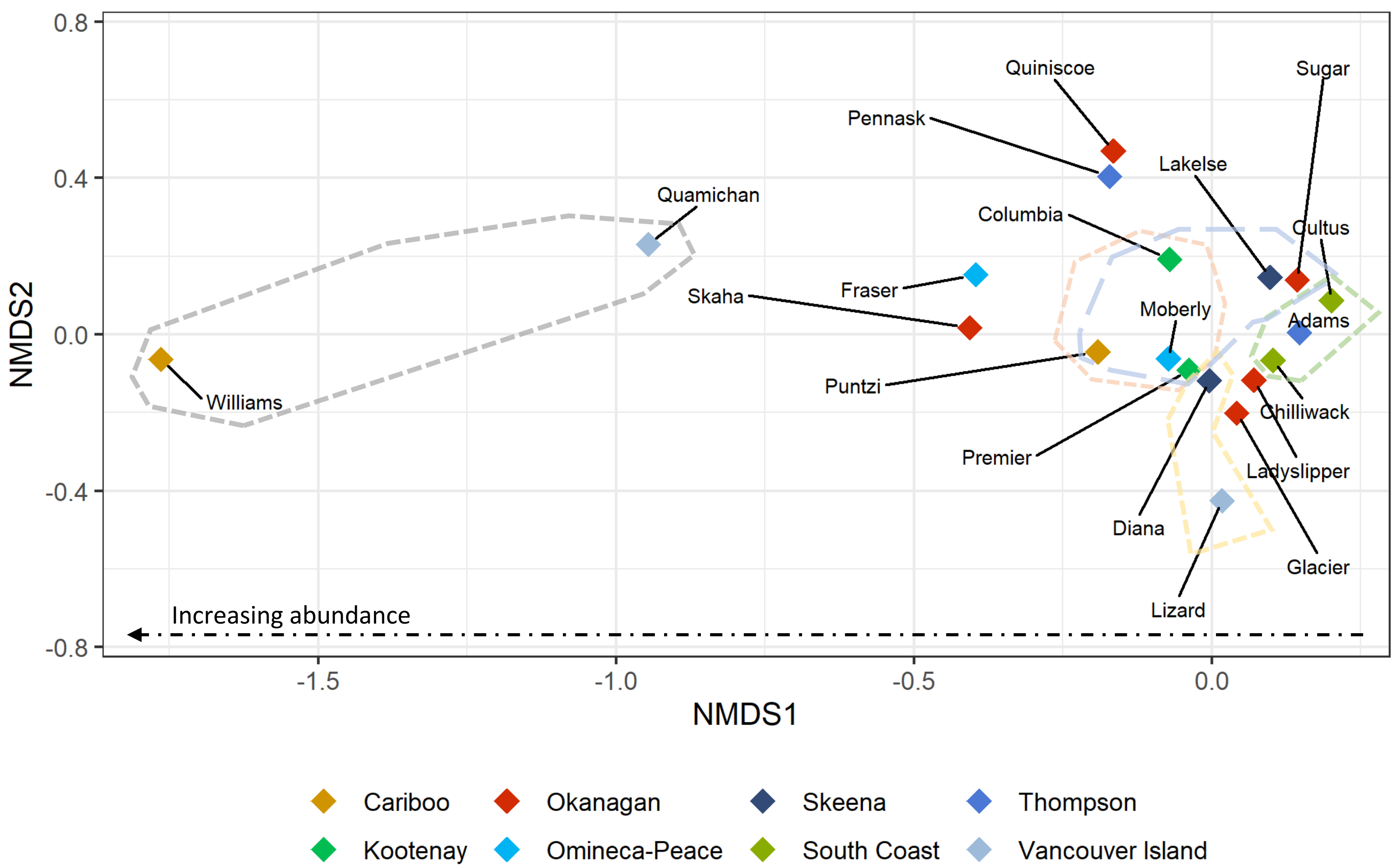

Figure 28: NMDS results for phytoplankton at select lakes across British Columbia during 2019
Note: NMDS analyses performed on data summarized to lowest taxonomic level

Legend for groupings:

Eutrophic cyanobacteria bloom lakes	High hardness lakes	Coastal Lakes	Deep oligotrophic lakes	Lakes with low cyanobacteria percent

2.3.2 Zooplankton

Zooplankton are microscopic grazing animals that feed upon bacteria, algae, and suspended organic particulates. They serve as a major source of food for fish. They do not reflect water chemistry changes as accurately as phytoplankton, but they are the next step in the aquatic food web that support critical fisheries across British Columbia.

Abundance

Total zooplankton abundance varied considerably between the various lakes in this study. For example, the shallow, eutrophic Quiniscoe Lake had the highest abundance (809 ± 1047 zoops/L) while the large, deep, oligotrophic Chilliwack Lake had the lowest (4 ± 2 zoops/L). There was a stark difference measured in zooplankton abundance between Quiniscoe Lake and the other nearby sub-alpine lakes in Cathedral Park (7-44 zoops/L) was not surprising because there were large differences noted across most parameters including both phytoplankton abundance (Figure 14) and community composition (Figure 22). The variation is likely related to the much higher primary productivity in Quiniscoe Lake, a factor of its internal nutrient loading and forested watershed (Figure 9). Other lakes that had high zooplankton productivitincluded Williams Lake (186 ± 158 zoops/L), Quamichan Lake (159 ± 108 zoops/L), and Columbia Lake (109 ± 83 zoops/L). For comparison, Okanagan Lake averaged 17 ± 14 zoops/L from 2011-2020 (Self and Larratt, 2021).

While there were no clear geographic patterns in zooplankton abundance (Figure 30), there was a clear connection between phytoplankton abundance and zooplankton abundance with the most productive lakes having the highest zooplankton and vice versa. The correlation was strongest between zooplankton and green algae (Pearson's R = 0.93) because green algae are a higher quality food source compared to other types of algae such as cyanobacteria (R=0.17). There was also a correlation between zooplankton abundance and depth with the three deepest lakes having the three lowest zooplankton abundances: Sugar Lake (11 ± 4 zoops/L), Adams Lake (8 ± 4 zoops/L) and Chilliwack Lake (4 ± 2 zoops/L). Deep lakes do not mix during the growing season and tend to have nutrients settle through their hypolimnions (Figure 7), significantly reducing productivity (Figure 14) and therefore reducing zooplankton abundance (Figure 29).

There are no lake-specific zooplankton Water Quality Objectives for any of the lakes in this study but the part of the Okanagan Lake zooplankton objective is that the growing season average biomass be >50 µg/L of zooplankton and Okanagan Lake results were close to the objective each year (Self and Larratt, 2021). Based on the average zooplankton density in Okanagan Lake, it is likely that most of the lakes in this study would far exceed the 50 µg/L threshold.

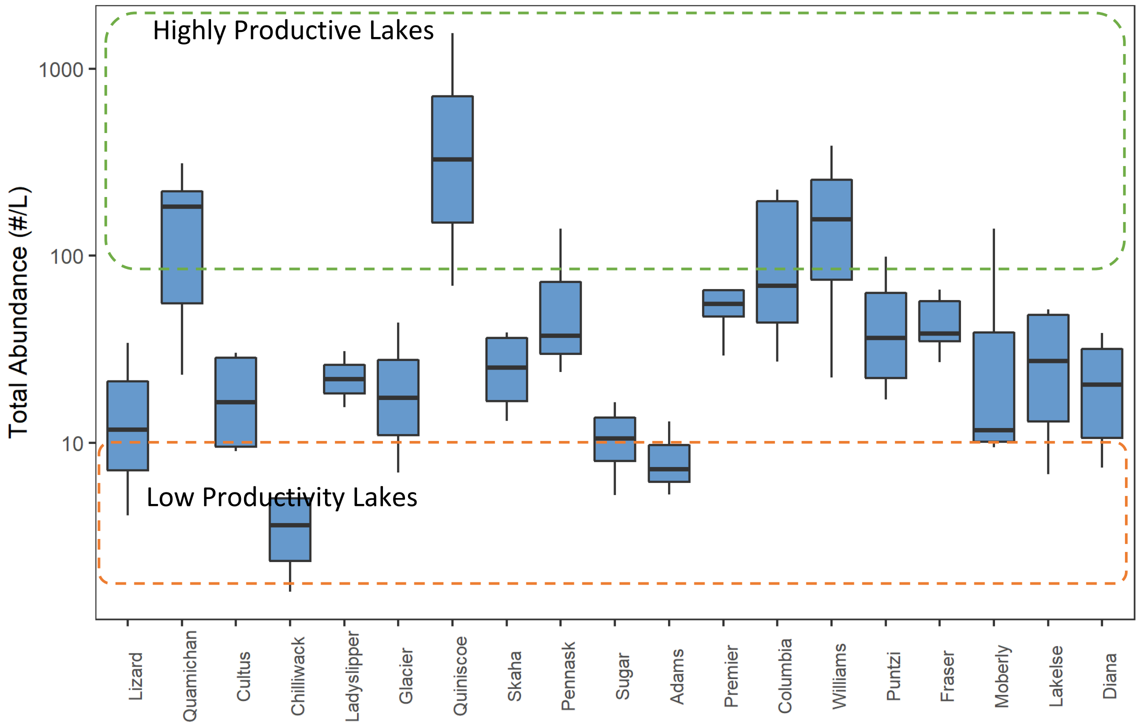

Figure 29: Zooplankton abundance at select lakes across British Columbia, 2015-2019

Note, y-axis is log-10 scale to better highlight variation in sites averaging <10/Litre

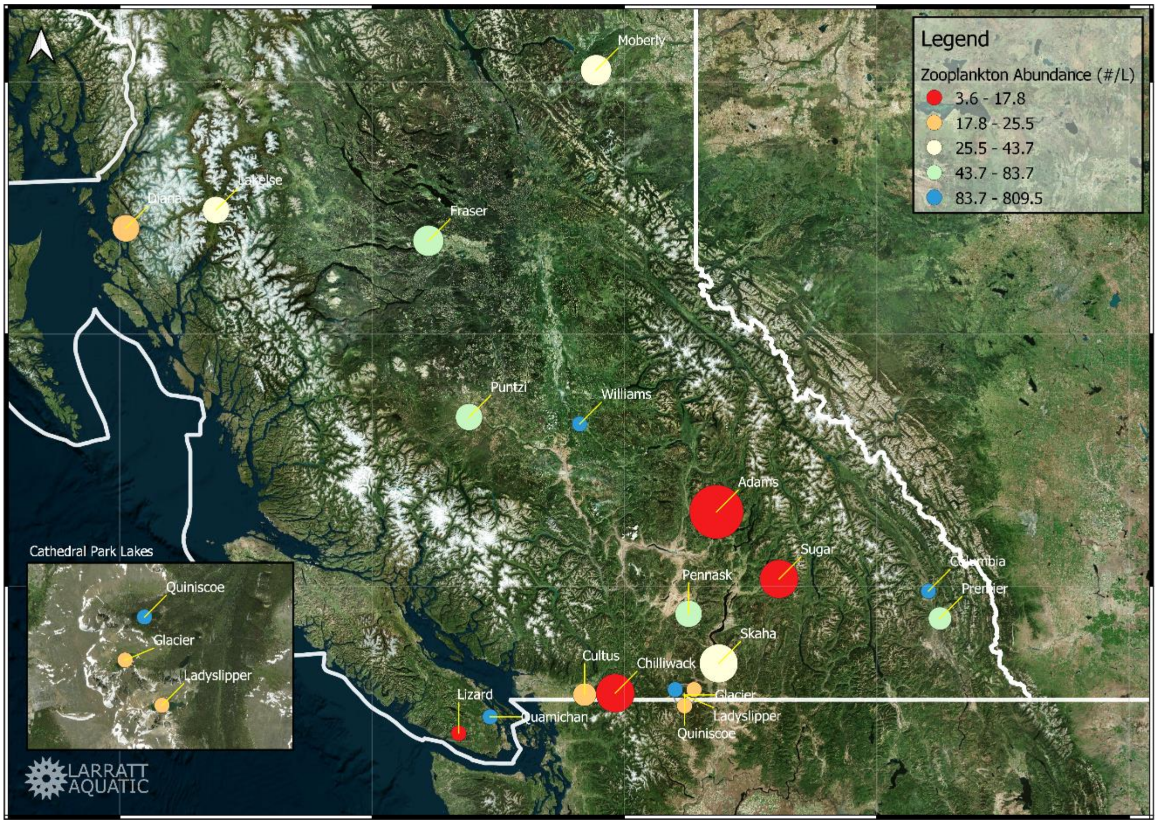

Figure 30: Map of mean zooplankton abundance at 19 study lakes across British Columbia, 2015-2019

Notes: -Size of bubbles relates to size and depth of lake with larger/deeper lakes = larger bubbles
-Three deepest/largest lakes have lowest zooplankton abundance

Comparison of High-Level Taxonomic Groups

As with phytoplankton, zooplankton can be lumped together into high-level groups to simplify analyses:

- Copepods were most numerous on average at 48% of zooplankton observed;
- Rotifers were second at 29% on average;
- Cladocerans averaged 23% across all sites.

Adams Lake had the highest percent of total abundance of copepods at 72 ± 21%. There were several sites that stood out with distinct zooplankton communities such as Glacier Lake that was dominated by Cladocera at 94 ± 3% but total abundance was low with only 25 ± 26 zoops/L during 2019.

Copepods and cladocerans are similar in size and feed upon larger algae cells, while rotifers are much smaller and feed on bacteria and organic detritus. Diana Lake was dominated by rotifers (51 ± 35%) with only 13 ± 9% copepods. Pennask Lake also averaged 42 ± 19% rotifers while the sub-alpine Ladyslipper and Quiniscoe lakes averaged 75 ± 6% and 63 ± 52% rotifers respectively. Williams Lake had one sample that contained 94% rotifers despite copepods being dominant in three of four samples (78-93% abundance on those dates). High densities of rotifers can indicate abundant bacteria in the water column and the densities in this study were highest during the spring at lakes where rotifers were most abundant (Figure 32).

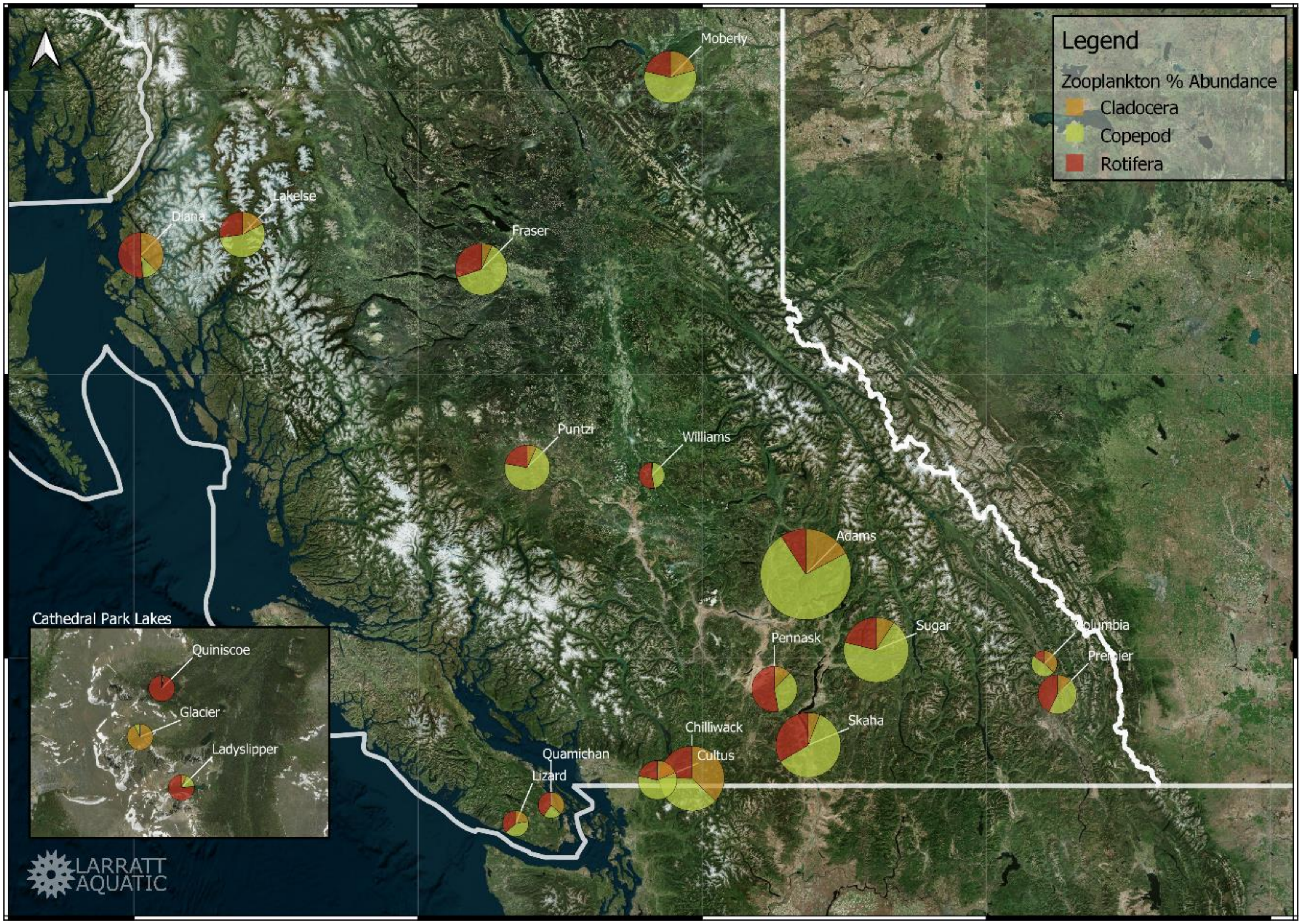

Figure 31: Map of zooplankton percent abundance at 19 study lakes across British Columbia, 2015-2019

Note: Size of bubbles relates to size and depth of lake with larger/deeper lakes = larger bubbles

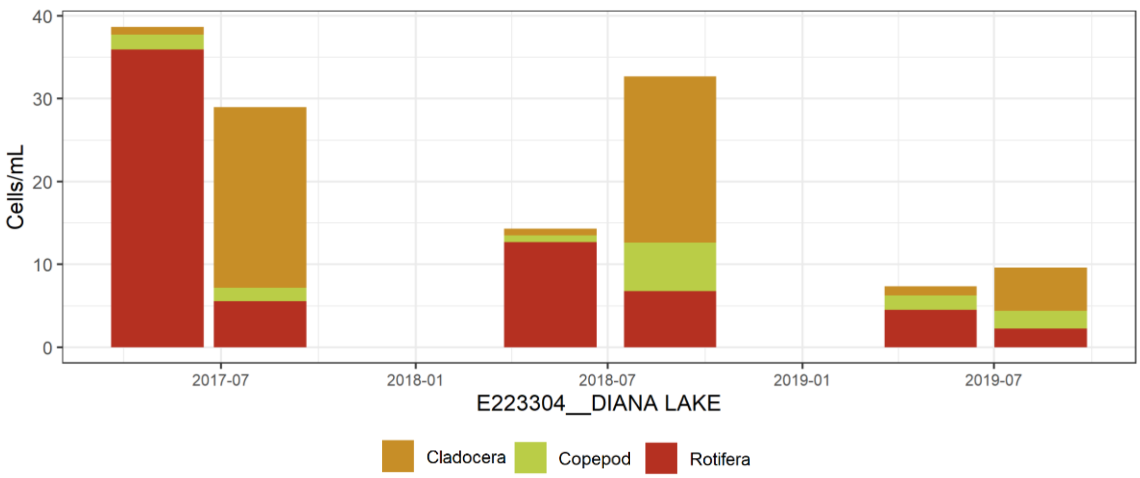

Figure 32: Zooplankton abundance by high level taxonomic groups at Diana Lake for each date, 2017-2019

Species Diversity

Zooplankton diversity is important to lake health. Monocultures are less desirable because of their reduced resiliency to change. Except for Ladyslipper and Glacier lakes in Cathedral Park, all sites averaged between 10-20 taxa of zooplankton observed per sample (Figure 33). The lakes with the greatest number of taxa observed were Puntzi Lake (18.5 ± 1.3 taxa/sample) and Pennask Lake (18.3 ± 1.1 taxa/sample); both lakes also had among the highest values on the Shannon-Weaver diversity index indicating that abundance was distributed between numerous species. Williams Lake had moderate richness averaging 14.8 ± 2.6 taxa/sample but was abundance was heavily dominated by the rotifer *Keratella cochlearis* (49% of total organisms counted) and therefore had a Shannon-Weaver index average of only 0.8 ± 0.5 (Figure 33). Glacier Lake had the least diverse zooplankton community with 92% of total abundance composed of one species, *Daphnia pulicarial*, and a Shannon-Weaver index of 0.3 ± 0.05.

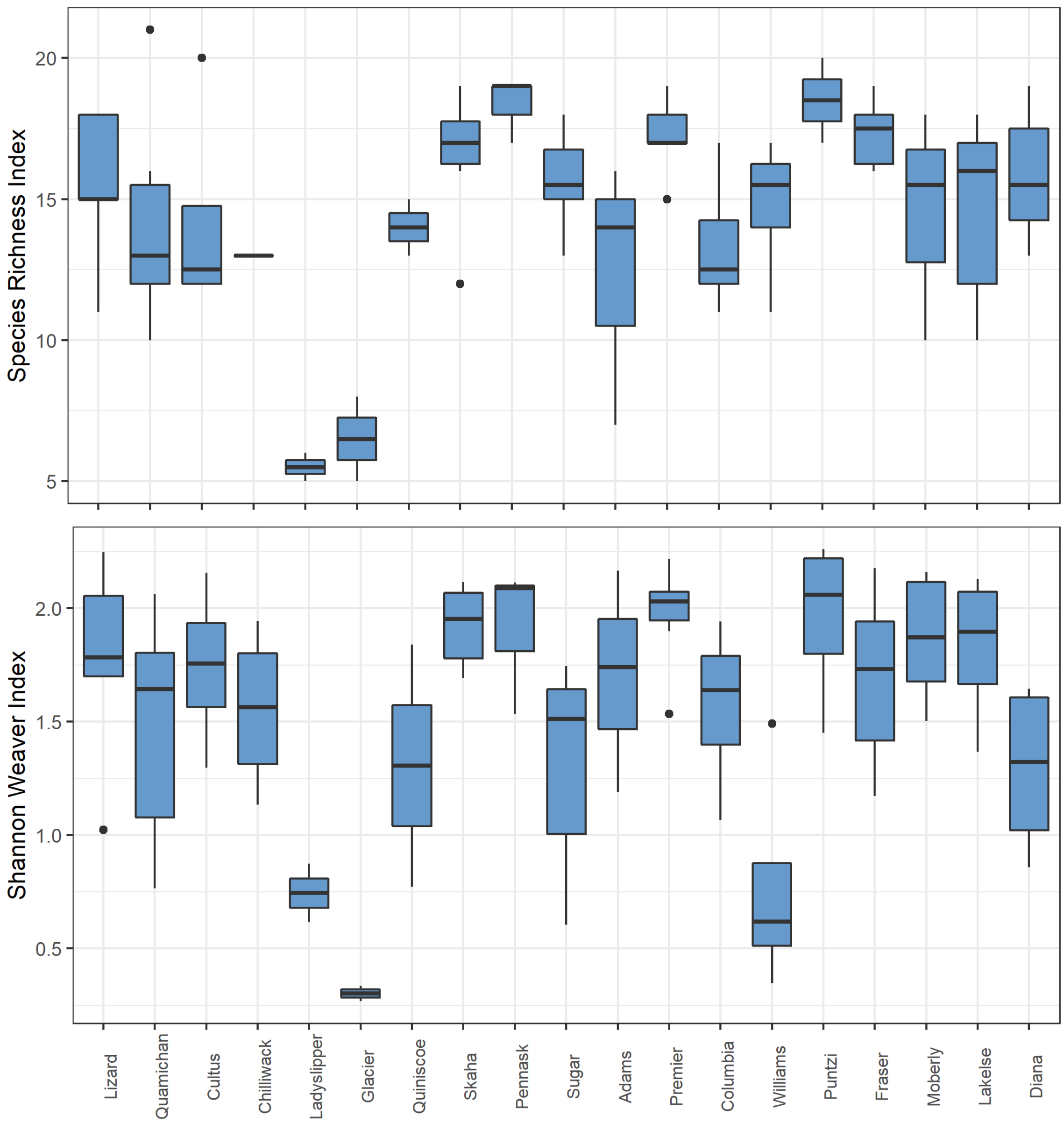

Figure 33: Species richness index (top) and Shannon Weaver diversity index (bottom) for zooplankton across 19 study lakes in British Columbia, 2015-2019

The five most abundant taxa composed most of the zooplankton abundance at all sites, ranging from 70% at Premier Lake to 100% at Ladyslipper and Glacier lakes (Table 6). The alpine lakes in Cathedral Park had the greatest concentration of zooplankton abundance in the five most abundant taxa, in part because they had very low abundance and low total species richness.

Table 6: Percent of total zooplankton abundance that was from the five most abundant taxa at each lake site

Site	Percent of total abundance that was top 5 taxa
0200434__COLUMBIA L	80%
0300037__CULTUS LAK	83%
0400411__FRASER L N	78%
0500119__SUGAR L @	83%
0500615__SKAHA L OP	72%
0603019__WILLIAMS L	97%
0603071__PENNASK LK	86%
0803038__PUNTZI LAK	83%
E206283__LIZARD LAK	71%
E206616__LAKELSE LA	79%
E207466__QUAMICHAN	79%
E207907__MOBERLY LA	72%
E223304__DIANA LAKE	91%
E228889__ADAMS LK O	84%
E303250__PREMIER LA	70%
E303413__CHILLIWACK	81%
E316770__LADYSLIPPE	100%
E316771__GLACIER LK	100%
E316772__QUINISCOE	98%
Mean	84%
SD	10%
Max	100%
Min	70%

Note: Colour scale is relative with green being most diverse and red being least diverse based on abundance of top 5 taxa

Community Composition

While the zooplankton communities were unique at each lake, there were some broad similarities. Copepods were most numerous and were the dominant taxa group at 11 of the 19 lakes studied (Table 7). Unfortunately, determining which type of copepod can be difficult depending on the life stage of the organism and 10 sites had the most common taxa identified as Neocopepoda[7], the infra-class level taxonomic group that includes all copepods (Table 7). The most common rotifers were from the genera *Keratella* and *Kellicotia*, both common throughout British Columbia.

[7] The taxonomic reports lists UID Calanoida/Cyclopoida nauplii but this was simplified to the proper taxonomic group that captures both calanoid and cylopoid copepods

Table 7: Most abundant zooplankton species at each lake and its percent abundance

Site	Lowest.Taxo.Level	Perc.Taxa
0200434__COLUMBIA L	Neocopepoda	36%
0300037__CULTUS LAK	Neocopepoda	43%
0400411__FRASER L N	Neocopepoda	45%
0500119__SUGAR L @	Neocopepoda	58%
0500615__SKAHA L OP	Neocopepoda	35%
0603019__WILLIAMS L	*Keratella cochlearis*	50%
0603071__PENNASK LK	*Kellicottia longispina*	31%
0803038__PUNTZI LAK	Neocopepoda	35%
E206283__LIZARD LAK	*Hesperodiaptomus novemdecimus*	32%
E206616__LAKELSE LA	Neocopepoda	27%
E207466__QUAMICHAN	*Ceriodaphnia dubia*	31%
E207907__MOBERLY LA	Neocopepoda	26%
E223304__DIANA LAKE	*Keratella cochlearis*	36%
E228889__ADAMS LK O	Neocopepoda	35%
E303250__PREMIER LA	Neocopepoda	32%
E303413__CHILLIWACK	*Daphnia rosea*	30%
E316770__LADYSLIPPE	*Kellicottia longispina*	77%
E316771__GLACIER LK	*Daphnia pulicaria*	92%
E316772__QUINISCOE	*Keratella quadrata*	70%

Legend:

Rotifera	Cladocera	Copepoda

Notes: -In many cases, the lowest taxonomic level identified was only to the infraclass level (e.g. Neocopepoda)

The different life stages of zooplankton play different roles within the aquatic ecosystem because of their change in size and feeding habits. Nauplii are an early stage of copepods that are significantly smaller than their adult forms and therefore consume smaller foodstuffs. Adult cladocerans and copepods are often large enough to see with the naked eye (>1 mm) and can feed on most types of phytoplankton but are also more visible to fish and likely to be predated. Nauplii were the most abundant life stage observed in most of the lakes (Columbia Lake, Williams Lake, Pennask Lake, Puntzi Lake, and Quamichan Lake), and were far more numerous than other life stages (Figure 34). It is not clear why these lakes had such high nauplii densities but may relate to lake phytoplankton productivity as these were among the most productive lakes with abundant food supply available for zooplankton growth and reproduction (Figure 14). Alternately, consumption of larger adult forms by fish may skew the zooplankton data towards higher abundance of smaller nauplii.

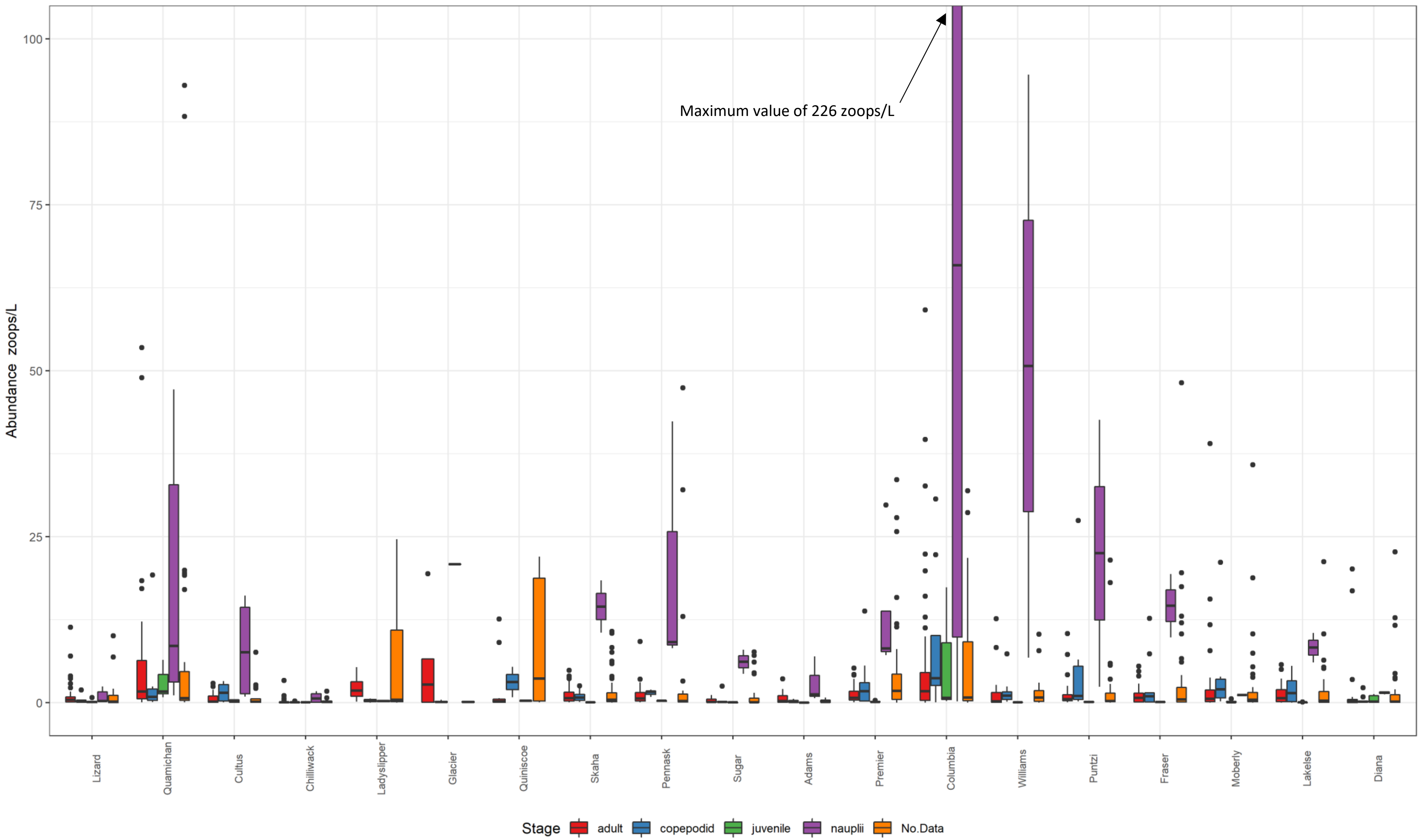

Figure 34: Zooplankton abundance by developmental stage in 19 study lakes across British Columbia, 2015-2019

Non-metric multidimensional scaling (NMDS) analysis was conducted on the taxonomic data as it was on the chemistry data. These analyses compare how the different lakes plot relative to one another across the species present.

Zooplankton did not cluster as well as phytoplankton around common water chemistry parameters. Instead, zooplankton data scaled with total abundance increasing left to right while the relative proportion of rotifers increased downwards along the y-axis (Figure 35). Since total zooplankton abundance correlated strongly with phytoplankton abundance, Figure 35 also illustrates an increase in total phytoplankton abundance. The x-axis effectively represents a blend of phytoplankton and zooplankton abundance with the most productive lakes lying on the right side of the plot while the least productive lakes were on the left side, although it was not a perfect relationship and some lower productivity lakes were further to the right than high productivity lakes.

A brief summary of conclusions from the zooplankton NMDS results were:

- Zooplankton community composition appears to have been affected by phytoplankton abundance.
- Quiniscoe Lake had by far the highest abundance of zooplankton and was dominated by rotifers and therefore sat in the bottom right corner of the graph.
- Adams Lake had very low total zooplankton abundance and was dominated by copepods and therefore sat in the upper left corner of the graph.

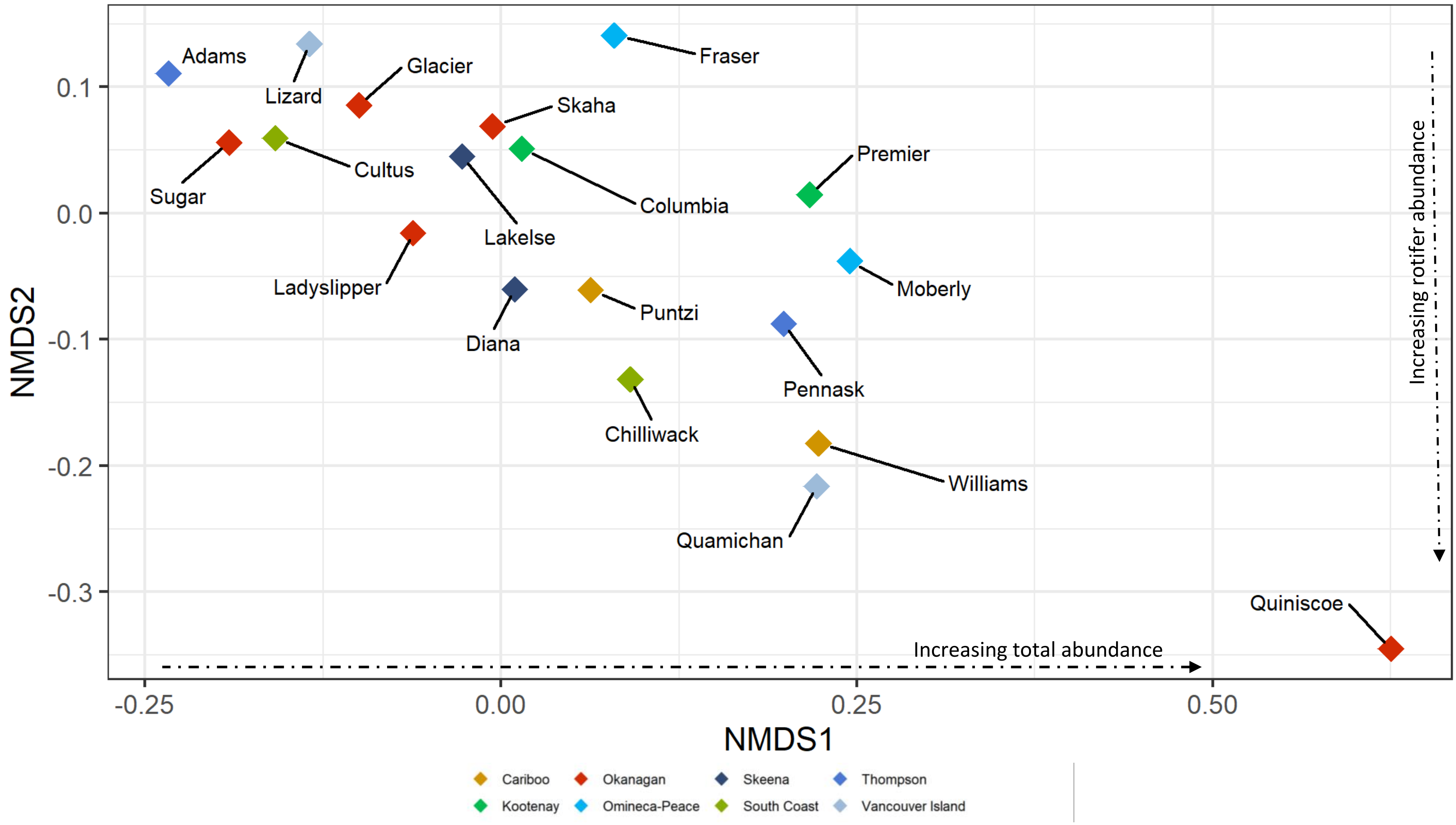

Figure 35: NMDS results for zooplankton from 19 study lakes across British Columbia during 2019

Note: NMDS analyses performed on data summarized to lowest taxonomic level

3.0 Conclusions

This report summarizes select data from the 2015-2019 B.C. Lake Monitoring Network with special focus on taxonomic analyses of phytoplankton and zooplankton samples collected at 19 lakes across British Columbia. Water chemistry data was assessed to provide context for lake productivity and community composition analyses.

The lakes studied covered a broad range of environments from the small, coastal Lizard Lake to the very large and deep Adams Lake to the sub-alpine Cathedral Park lakes, to the boreal Moberly Lake. Despite these physical, limnological, and environmental differences, there were commonalities derived from basic factors. For example, depth affected nutrient cycling and this in turn reduced phytoplankton productivity, which then affected water clarity and zooplankton abundance that would then affect fish populations. Proximity to an urban/agricultural area was also important and a major factor accelerating the productivity of lakes such as Quamichan and Williams lakes. Skaha Lake is adjacent to Penticton but is much deeper than either Quamichan or Williams lakes and this likely moderated its productivity. However, some lakes are naturally productive such as Quiniscoe Lake, a small sub-alpine lake whose productivity is attributed to internal nutrient recycling. Strong internal nutrient recycling was suspected at Quamichan Lake, Williams Lake, Puntzi Lake, Pennask Lake, Fraser Lake, and Quiniscoe Lake and this led to phytoplankton communities with high proportions of potentially toxic cyanobacteria.

Water quality amongst the 19 study lakes varied dramatically. The incredibly deep and oligotrophic Adams Lake had high water clarity, low phosphorus, and low abundance of phytoplankton and zooplankton. Other oligotrophic lakes were Sugar Lake and Chilliwack Lake, both large and deep, and they exhibited similar water quality and biological characteristics. On the other end of the spectrum were lakes in which numerous metrics signaling poor aquatic health. The hypereutrophic Quamichan Lake near Duncan is likely in the poorest health with low water clarity, oxygen depletion, the highest concentrations of every major nutrient, frequent intense HABs that led to pet deaths during 2016, and low phytoplankton diversity. Williams Lake also exhibited metrics of poor health including poor water clarity, extremely high phytoplankton abundance, and a near monoculture of the cyanobacteria *Oscillatoria tenuis*.

Table 8 summarizes the findings of this report for 2015-2020 while Table 9 and Table 10 compare results for those sites that have established water quality objectives. Colour coding in Table 8 is used to provide context for the numerical values with cells that are orange or red having poorer water quality from the perspective of nutrient enrichment. The hypereutrophic Quamichan Lake that experiences toxic cyanobacteria blooms had the most red-coloured cells while the oligotrophic Chilliwack Lake had the most green-coloured cells.

Water quality objectives exist for Williams Lake, Lakelse Lake, and Columbia Lake and except for very high chlorophyll-a in Williams Lake, all objectives were met during 2015-2020 (Table 10).

Table 8: Summary table of physical, chemical, and biological data (Mean ± SD)

	Lizard Lake	Quamichan Lake	Cultus Lake	Chilliwack Lake	Ladyslipper Lake	Glacier Lake	Quiniscoe Lake	Skaha Lake	Pennask Lake	Sugar Lake	Adams Lake	Premier Lake	Columbia Lake	Williams Lake	Puntzi Lake	Fraser Lake	Moberly Lake	Lakelse Lake	Diana Lake
	South >> North by Region																		
Temperature	15.2 ± 9	15.8 ± 9.3	19 ± 7	14.9 ± 5.9	10.4 ± 2.3	10.8 ± 0.8	11 ± 2.2	10.4 ± 9.4	13.6 ± 3.9	12.4 ± 7.8	11.7 ± 6.3	15.2 ± 6.1	15.4 ± 6.1	13.1 ± 7.2	13.1 ± 5.8	11.7 ± 5	10.4 ± 4	10.2 ± 1.3	15.3 ± 5.2
Secchi Depth	7.6 ± 1.1	1.4 ± 0.6	8.2 ± 3.5	12.3 ± 3.6	8.5 ± 0.8	5 ± 0	4.7 ± 0.8	6.4 ± 1.3	2.8 ± 0.7	8.5 ± 2.2	12.9 ± 3.4	10.8 ± 1.6	4 ± 0.5	1.2 ± 0.2	4.9 ± 2.3	2.9 ± 0.7	2.7 ± 1.8	2.7 ± 0.7	2.1 ± 0.8
Dissolved Oxygen	10.1 ± 1.7	11.1 ± 4.2	9.8 ± 1.8	9.3 ± 1	8.9 ± 0.7	8.7 ± 1	9 ± 0.5	11 ± 2.6	8.9 ± 0.9	9.8 ± 1	10.3 ± 1.2	9.4 ± 0.7	9.5 ± 1.1	10.4 ± 1.2	8.9 ± 0.9	10.5 ± 1.4	10.4 ± 1	13.2 ± 1.5	11.1 ± 2.7
Silica	2.39 ± 0.5	1.99 ± 1.96	3.17 ± 3.05	4.62 ± 1.79	8.81 ± 0.4	8.6 ± 0.98	8.86 ± 0.66	6.09 ± 0.76	10.22 ± 0.75	5.68 ± 0.98	6.14 ± 0.31	2.21 ± 0.43	5.57 ± 2.05	9.25 ± 6.34	0.43 ± 0.46	4.47 ± 1.08	2.99 ± 0.44	5.53 ± 0.8	1.4 ± 0.48
TN	0.146 ± 0.061	1.704 ± 0.899	0.145 ± 0.043	0.084 ± 0.026	0.064 ± 0.004	0.182 ± 0.004	0.252 ± 0.131	0.219 ± 0.02	0.65 ± 1.024	0.101 ± 0.039	0.13 ± 0.017	0.193 ± 0.022	0.22 ± 0.04	0.864 ± 0.298	0.679 ± 0.331	0.296 ± 0.017	0.313 ± 0.049	0.09 ± 0.029	0.148 ± 0.021
Ammonia	0.0094 ± 0.0132	0.5575 ± 0.8384	0.0033 ± 0.0018	0.0025 ± 0	0.0025 ± 0	0.0025 ± 0	0.0384 ± 0.0698	0.0025 ± 0	0.0091 ± 0.008	0.0036 ± 0.0024	0.0059 ± 0.0039	0.0036 ± 0.0024	0.0025 ± 0	0.0186 ± 0.0159	0.0447 ± 0.0905	0.0078 ± 0.0024	0.019 ± 0.0208	0.0038 ± 0.0031	0.0042 ± 0.0034
NO3+NO2	0.0123 ± 0.0171	0.1491 ± 0.1823	0.037 ± 0.06	0.0351 ± 0.0254	0 ± 0	0 ± 0	0 ± 0	0.0004 ± 0.0016	0.007 ± 0.0118	0.0406 ± 0.038	0.0659 ± 0.0353	0.0003 ± 0.001	0 ± 0	0.0408 ± 0.0596	0.0606 ± 0.0722	0.0039 ± 0.0061	0.097 ± 0.0366	0.02 ± 0.0229	0.011 ± 0.0092
TP	0.0058 ± 0.0037	0.3173 ± 0.1467	0.0038 ± 0.001	0.0015 ± 0.0009	0.0057 ± 0.0008	0.0486 ± 0.0395	0.0132 ± 0.0017	0.0068 ± 0.0025	0.0202 ± 0.0093	0.0017 ± 0.0011	0.0026 ± 0.0017	0.0035 ± 0.0019	0.0064 ± 0.0041	0.0418 ± 0.0347	0.0162 ± 0.018	0.0154 ± 0.0071	0.0078 ± 0.0084	0.0042 ± 0.002	0.0042 ± 0.0011
TDP	0.0023 ± 0.0014	0.2526 ± 0.1111	0.0021 ± 0.0006	0.001 ± 0	0.0018 ± 0.0011	0.0125 ± 0.002	0.0063 ± 0.0009	0.0033 ± 0.0011	0.0072 ± 0.0019	0.0016 ± 0.0011	0.0011 ± 0.0004	0.0026 ± 0.0013	0.0025 ± 0.0015	0.0153 ± 0.0152	0.0171 ± 0.0152	0.008 ± 0.0029	0.0032 ± 0.0026	0.0021 ± 0.0016	0.0024 ± 0.0009
Ortho P	0.0005 ± 0	0.25827 ± 0.24505	0.0005 ± 0	0.0005 ± 0	0.0005 ± 0	0.00455 ± 0.00445	0.01038 ± 0.01749	0.00068 ± 0.00061	0.0017 ± 0.00158	0.0007 ± 0.00045	0.00056 ± 0.00019	0.0007 ± 0.00041	0.0008 ± 0.00043	0.00997 ± 0.01256	0.00819 ± 0.01274	0.00257 ± 0.00169	0.00105 ± 0.0009	0.00083 ± 0.00082	0.0005 ± 0
Chl-a (mg/L)	0.00296 ± 0.00371	0.04212 ± 0.01736	0.00166 ± 0.00106	0.00057 ± 0.00027	0.00075 ± 0.00007	0.00088 ± 0.00037	0.00512 ± 0.00315	0.00361 ± 0.00318	0.00775 ± 0.00404	0.00139 ± 0.00135	0.0007 ± 0.00029	0.00088 ± 0.00068	0.00126 ± 0.00041	0.0142 ± 0.00683	0.00383 ± 0.00278	0.00382 ± 0.0012	0.00159 ± 0.00114	0.00153 ± 0.00063	0.00101 ± 0.00069
Phyto Abundance	940 ± 854	18744 ± 17528	246 ± 222	192 ± 274	225 ± 150	340 ± 293	2657 ± 2800	1172 ± 512	2138 ± 586	325 ± 267	210 ± 173	406 ± 229	458 ± 313	42457 ± 20022	1244 ± 493	1346 ± 964	571 ± 137	253 ± 139	1667 ± 1915
Phyto Species Richness	45 ± 11	31 ± 5	25 ± 5	24 ± 7	33 ± 4	37 ± 5	53 ± 11	46 ± 22	60 ± 6	40 ± 7	33 ± 13	23 ± 11	58 ± 20	20 ± 7	24 ± 10	56 ± 11	47 ± 4	52 ± 8	32 ± 4
Phyto Shannon-Weaver	2.1 ± 0.7	1.2 ± 0.4	1.9 ± 0.5	2 ± 0.7	2 ± 0.1	1.9 ± 0.1	1.9 ± 0.1	2 ± 0.5	1.6 ± 0.3	2 ± 0.7	1.9 ± 0.5	1.3 ± 0.4	2.4 ± 0.6	0.6 ± 0.5	0.8 ± 0.1	2.3 ± 0.3	1.7 ± 0.4	2.5 ± 0.5	1.4 ± 0.7
Zoops Abundance	16 ± 12	159 ± 108	19 ± 11	4 ± 2	23 ± 11	25 ± 26	809 ± 1047	26 ± 11	67 ± 63	11 ± 4	8 ± 4	54 ± 14	109 ± 83	186 ± 158	49 ± 37	45 ± 16	40 ± 52	29 ± 20	22 ± 13
Zoops Species Richness	15 ± 3	14 ± 4	14 ± 4	13 ± 0	6 ± 1	7 ± 2	14 ± 1	17 ± 2	18 ± 1	16 ± 2	12 ± 5	17 ± 1	13 ± 2	15 ± 3	19 ± 1	17 ± 1	15 ± 3	15 ± 3	16 ± 2
Zoops Shannon-Weaver	1.8 ± 0.5	1.5 ± 0.5	1.7 ± 0.4	1.6 ± 0.4	0.7 ± 0.2	0.3 ± 0	1.3 ± 0.8	1.9 ± 0.2	1.9 ± 0.3	1.3 ± 0.5	1.7 ± 0.5	2 ± 0.2	1.6 ± 0.3	0.8 ± 0.5	2 ± 0.4	1.7 ± 0.4	1.9 ± 0.3	1.8 ± 0.3	1.3 ± 0.4

Note: colour scale for each parameter is relative to that parameter with red cells having the poorest water quality and green cells having the highest water quality for a given parameter from a perspective of eutrophication and nutrient enrichment. That is a eutrophic, highly productive lake (Quamichan Lake) will tend to have more orange/red cells than an oligotrophic lake that will be more green (Adams Lake). Colour scale does not reflect attainment of objectives

Table 9: Lake Specific Water Quality Objectives

Objectives (Nordin, 2005)	**Williams Lake**	**Columbia Lake**	**Lakelse Lake**
Secchi Depth (m) (growing season average)	≥1.2		
Dissolved Oxygen (mg/L) (minimum in bottom waters)	≥4.5		≥6
TP (mg/L as P) (maximum at spring overturn)	≤0.020	≤0.008	≤0.010
Chlorophyll-a (µg/L) (growing season average)	≤5		≤3

Table 10: Attainment of lake specific water quality objectives, 2015-2020

Objectives (Nordin, 2005)	**Williams Lake**	**Columbia Lake**	**Lakelse Lake**
Secchi Depth (m) (growing season average)	1.2 ± 0.2		
Dissolved Oxygen (mg/L) (minimum in bottom waters)			10.6 ± 2.2
TP (mg/L as P) (maximum at spring overturn)	0.075 ± 0.099	0.009 ± 0.018	0.005 ± 0.005
Chlorophyll-a (µg/L) (growing season average)	14.2 ± 6.8		1.6 ± 0.7

Note: Dissolved oxygen in hypolimnion of Williams Lake not recorded in EMS

Legend:

Achieve objective	Did not achieve objective	No Data/ No Objective

4.0 Recommendations

This report makes the following recommendations:

- Continue to monitor these lakes to track year-over-year trends
- Repeat the analyses performed in this report periodically, for example every three years and update the taxonomic information.
    - Included R scripts may allow ENV staff to perform these analyses more frequently.
- Continue to have phytoplankton taxonomy samples analyzed to species level as this provides information for determining the ratio of pollution sensitive and pollution indicator taxa. NMDS analyses revealed some loss of information in reducing taxonomic resolution (see Appendix 4). Variety level identification does not appear to be worth the cost as very few samples had any taxa that could be identified to that level.
- Consider estimating biomass from 2015-2019 data using cell measurements collected from 2020 taxonomic results.
- Zooplankton identification could be reduced to genus or even family level identification because existing data indicate that obtaining higher resolution is routinely unrealistic and was not attained.
- Investigate lakes suspected to have internal nutrient loading for dissolved oxygen depletion using field profiles (Williams Lake, Puntzi Lake, Pennask Lake, Quiniscoe Lake)
- If any major lake renovation or restoration efforts are made, the details of those projects should be provided to this study to aid in data interpretation. Conversely, repeating this report could help gauge the effectiveness of remedial efforts in eutrophic lakes or nutrient enhancement efforts in ultra-oligotrophic lakes.

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6.0 Appendices

Appendix 1: Sampling Data

All data used in this report can be found in the following Excel files that were supplied with the report:

- Water chemistry data: "EMS_Export_2015-2020.csv"
- Cleaned Taxonomy Data: "ENV Taxonomic Database.csv"
- Master Taxonomy File: "Master Taxonomy Table.xlsx"
- Taxonomic Reconciliation Table: "Taxonomic Reconciliation Table.xlsx"
- Site information and specific water quality objectives: "Analysis Sites.xlsx"

Appendix 2: Data Management, Statistics, and Graphing Overview

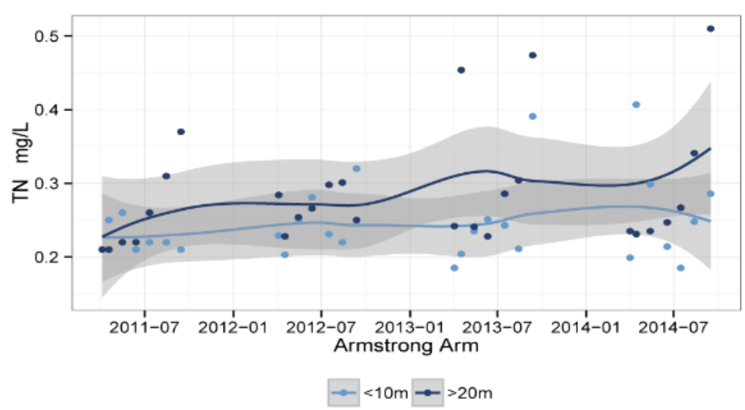
Statistical analyses were performed on data to support interpretations made throughout this report. The use of the word 'significantly' within this report is understood to signify that the claim being made has stood up under statistical analysis. Unless otherwise stated, all statistical analyses were performed to a confidence of greater than or equal to 95% ($p \leq 0.05$). The ± symbol indicates plus or minus the standard deviation throughout this report.

Water quality data often contains non-detect values for many parameters. Non-detect values were converted to ½ detection limit for all calculations.

Trends were determined through Mann-Kendall linear regression. Mann-Kendall is a non-parametric test for linearity in data. The test produces a Tau-value and a p-value. The Tau value gives the direction of the data and the p-value indicates whether the trend is statistically significant.

Throughout this report the monthly sampling data was grouped seasonally for additional analyses. March, April, and May data were combined as "Spring"; June, July, and August as "Summer"; and September as "Fall".

Correlations were performed using the Pearson's Correlation method and all R values reported at Pearson's Correlation Coefficients.



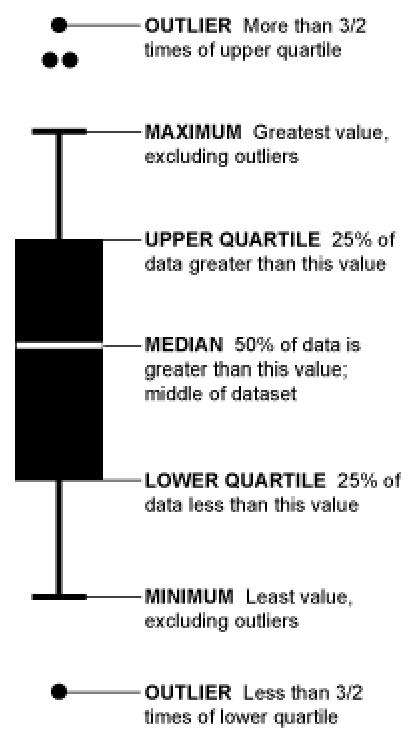


Figure i: Example scatterplot and boxplot
Includes all data for a parameter sorted by depth, LOESS polynomial trendlines and the standard errors of those trendlines are also included. Example boxplot is labeled with key information. Whiskers represent the distance to the highest or lowest point within 1.5 * IQR where IQR represents the range between the upper and lower quartiles.

Data Cleaning

Taxonomic data was supplied to LAC in the form of individual lab report spreadsheets with each spreadsheet containing the data from one site on one date as either zooplankton or phytoplankton. The first step in analyzing the data was therefore to combine these spreadsheets into a master database of taxonomic data.

This process was performed using R programming to increase efficiency, remove the potential for transcription errors, and be agnostic to the number of sites (i.e. more sites could be added easily without changing code or any manual data manipulation). The R code loads all excel files within a folder directory and parses them based on the report template, extracting both the results and metadata. These data were then combined into a messy database that included many duplicate parameters because of typos and minor variations in spelling of species names. The database was linked to a table of site information to correct spelling changes in site names from the lab reports. Combining the database with the taxonomic reconciliation table allowed for rapid cleaning of taxonomic data by merging duplicated taxonomic names and correcting spelling errors. Use of the taxonomic reconciliation table also makes it relatively straightforward to update taxonomic names if species are moved between taxa in the future without changing the original lab reports in any way and therefore not losing any information. This was saved as the file "ENV Taxonomic Database.csv" in the final project files folder.

Some assumptions were required in the handling of the taxonomic data and these are listed below:

- The lab reports contained numerous instances of values below a detection limit. It was assumed that all non-detect values represented taxa that were spotted in the sample during the qualitative overview but whose densities were too low to register during quantitative analysis. The data stored in the ENV Taxonomic Database includes all non-detect values as they were reported by the lab. However, subsequent analyses of the data required a conversion of these values to ½ of the reported detection limit.
- There were numerous instances of unidentified or poorly identified taxa in the lab reports. It is not always possible to identify every organism observed because it may be damaged in some way or lacking important identifiable markings. Lab reports included these results as formulations of "UID" and any information that they had. For example, a radially symmertrical diatom may be labelled as "UID Diatom" or "UID Centrate" etc. For analysis in this report, these taxa were linked through the taxonomic reconciliation table to the lowest possible taxonomic level which in this case would be the class level that includes all diatoms, Bacillariophyceae. This allowed all taxonomic data to be included in analysis for the sake of total abundance values.
- Some taxa are visually very similar and can be difficult to differentiate in all cases because of missing identifiable features or obstructions on the slide. There were numerous instances of samples with two combined taxonomic names; for example, *Cyclotella/Stephanodiscus*. Without reanalyzing a sample, it is not possible to know which was the real taxa observed. Through the taxonomic reconciliation table, these samples were flagged as being double species and identified to the lowest common taxonomic level. In this case it would be the family level group Stephanodiscaceae.

Species level data was used throughout of the report for abundance, diversity, and community composition analyses but these data required a cleaning stage before use. The raw lab data contained duplicate taxa and typos that were corrected by joining the data with the taxonomic reconciliation table and then the results were summed by site and date such that all duplicate taxa names were combined into a single value. This same process was used to simplify the data to genus level, order level, and high-level taxonomic group for other analyses.

Non-Detect Value Screening

Many water parameters are present at or below the detectable limit in the natural environment and in the data reported here. A variety of techniques exist for dealing with non-detection data through estimating values prior to subsequent analyses. Techniques for handling non-detection values must be considered carefully, as they can influence interpretations of subsequent analyses. For instance, if many non-detectable values occur in a data set, substituting all non-detectable values with 0 is likely to underestimate the true value, and does not accurately reflect the variability that occurs in a sampled parameter. Treating the non-detectable values as a NULL or acting as if they were not sampled, overestimates the actual value because too much emphasis is given to detected values. Likewise, substituting all non-detectable values with ½ of the detection limit frequently causes over-estimation of true values, particularly in older data with higher detection limits. Non-detect values were converted to ½ the detection limit for this report and compared to the detection limit over time to ensure that any trends stated in this report were based on real data and not artificial non-detect conversions.

Mann-Kendall Trend Analysis

Mann-Kendall trend tests (implemented in the “Kendall” package in R; (McLeod 2013)) were used to identify and assess the direction and statistical significance of trends in water quality measurements over time. The Mann-Kendall test is a non-parametric statistical test, which, unlike traditional regression analysis, does not assume normally distributed data (Hipel and McLeod 2005). This is a key attribute of this test as water quality data are typically not normally distributed, with many low and fewer high values. In cases where patterns in water quality are likely to differ markedly among months (e.g., due to seasonal hydrological patterns), seasonal Mann-Kendall tests can be used in the future to compare time series among the same months in different years in order to better determine overarching trends.

The Mann-Kendall trend test provides a p-value analogous to that provided by simple linear regression, from which statistical significance is determined at an alpha level of 0.05. The relative strength and direction of trends is measured through a second test statistic, Kendall’s tau (T) rank correlation coefficient. Tau ranges from -1 to 1 with negative and positive values indicating negative and positive correlations (trends) respectively, and the departure from zero indicating the relative strength of the trend (Helsel and Hirsch 2002).

Trends are considered over various time frames within this report. In Table 0-3, trends reflect the entirety of the 2000-2019 data set. Within the body of the report, however, sub-trends are considered. For example. If a parameter increased from 2000-2012 and then stabilized from 2012-2019 it would be identified as increasing in Table 0-3 but may not be indicated within the body of the text because the trend was not active in 2019. Unless specified, the date range for all trends is 2000-2019 or as many years of data as exist.

Kruskal-Wallis Test of Difference

The Kruskal–Wallis One-Way Analysis of Variance by Ranks is a non-parametric method for testing if samples originate from the same distribution, that is, if the means of two variables are significantly different. It is used to compare more than two independent or non-related samples. It is the non-parametric equivalent of the more traditional ANOVA statistical test. The calculation produces a p-value from which statistical significance is determined (Spurrier, 2003).

Non-metric Multidimensional Scaling

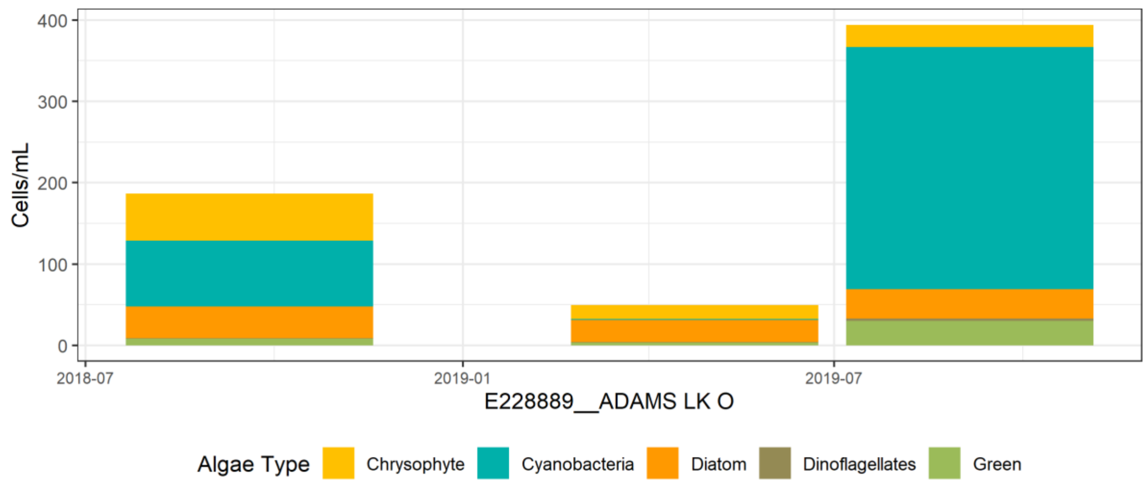
Non-metric multidimensional scaling (NMDS) analysis is a statistical method used to collapse variation in many dimensions (e.g. sample parameters) into 2-dimensions for plotting. This is valuable for interpretating the variation between sites across a large number of variables. NMDS uses rank ordering and is therefore versatile when analyzing data that vary over orders of magnitude and different units such as orthophosphate and conductivity. NMDS was employed via the "Vegan" R package (Oksanen, 2020).

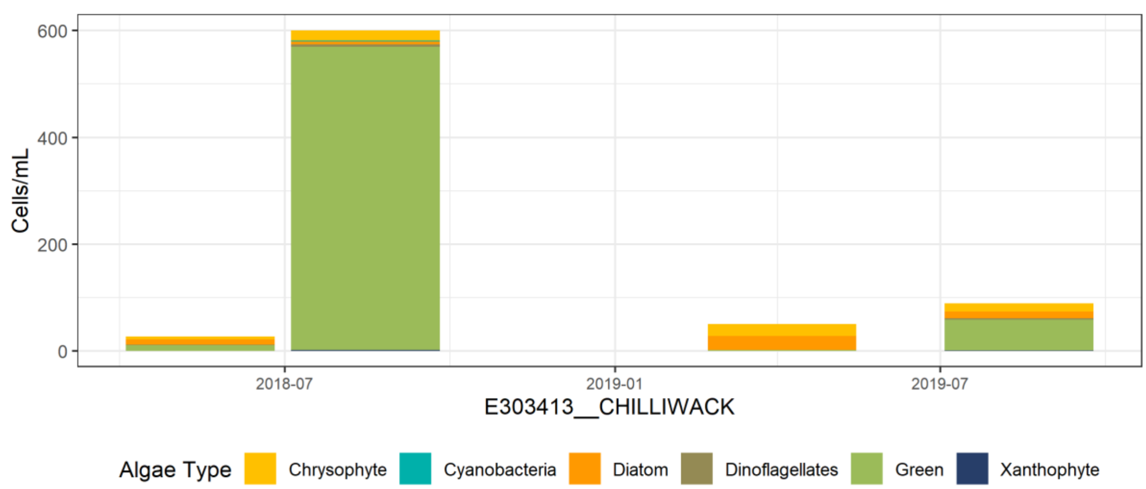
NMDS requires multiple variables with paired data and no missing values, that is there must be a corresponding value for every parameter for every date in the database. With long-term databases such as EMS there are many instances of this error arising and so steps were taken to clean the data prior to the NMDS computation. There were two approaches taken in handle missing data. Firstly with the water chemistry, empty values were substituted with the mean for a given site and parameter. For taxonomy data it was assumed that parameters without values were not observed at a given site and date and were substituted with a 0 value.

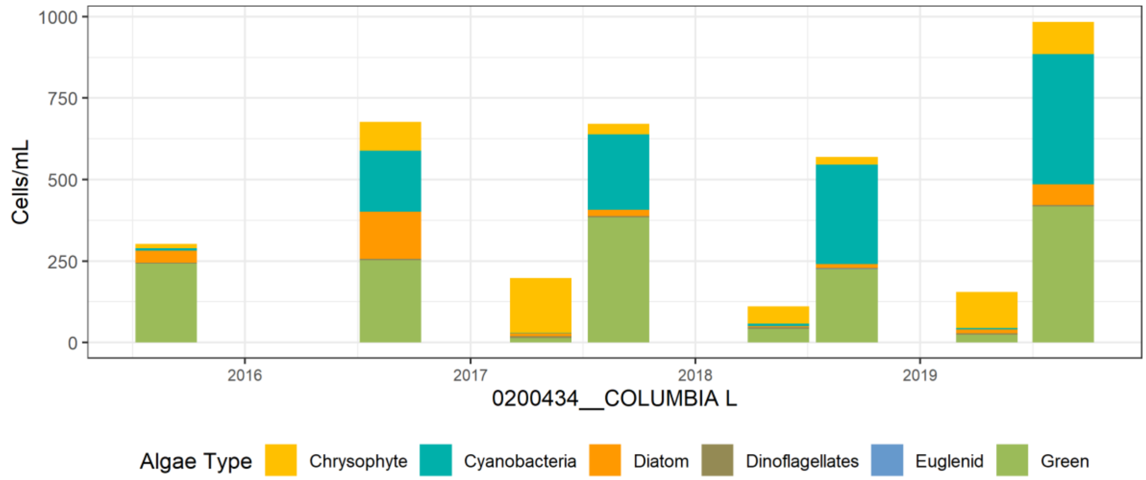
Appendix 3: Phytoplankton and Zooplankton Abundance Graphs

Note: The number of times each site was sampled varied depending on the site and is reflected in the number of bars displayed in each figure below.

Phytoplankton






Cells/mL
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750
500
250
0
2016
2017
2018
2019
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Algae Type
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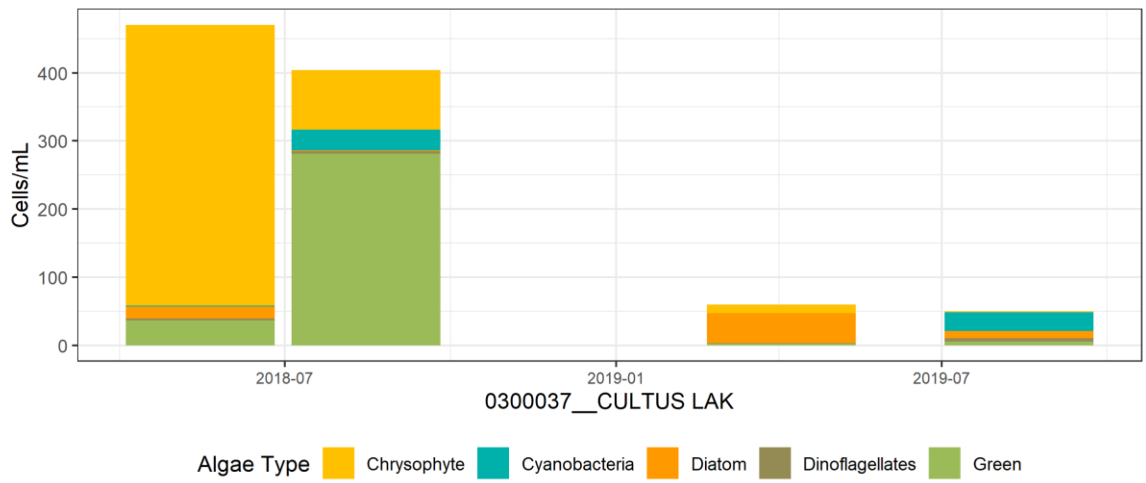
Cyanobacteria
Diatom
Dinoflagellates
Euglenid
Green


Cells/mL
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300
200
100
0
2018-07
2019-01
2019-07
0300037__CULTUS LAK
Algae Type
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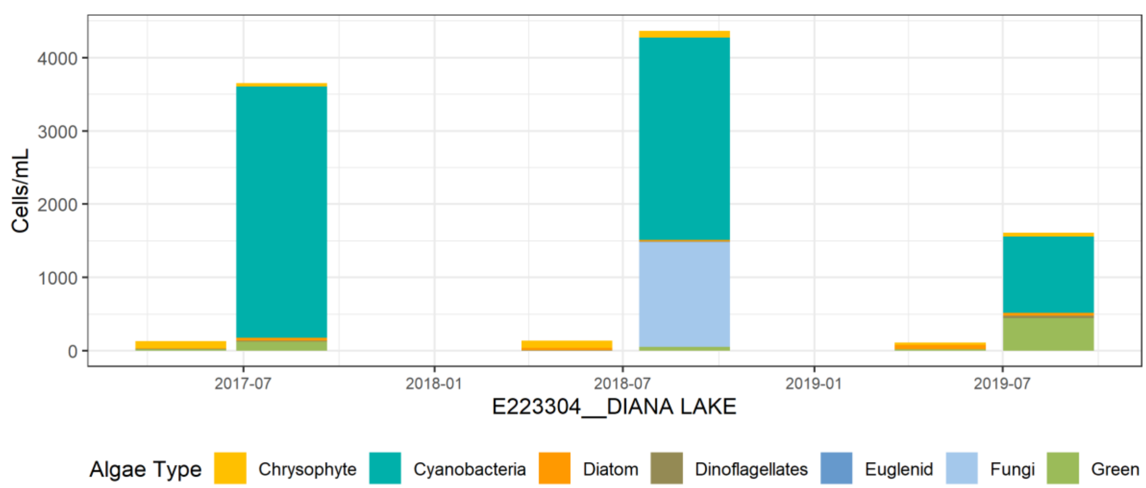
Cyanobacteria
Diatom
Dinoflagellates
Green


Cells/mL
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3000
2000
1000
0
2017-07
2018-01
2018-07
2019-01
2019-07
E223304__DIANA LAKE
Algae Type
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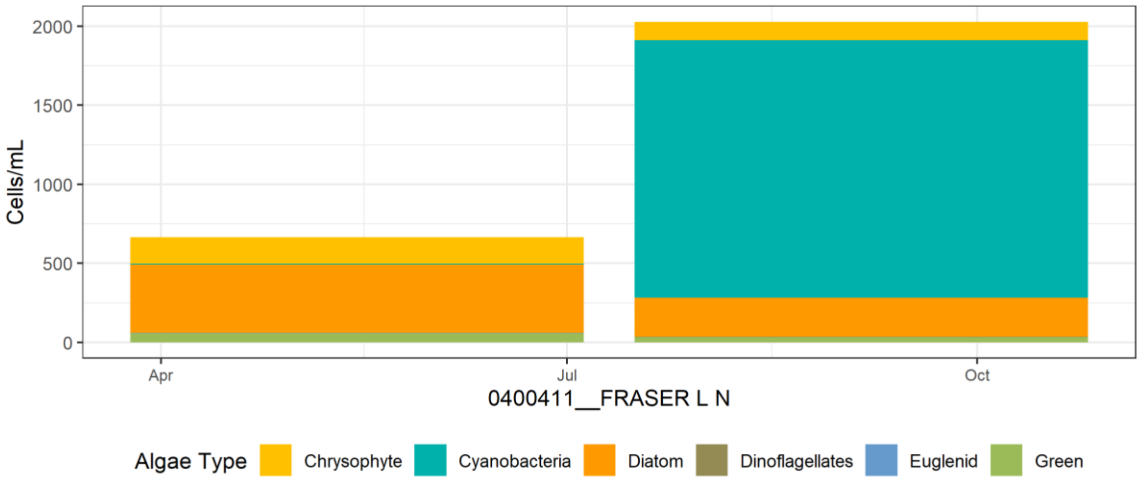
Cyanobacteria
Diatom
Dinoflagellates
Euglenid
Fungi
Green


Cells/mL
2000
1500
1000
500
0
Apr
Jul
Oct
0400411__FRASER L N
Algae Type
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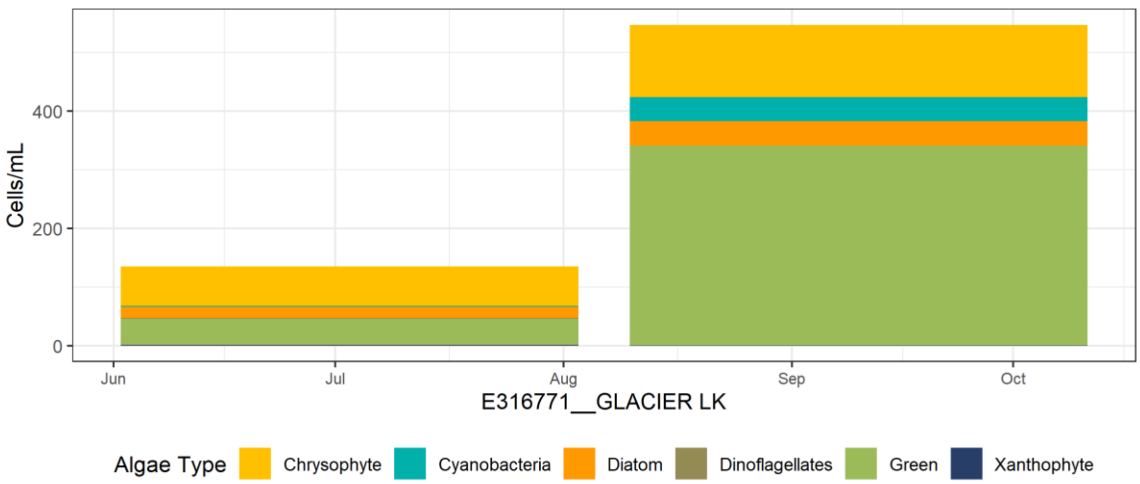
Cyanobacteria
Diatom
Dinoflagellates
Euglenid
Green


Cells/mL
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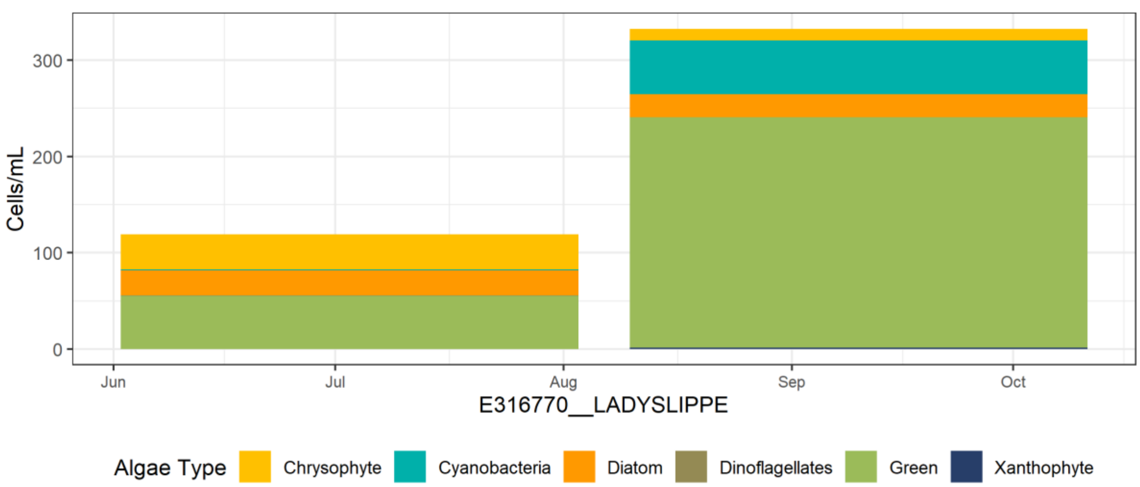
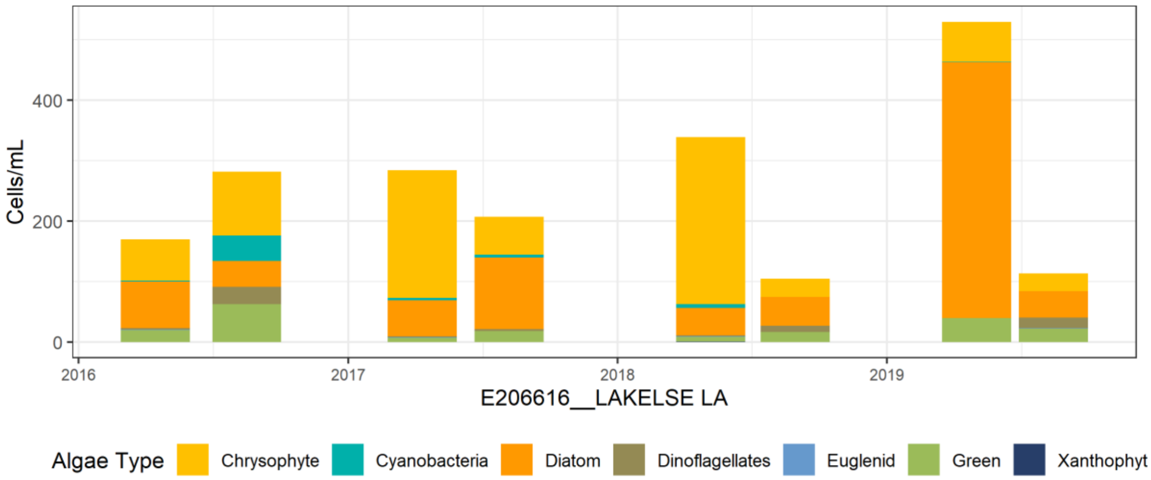
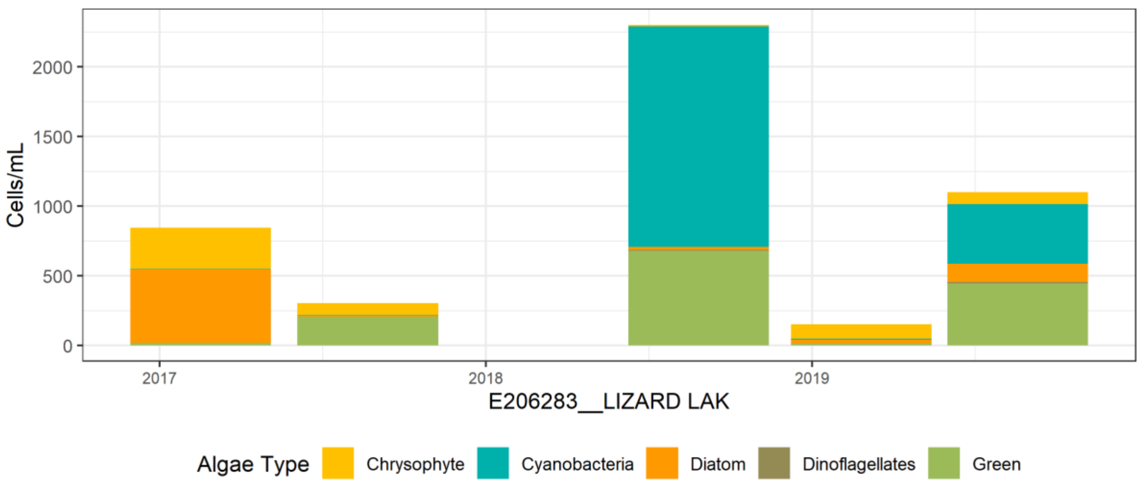
200
0
Jun
Jul
Aug
Sep
Oct
E316771__GLACIER LK
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Green
Xanthophyte

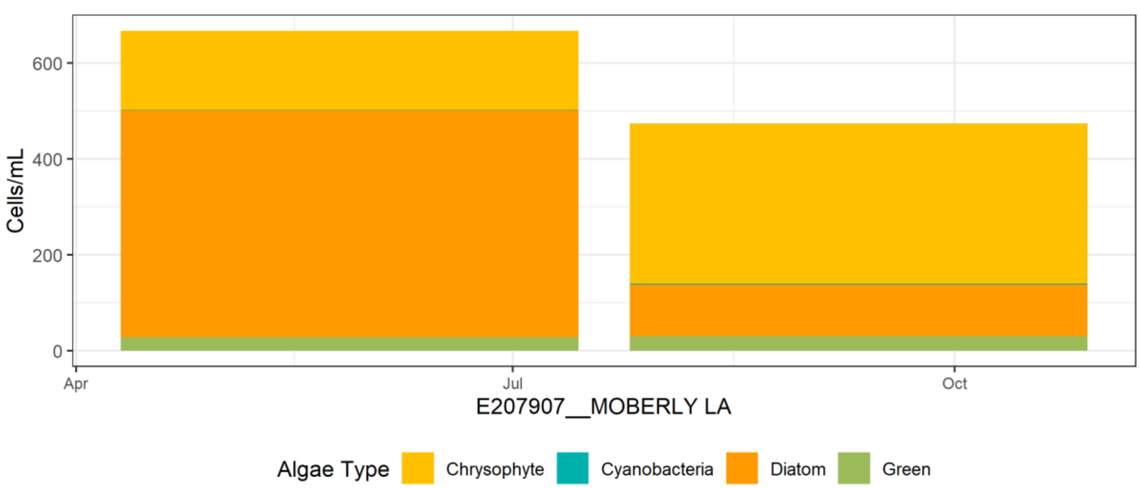

Cells/mL
300
200
100
0
Jun
Jul
Aug
Sep
Oct
E316770__LADYSLIPPE
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Green
Xanthophyte



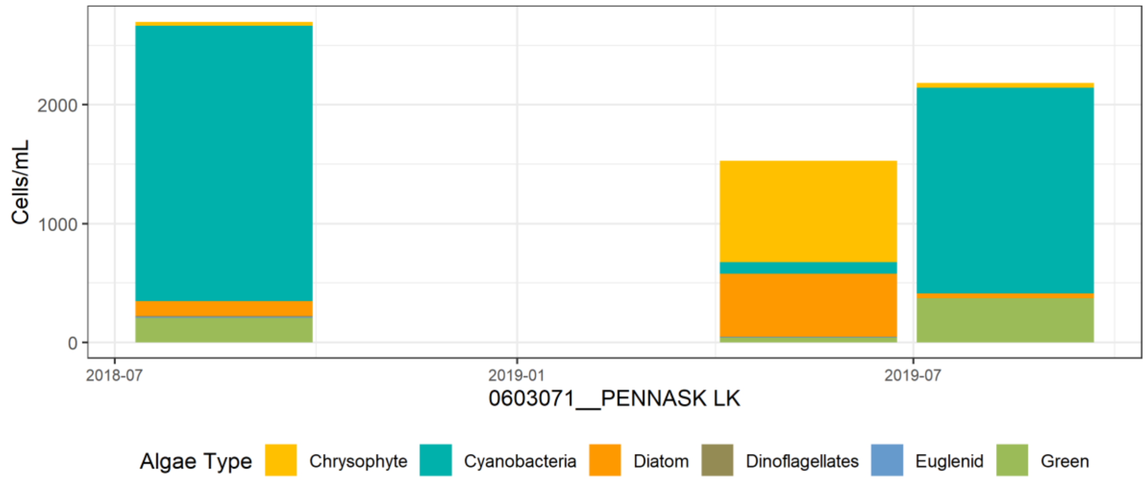
Cells/mL
400
200
0
2016
2017
2018
2019
E206616__LAKELSE LA
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Euglenid
Green
Xanthophyt



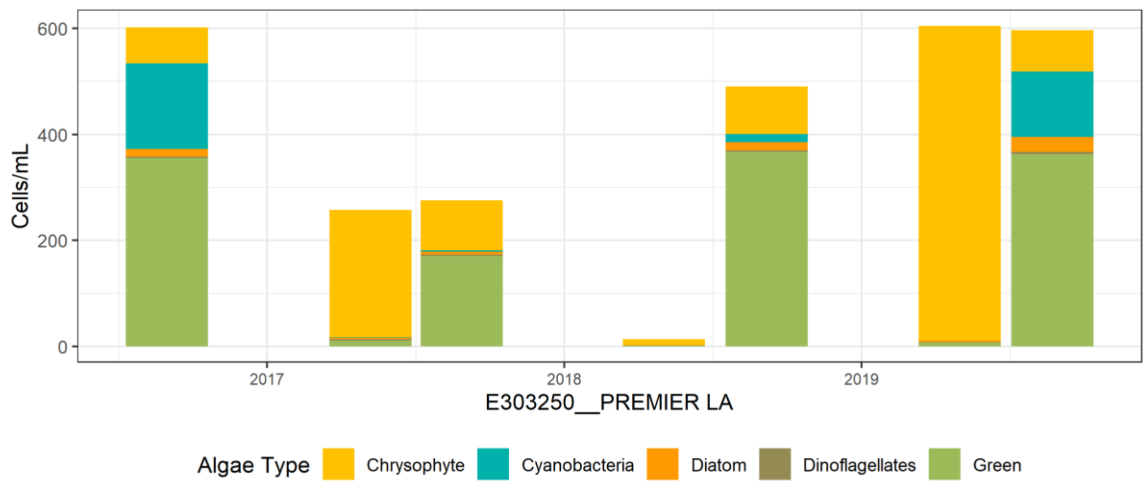
Cells/mL
2000
1500
1000
500
0
2017
2018
2019
E206283__LIZARD LAK
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Green



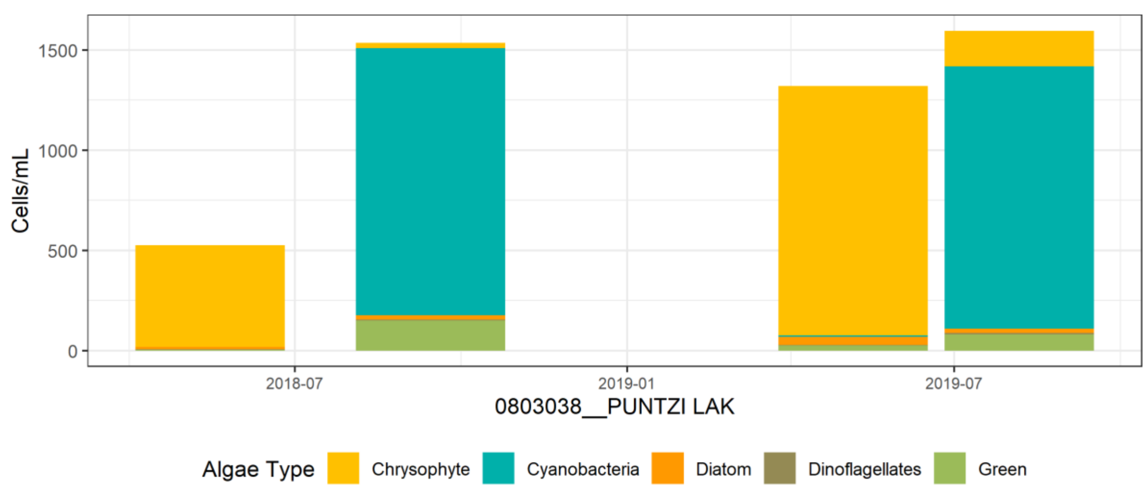
Cells/mL
600
400
200
0
Apr
Jul
Oct
E207907__MOBERLY LA
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Green



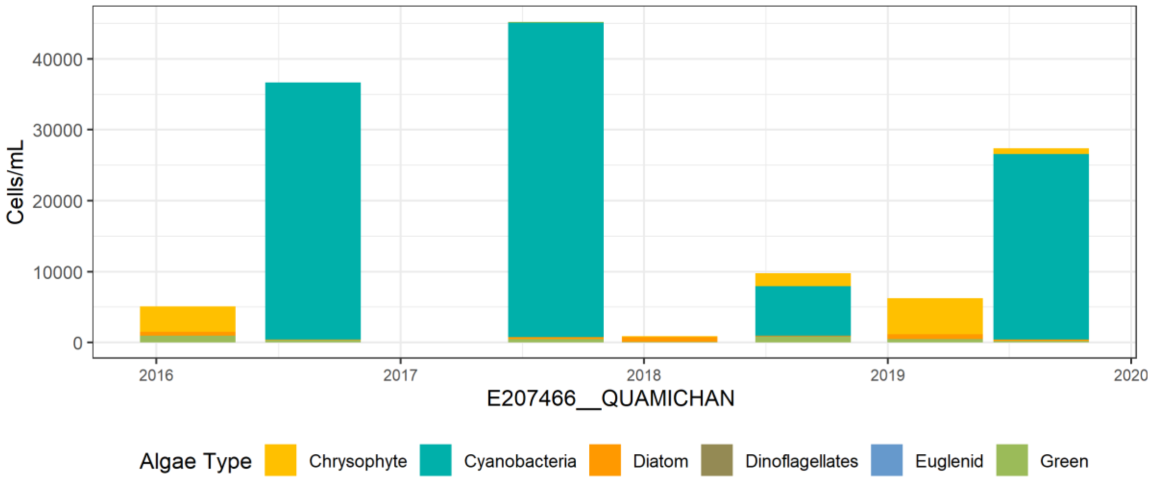
Cells/mL
2000
1000
0
2018-07
2019-01
2019-07
0603071__PENNASK LK
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Euglenid
Green

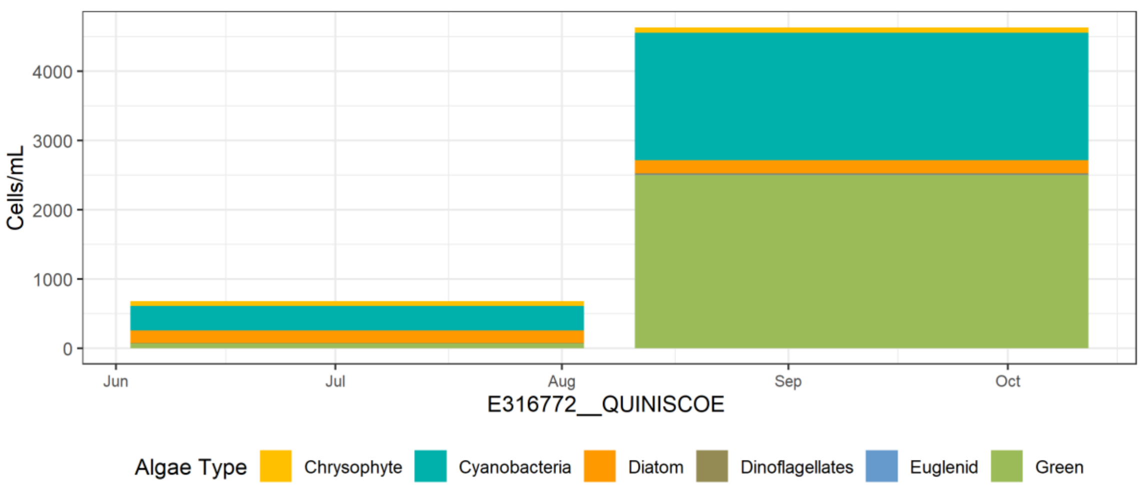


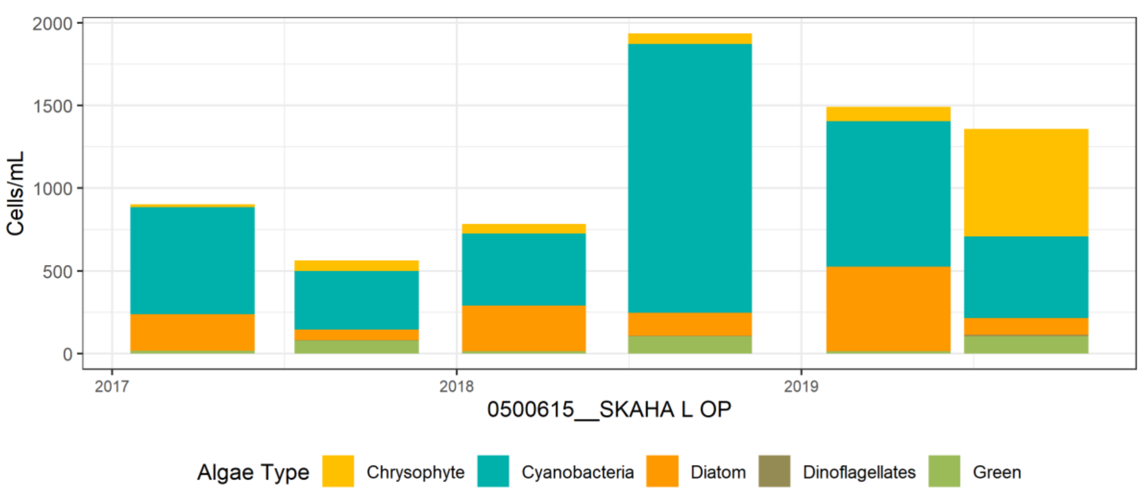
Cells/mL
600
400
200
0
2017
2018
2019
E303250__PREMIER LA
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Green

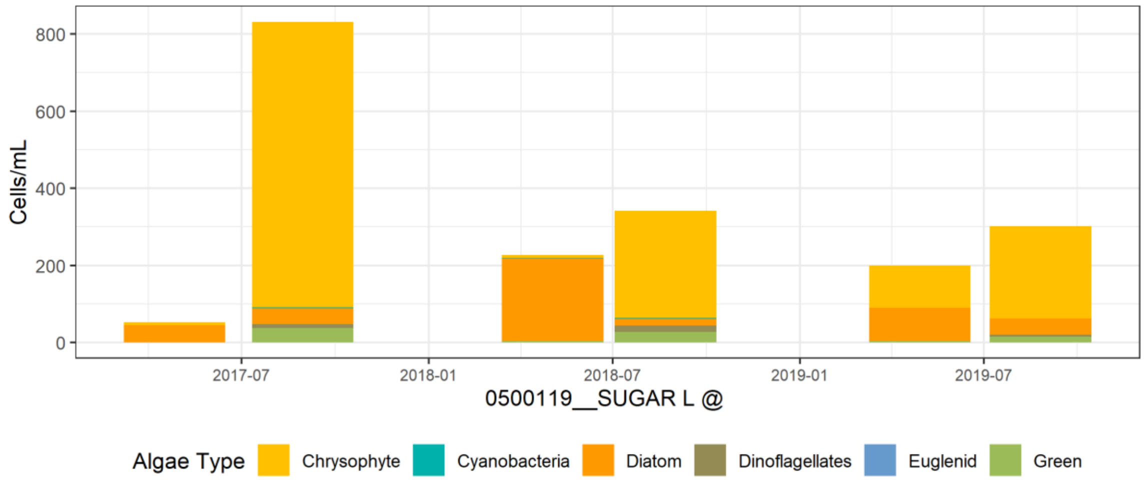


Cells/mL
1500
1000
500
0
2018-07
2019-01
2019-07
0803038__PUNTZI LAK
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Green

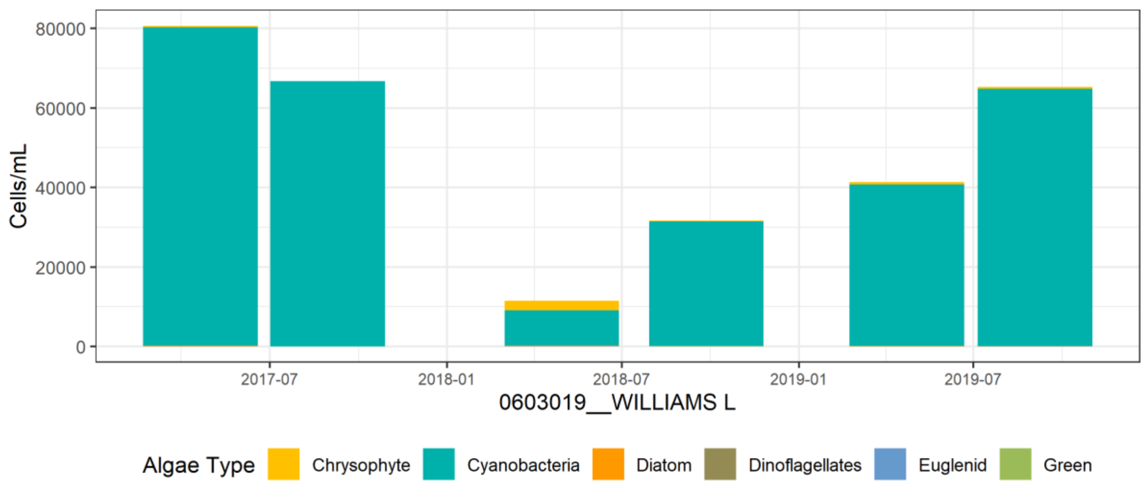

Cells/mL
40000
30000
20000
10000
0
2016
2017
2018
2019
2020
E207466__QUAMICHAN
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Euglenid
Green


Cells/mL
4000
3000
2000
1000
0
Jun
Jul
Aug
Sep
Oct
E316772__QUINISCOE
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Euglenid
Green


Cells/mL
2000
1500
1000
500
0
2017
2018
2019
0500615__SKAHA L OP
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Green

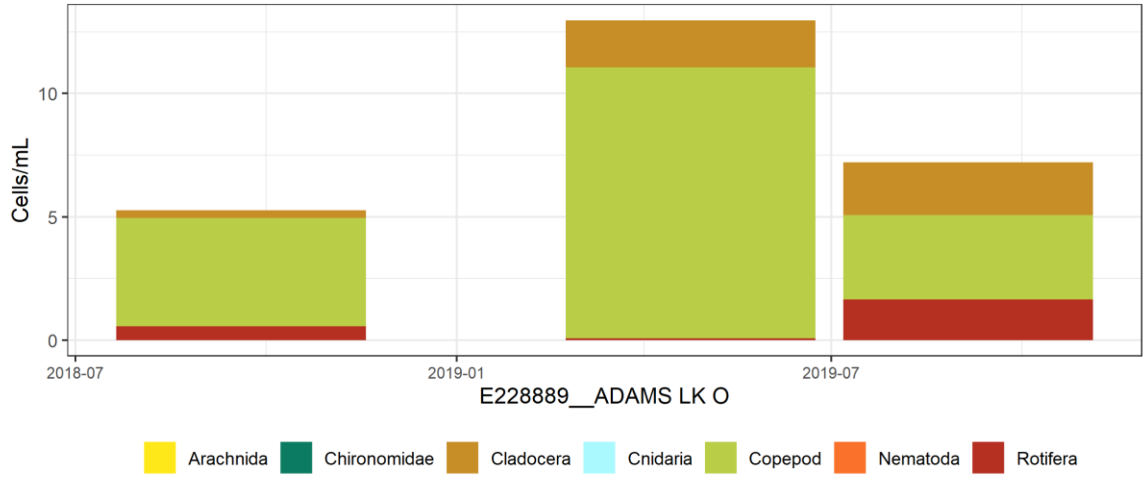


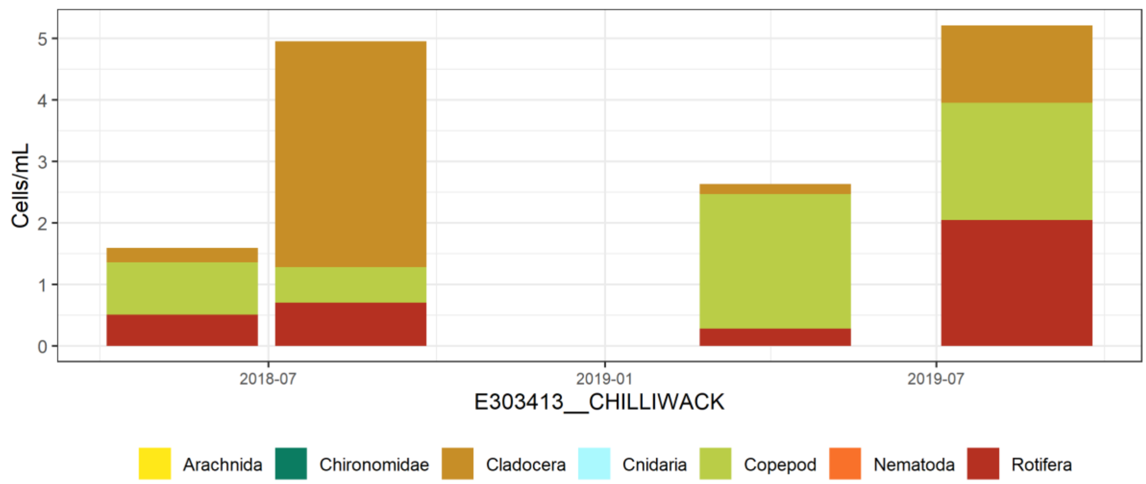
Cells/mL
800
600
400
200
0
2017-07
2018-01
2018-07
2019-01
2019-07
0500119__SUGAR L @
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Euglenid
Green

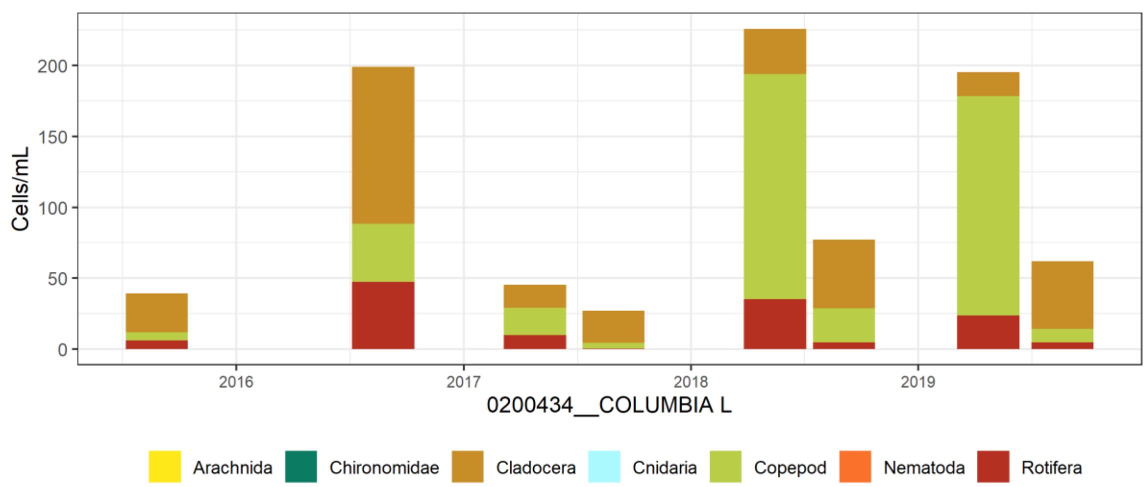


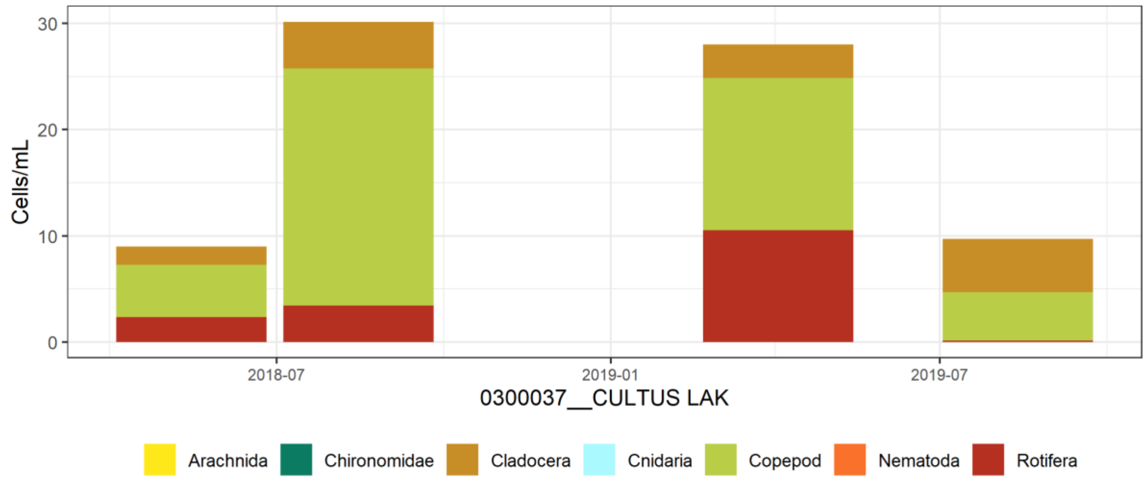
Cells/mL
80000
60000
40000
20000
0
2017-07
2018-01
2018-07
2019-01
2019-07
0603019__WILLIAMS L
Algae Type
Chrysophyte
Cyanobacteria
Diatom
Dinoflagellates
Euglenid
Green

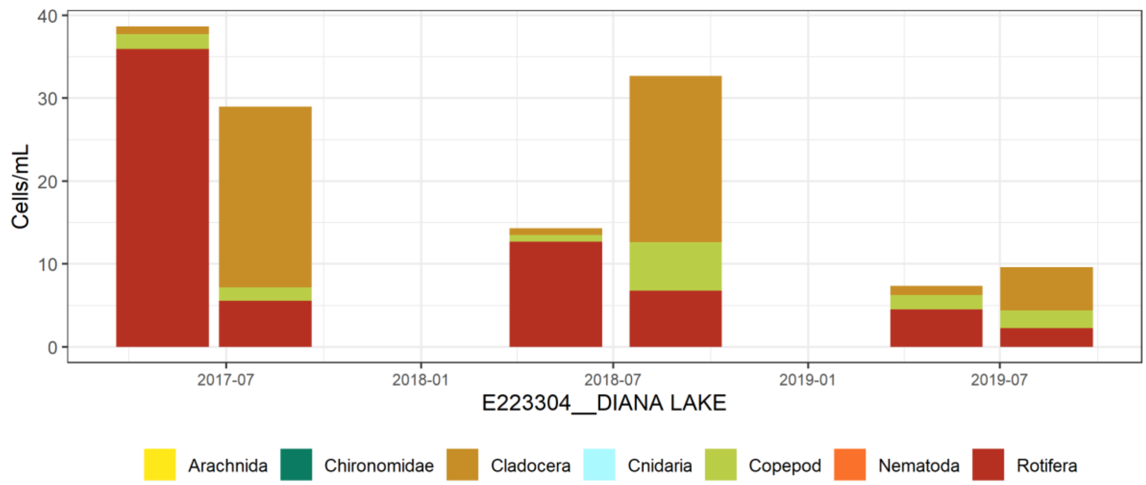
Zooplankton

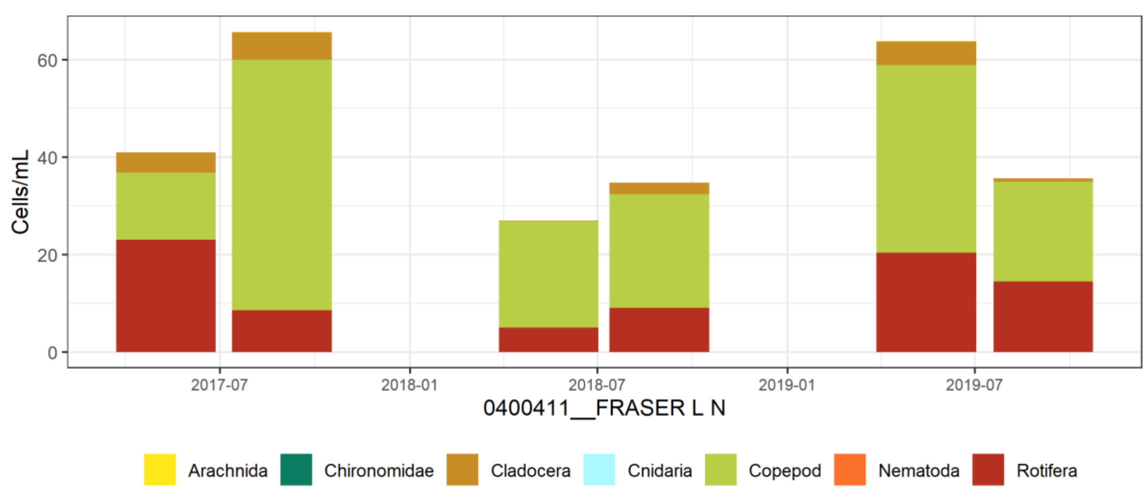


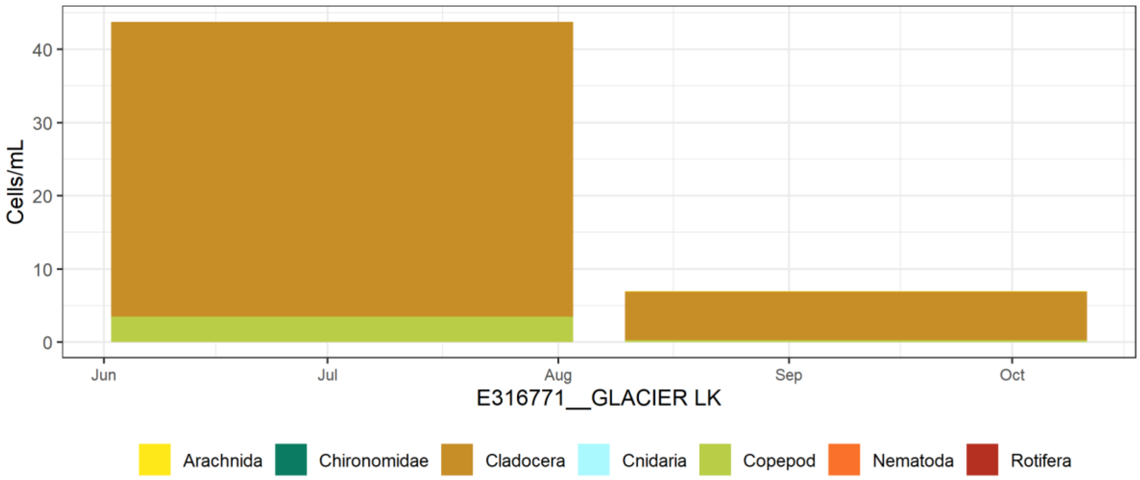


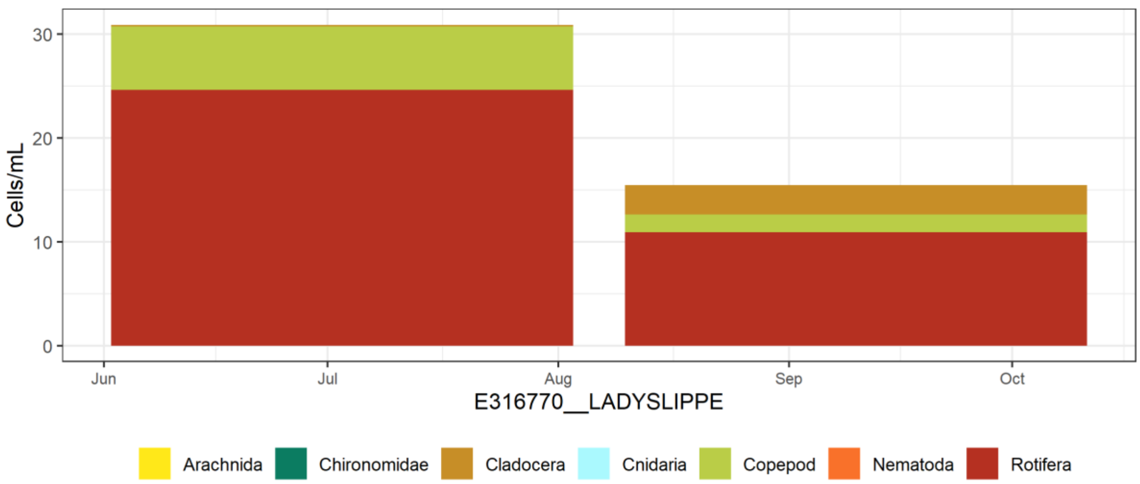


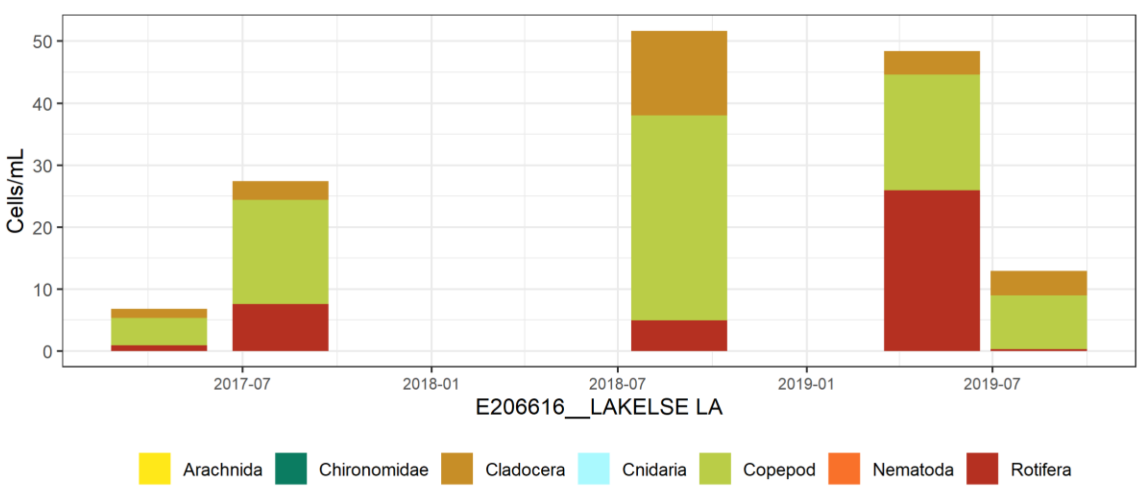

30
20
10
0
Cells/mL
2018-07
2019-01
2019-07
0300037__CULTUS LAK
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera

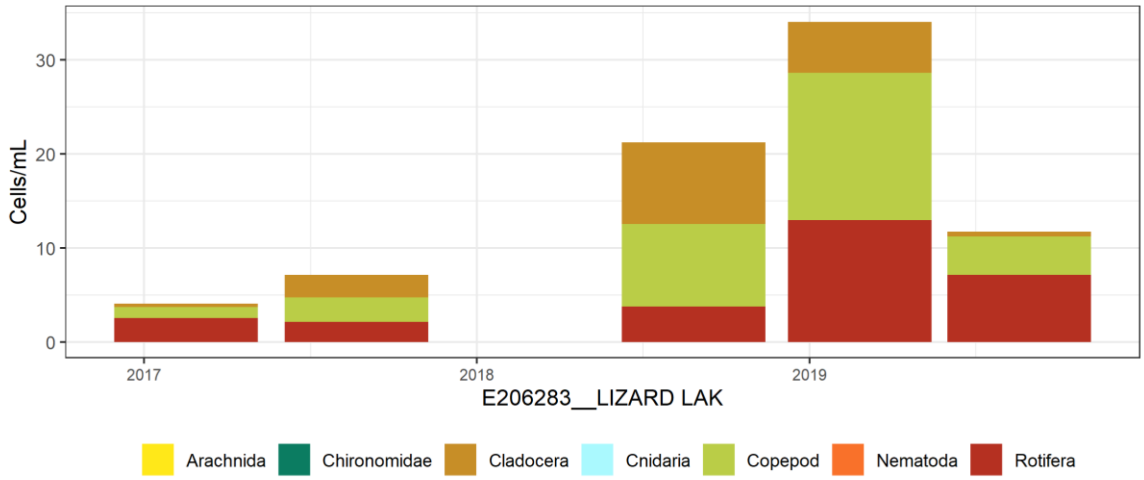

40
30
20
10
0
Cells/mL
2017-07
2018-01
2018-07
2019-01
2019-07
E223304__DIANA LAKE
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera

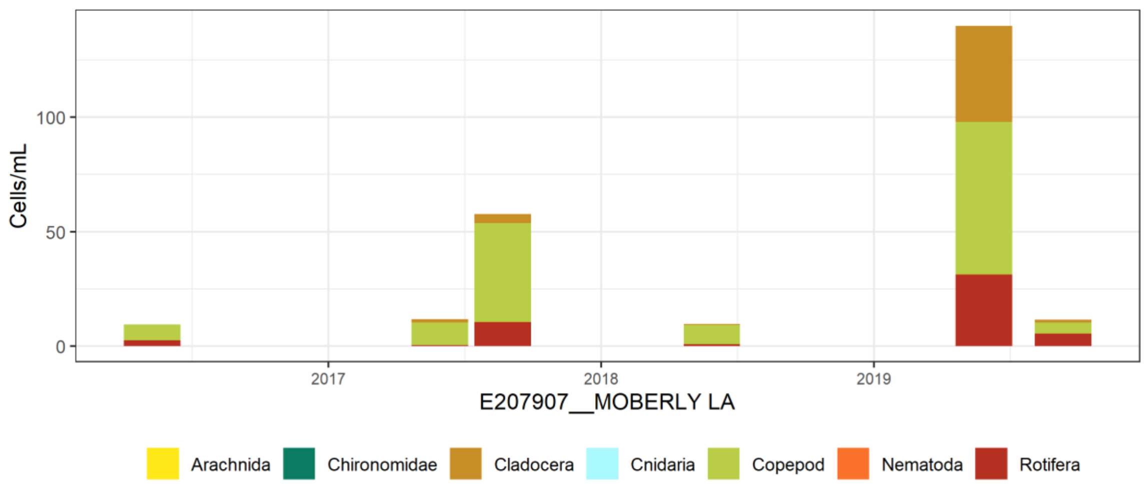

60
40
20
0
Cells/mL
2017-07
2018-01
2018-07
2019-01
2019-07
0400411__FRASER L N
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera

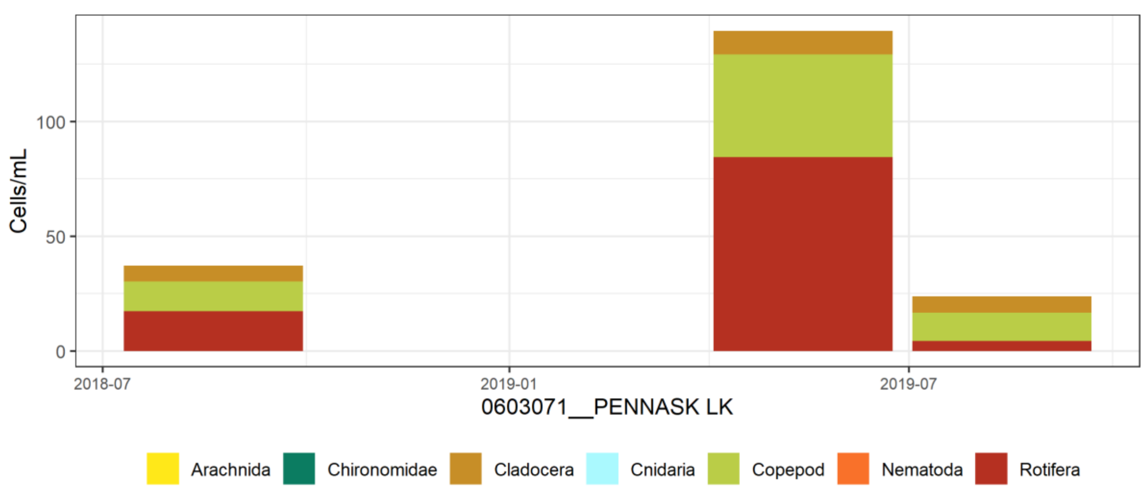

Cells/mL
40
30
20
10
0
Jun
Jul
Aug
Sep
Oct
E316771__GLACIER LK
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera

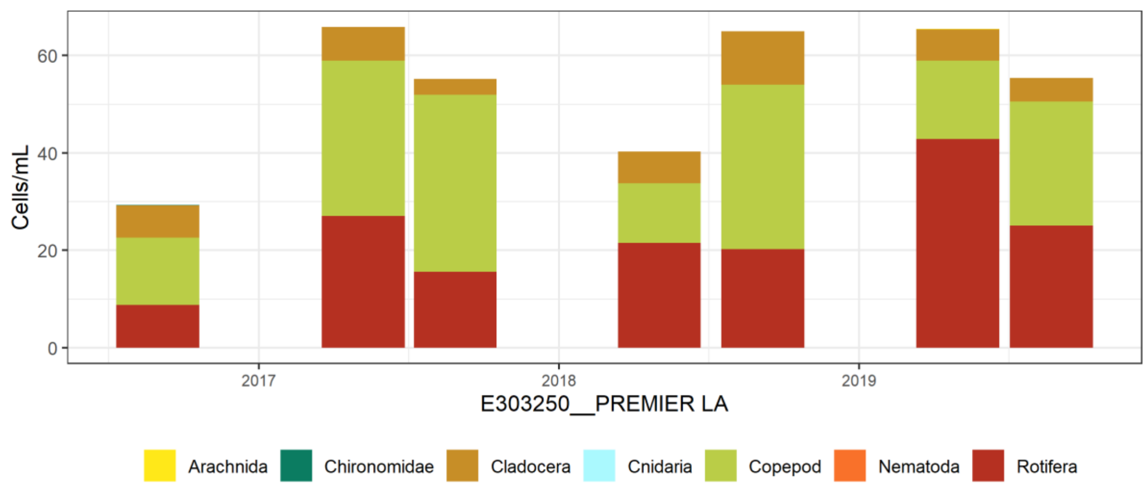

Cells/mL
30
20
10
0
Jun
Jul
Aug
Sep
Oct
E316770__LADYSLIPPE
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera


Cells/mL
50
40
30
20
10
0
2017-07
2018-01
2018-07
2019-01
2019-07
E206616__LAKELSE LA
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera

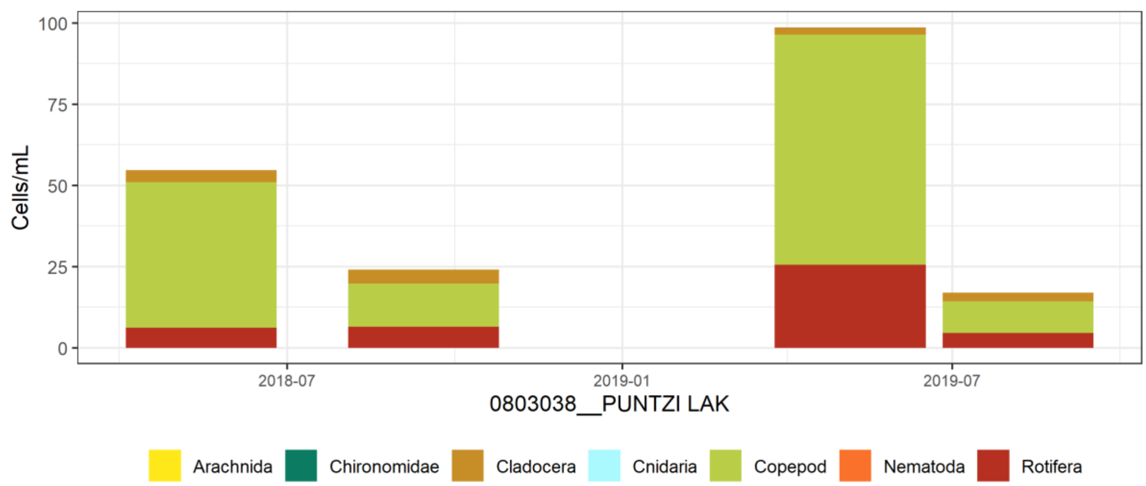

Cells/mL
30
20
10
0
2017
2018
2019
E206283__LIZARD LAK
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera


Cells/mL
100
50
0
2017
2018
2019
E207907__MOBERLY LA
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera

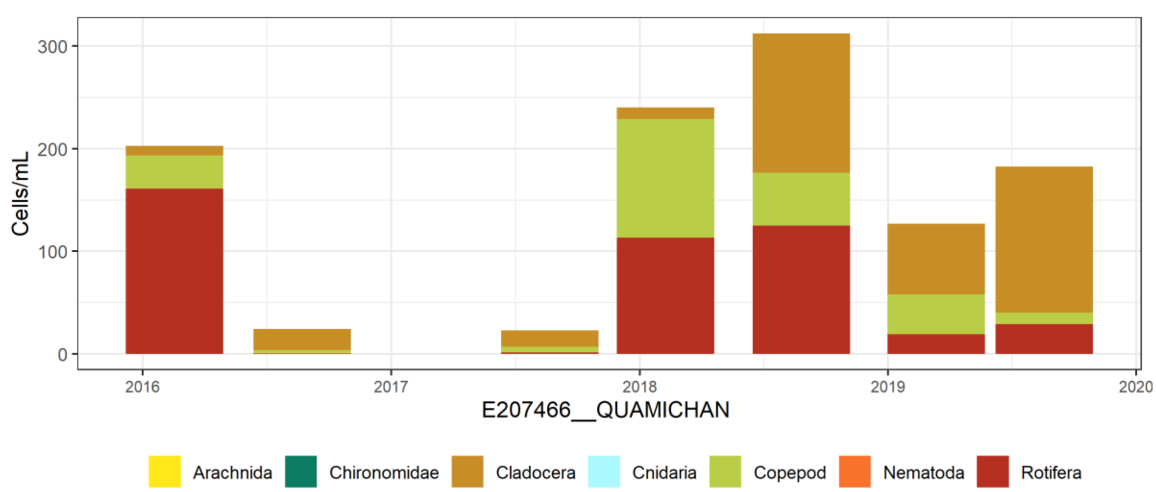

Cells/mL
100
50
0
2018-07
2019-01
2019-07
0603071__PENNASK LK
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera



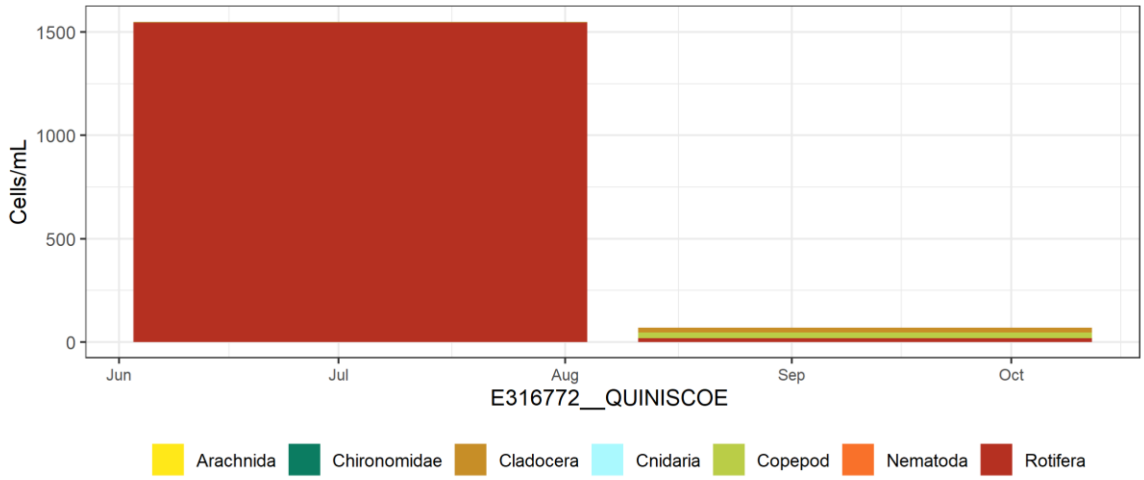
Cells/mL
60
40
20
0
2017
2018
2019
E303250__PREMIER LA
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera

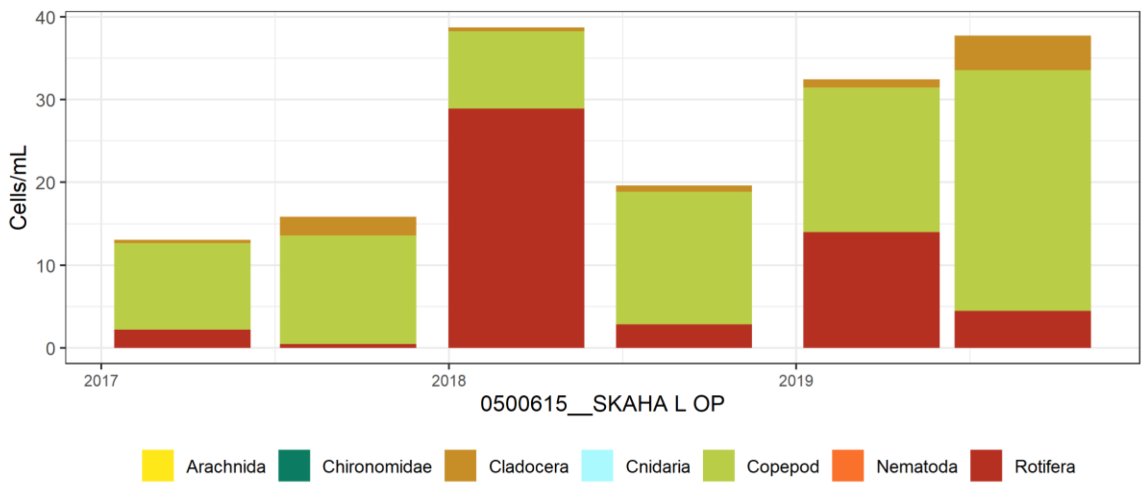


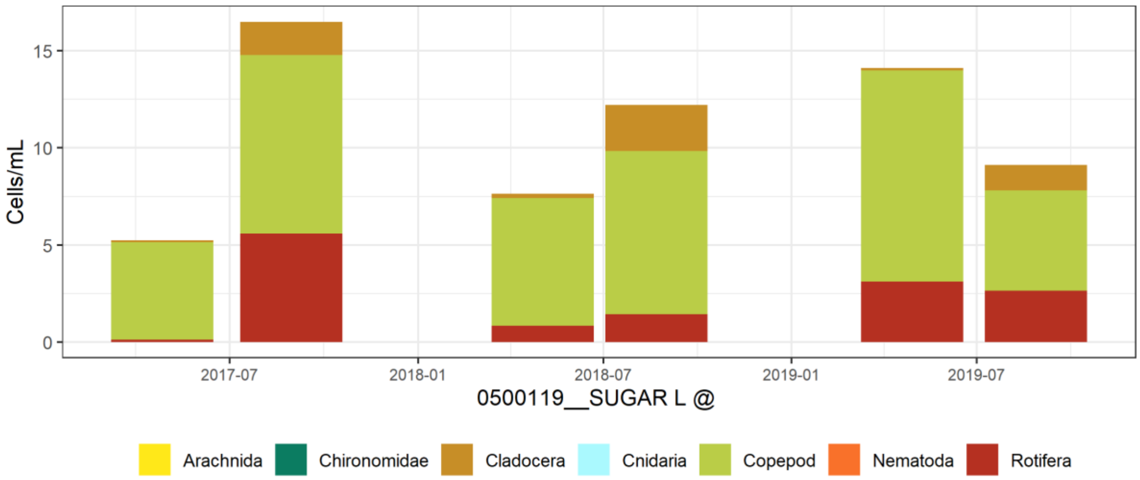
Cells/mL
100
75
50
25
0
2018-07
2019-01
2019-07
0803038__PUNTZI LAK
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera



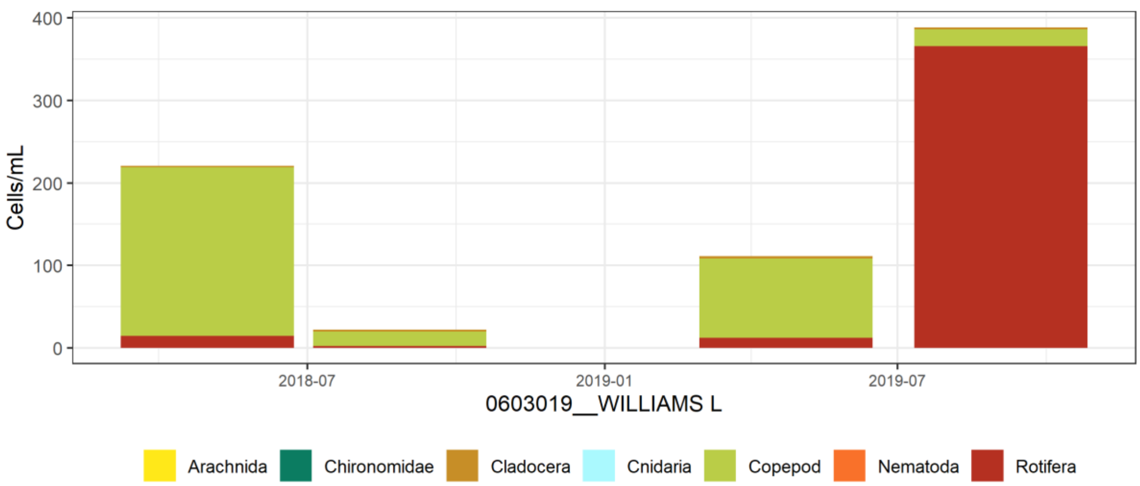
Cells/mL
300
200
100
0
2016
2017
2018
2019
2020
E207466__QUAMICHAN
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera


1500
1000
500
0
Cells/mL
Jun
Jul
Aug
Sep
Oct
E316772__QUINISCOE
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera


40
30
20
10
0
Cells/mL
2017
2018
2019
0500615__SKAHA L OP
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera



Cells/mL
15
10
5
0
2017-07
2018-01
2018-07
2019-01
2019-07
0500119__SUGAR L @
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera



Cells/mL
400
300
200
100
0
2018-07
2019-01
2019-07
0603019__WILLIAMS L
Arachnida
Chironomidae
Cladocera
Cnidaria
Copepod
Nematoda
Rotifera

Appendix 4: Comparison of Community Composition at Different Taxonomic Levels

List of Figures in this appendix

The current monitoring program utilizes a highest possible taxonomic resolution approach with diatoms identified to sub-species when possible. While having these data available is potentially valuable, we have reviewed whether there could be a benefit to reducing taxonomic identification to genus level and passing the cost savings to other aspects of the program such as increased number of samples or greater analysis.

Non-metric multidimensional scaling (NMDS) analysis was conducted on the taxonomic data as it was on the chemistry data. These analyses compare how the different lakes plot relative to one another at different taxonomic levels with the goal of determining if additional analytical value was being obtained from very precise identification or if less precise identification would provide equal analytical value at less cost. NMDS ranks the relative importance of each taxa to each lake and compresses multiple dimensions of variation into two such that the lakes will be plotted adjacent to the taxa that best explained the variation at that site. If the sites move positions relative to each other on the graph when analyzed at different taxonomic levels, we can interpret this as meaning that moving up the taxonomic levels is changing the interpretation of community composition and therefore information is being lost.

The analyses revealed that there was little change in lake position relative to taxa when changing taxonomic resolution between the lowest taxonomic level (species but in a handful of cases, variety) and up to the high level taxonomic groups at most sites during 2019[8]. Figure A4- 1 to Figure A4- 4 illustrate this by connecting the results of NMDS at different levels by a dashed gray line; short line segments between points indicate little change in NMDS results when comparing the taxonomic levels while long line segments indicate changes that could affect the interpretation of results, i.e. information may be being lost.

Most sites clustered together at the different levels with very short line segments (Figure A4- 9) but some sites did shift in meaningful ways. These include: Columbia Lake (Figure A4- 5), Skaha Lake (Figure A4- 6), Lizard Lake (Figure A4- 7), Quamichan Lake (Figure A4- 8), Diana Lake (Figure A4- 9), and Quiniscoe Lake (Figure A4- 10). At Columbia, Skaha, and Diana lakes, it was the high level taxa results that were most different while Lizard, Quamichan, Quiniscoe it was the species level that was most different.

These results therefore indicate that there would be a loss of information as a result of reducing taxonomic identification from the current program of lowest taxonomic level to a higher level. The loss of information by moving from species to genus level identification would be small for most sites. Species level identification allows enumeration of pollution tolerant and pollution sensitive species of the same genus. It is recommended that the current system be maintained.

[8] 2019 was chosen because it had the largest number of lake/sample combinations. New lakes were added each year and earlier years had many fewer lakes. For example, only Columbia Lake had taxonomic data in 2015.

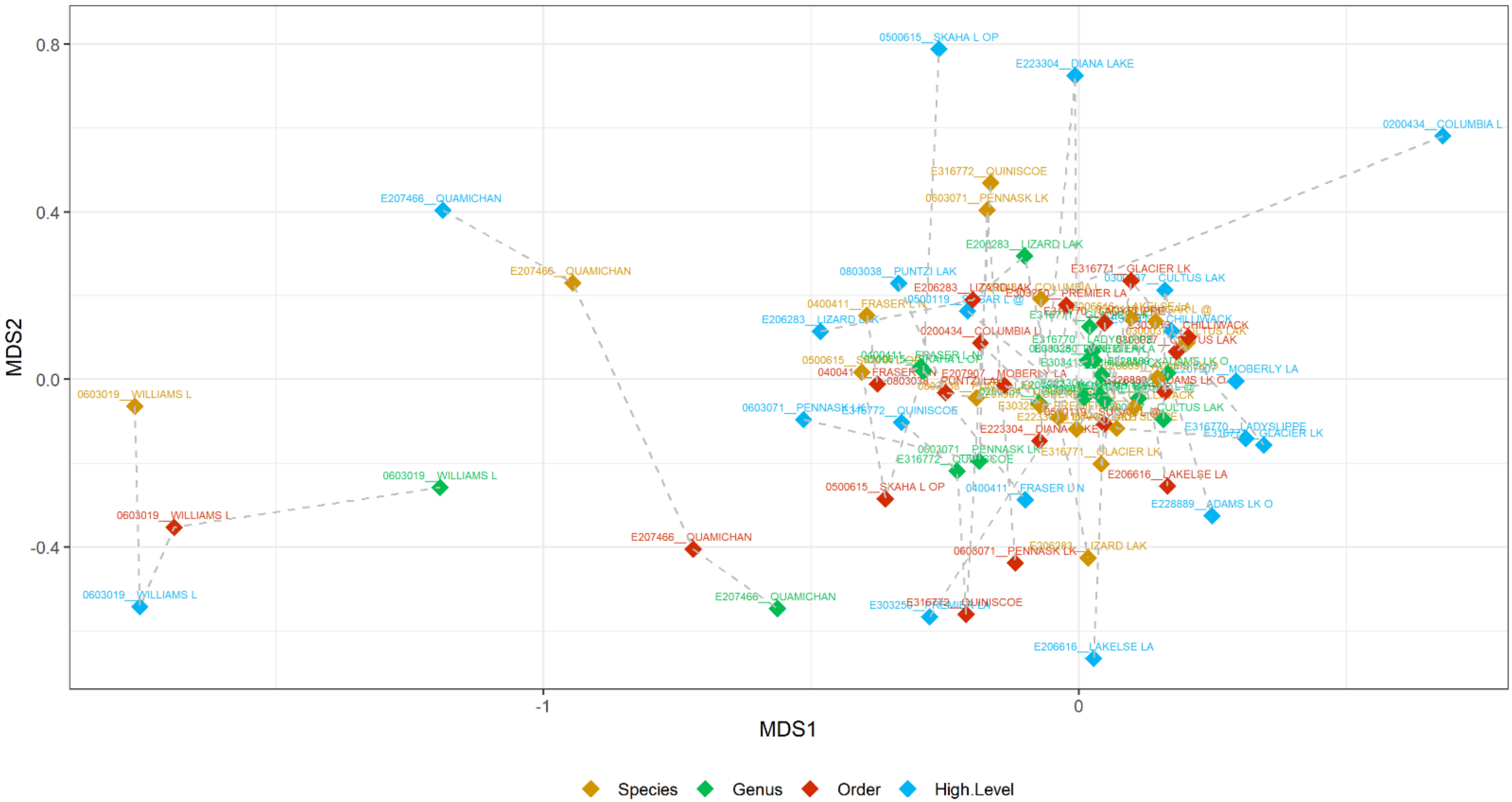


Figure A4- 1: Comparison of NMDS results at different taxonomic levels across all sites

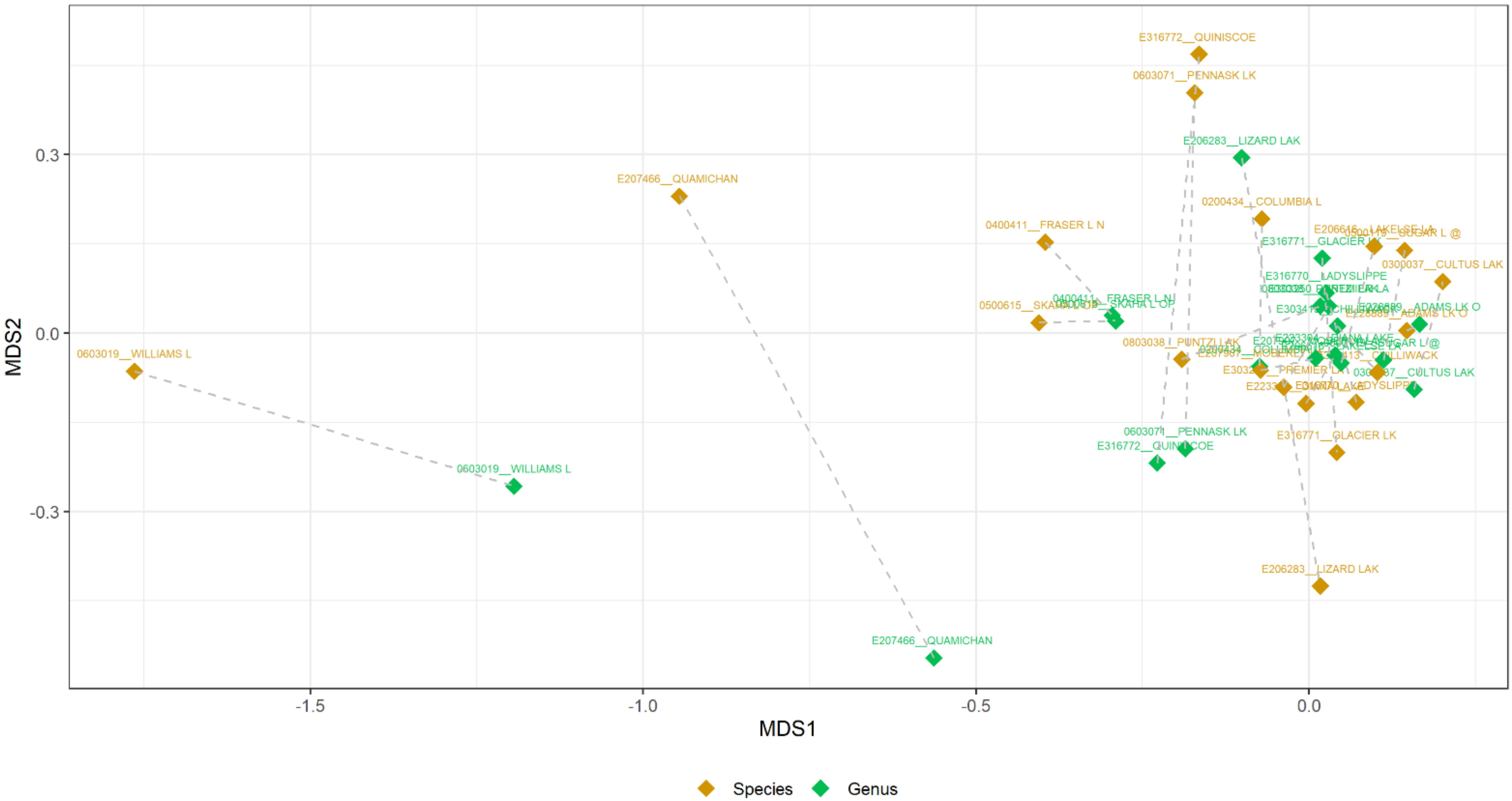


Figure A4- 2: Comparison of NMDS results at species and genus levels across all sites

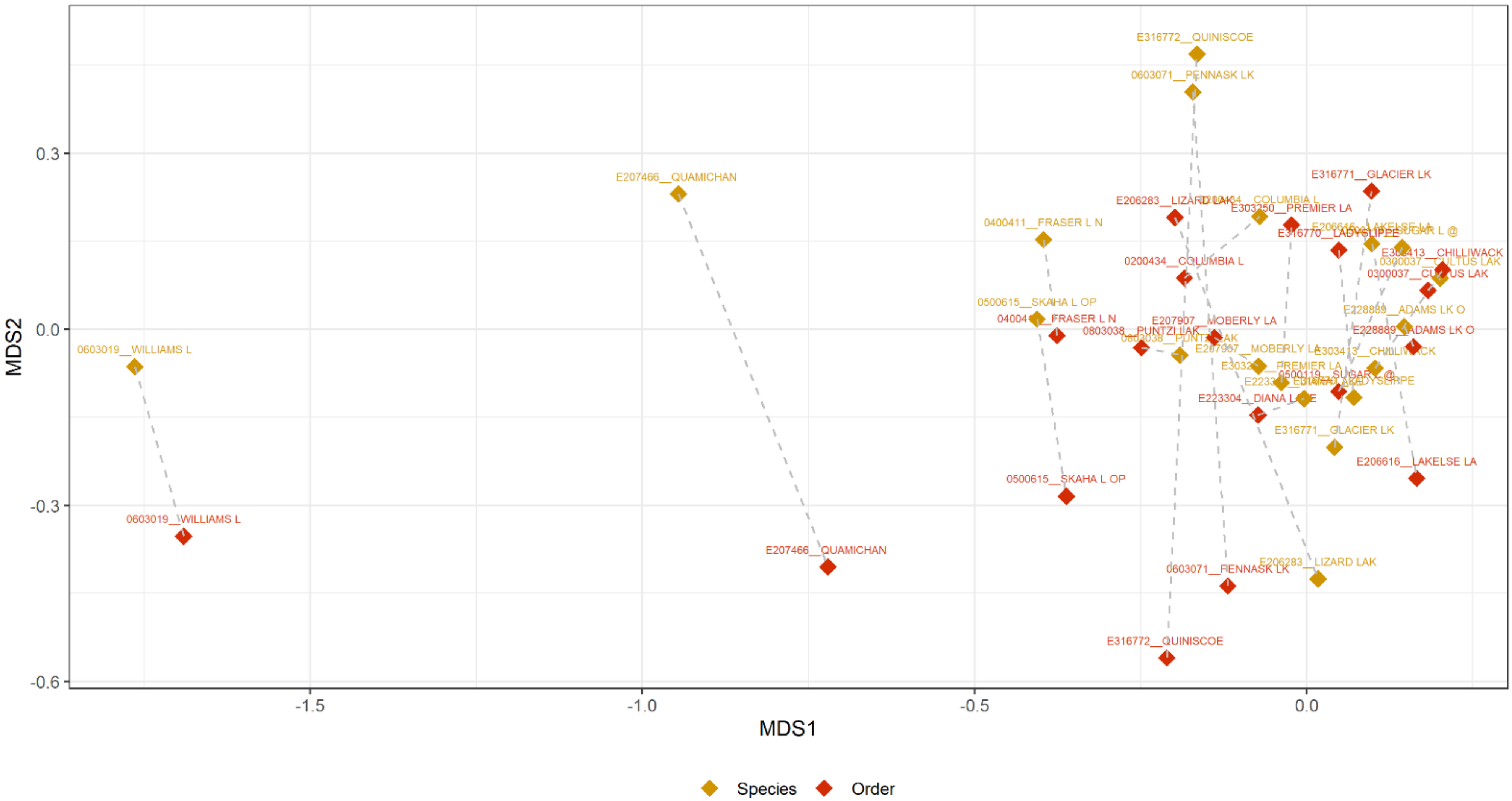


Figure A4- 3: Comparison of NMDS results at species and order levels across all sites

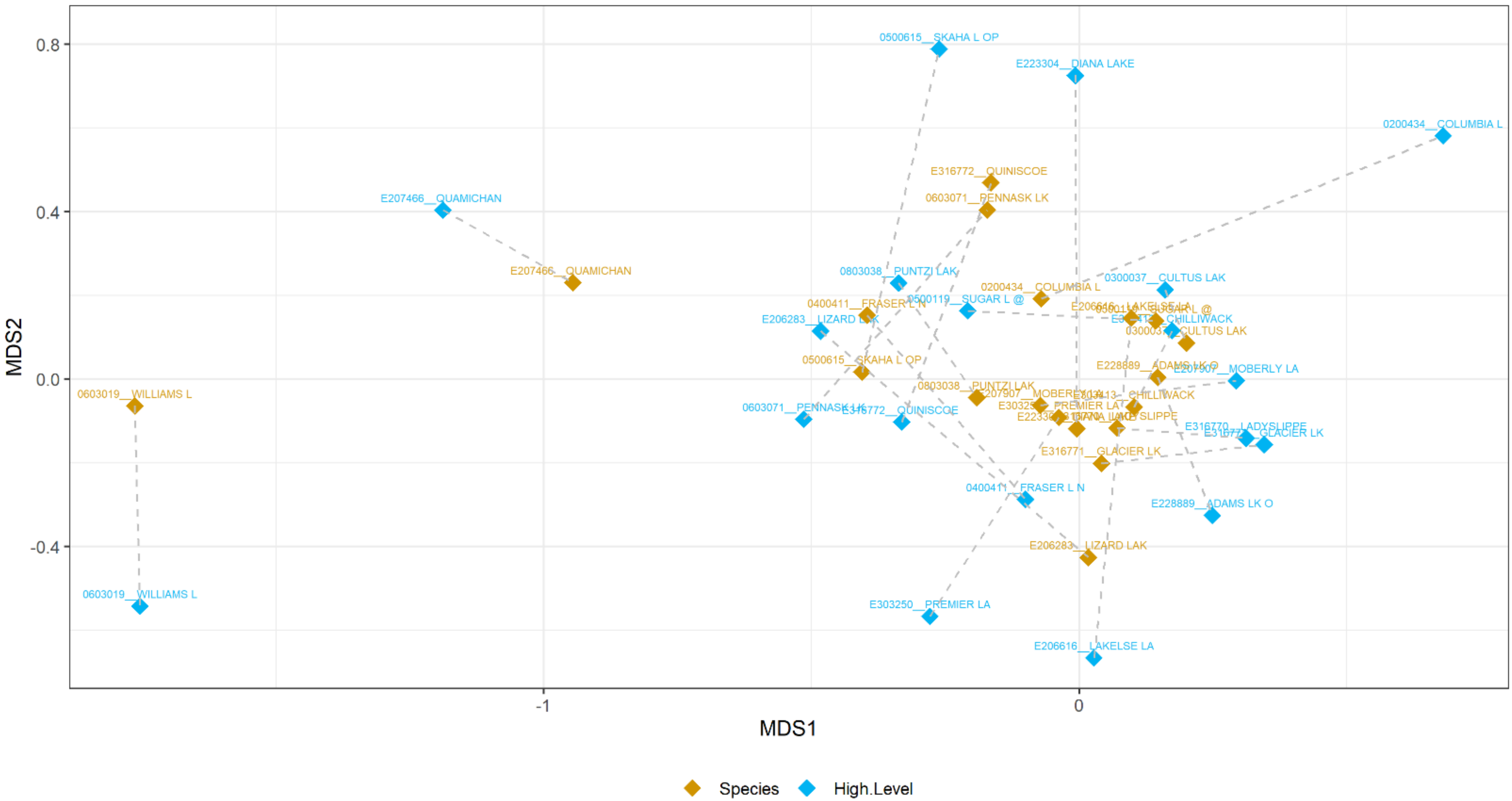


Figure A4- 4: Comparison of NMDS results at species and high level taxonomic groups

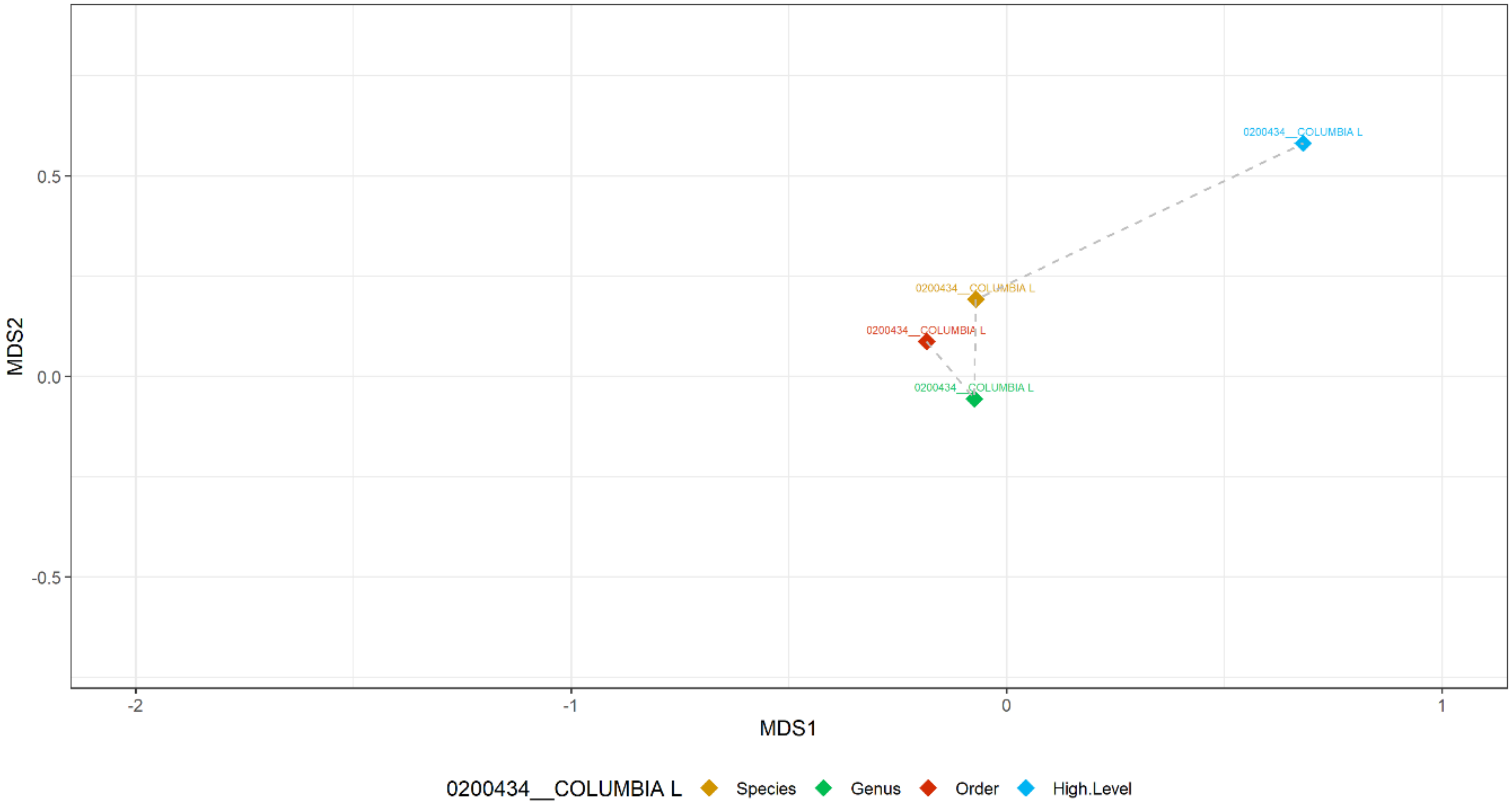


Figure A4- 5: Comparison of NMDS results at species and high level taxonomic groups for Columbia Lake

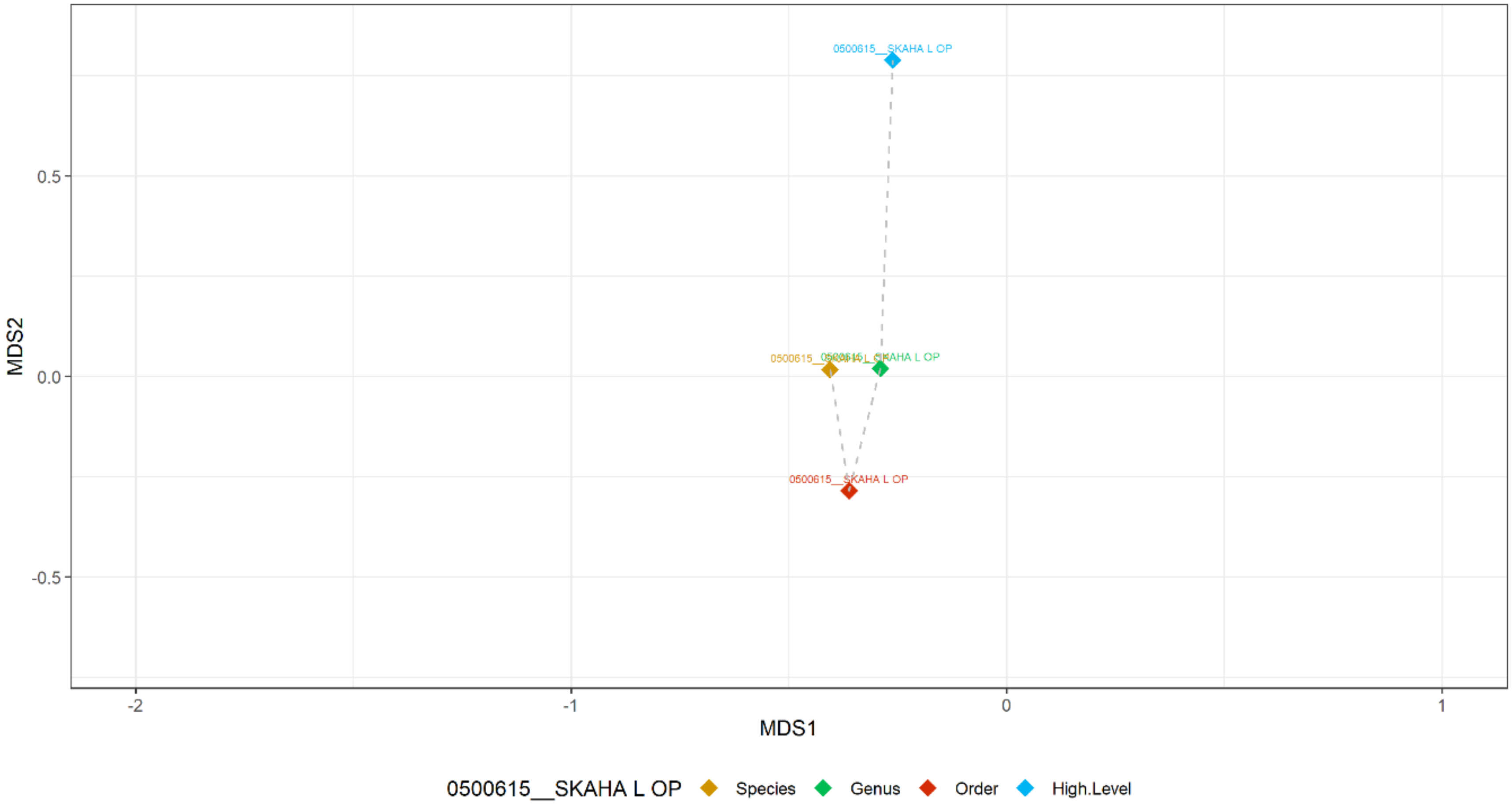


Figure A4- 6: Comparison of NMDS results at species and high level taxonomic groups for Skaha Lake

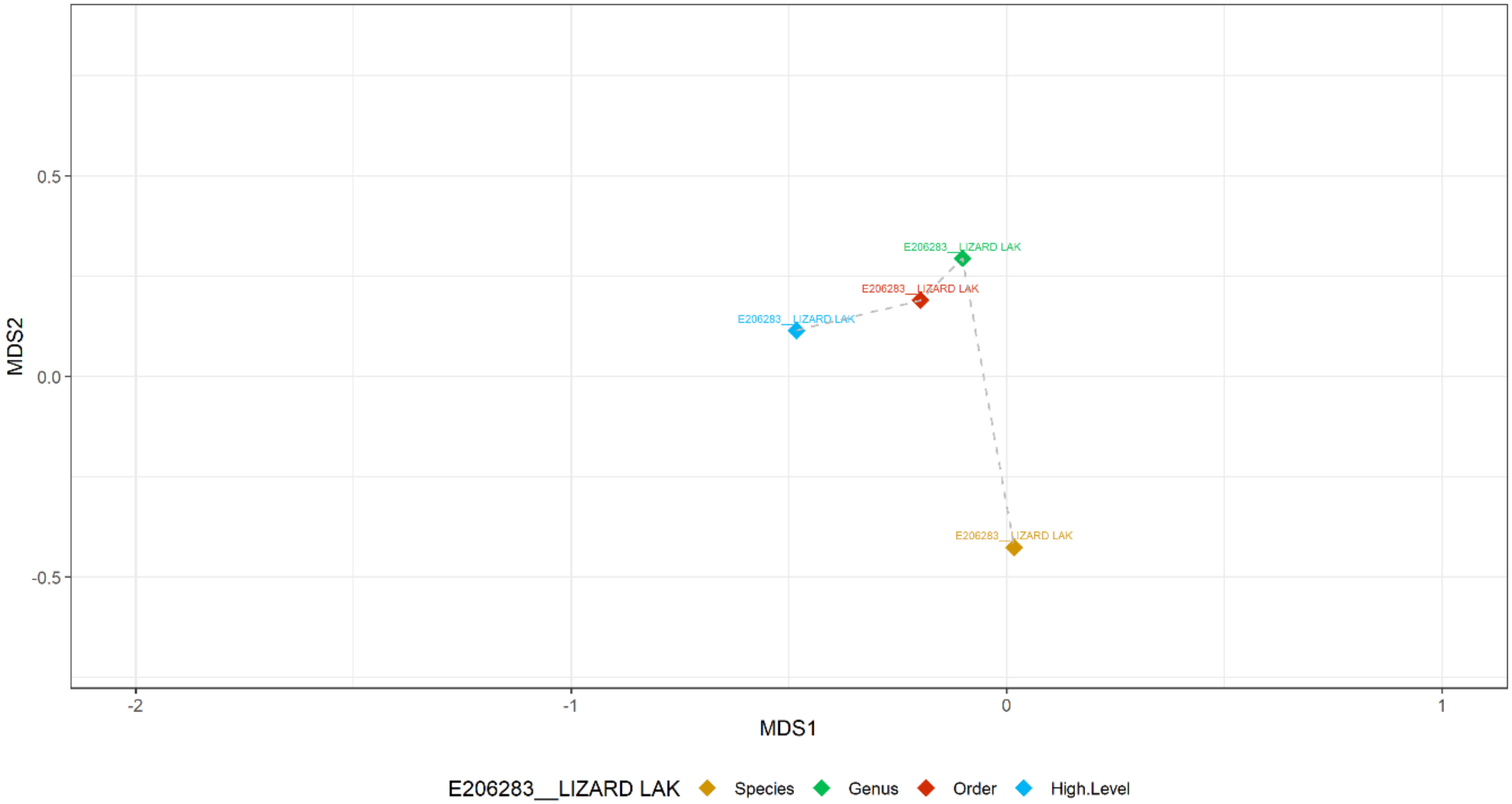


Figure A4- 7: Comparison of NMDS results at species and high level taxonomic groups for Lizard Lake

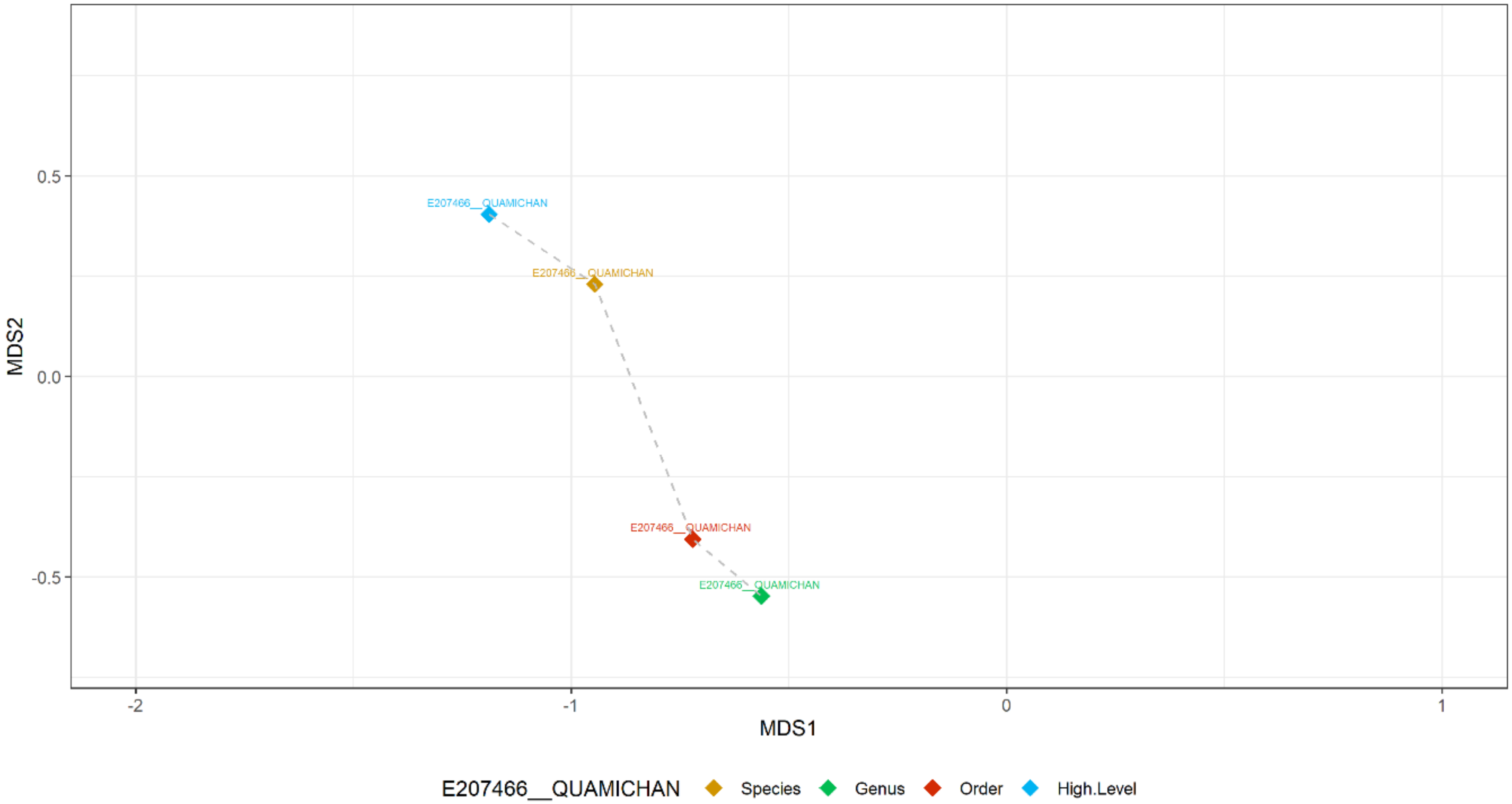


Figure A4- 8: Comparison of NMDS results at species and high level taxonomic groups for Quamichan Lake

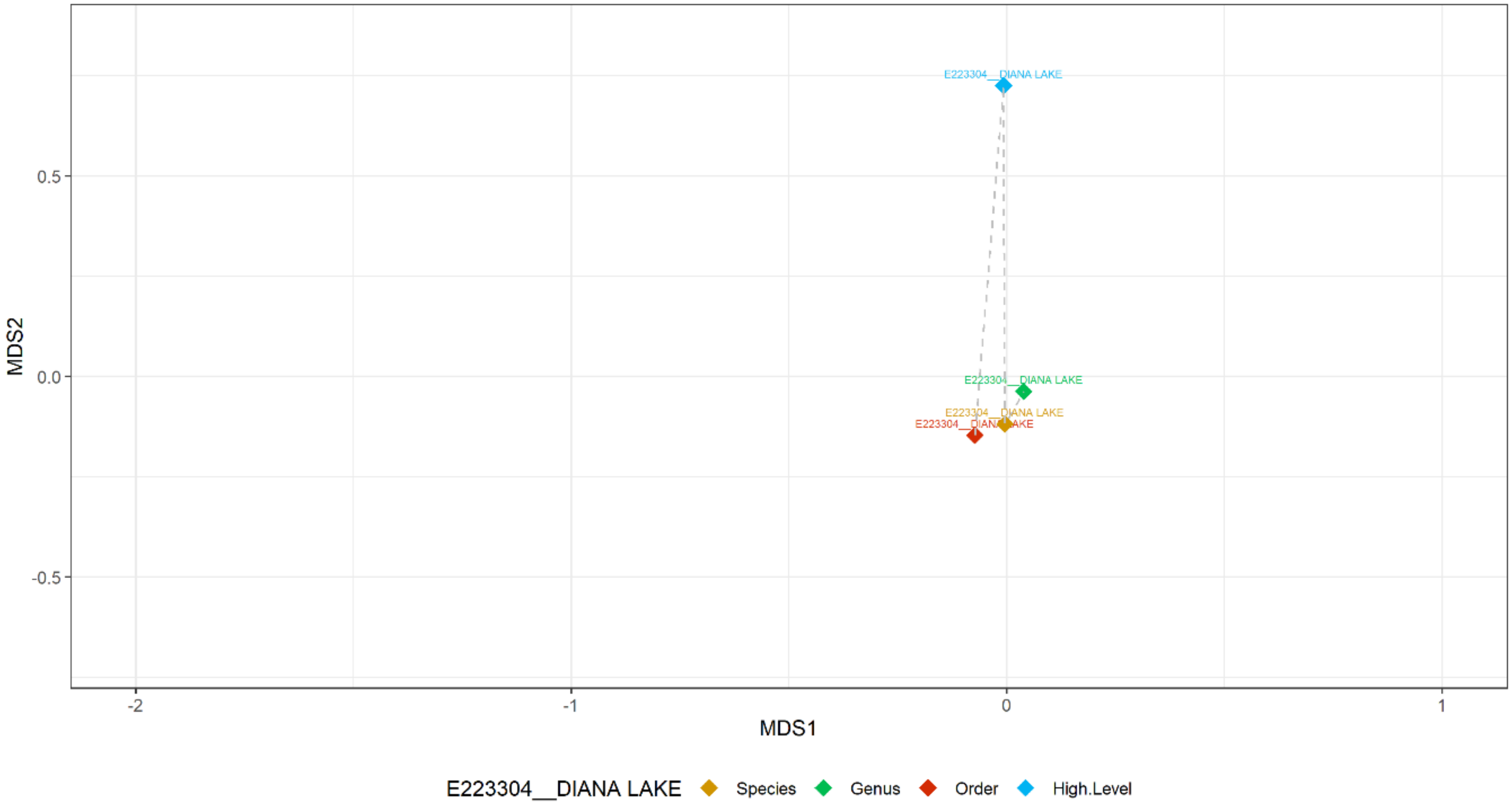


Figure A4- 9: Comparison of NMDS results at species and high level taxonomic groups for Diana Lake

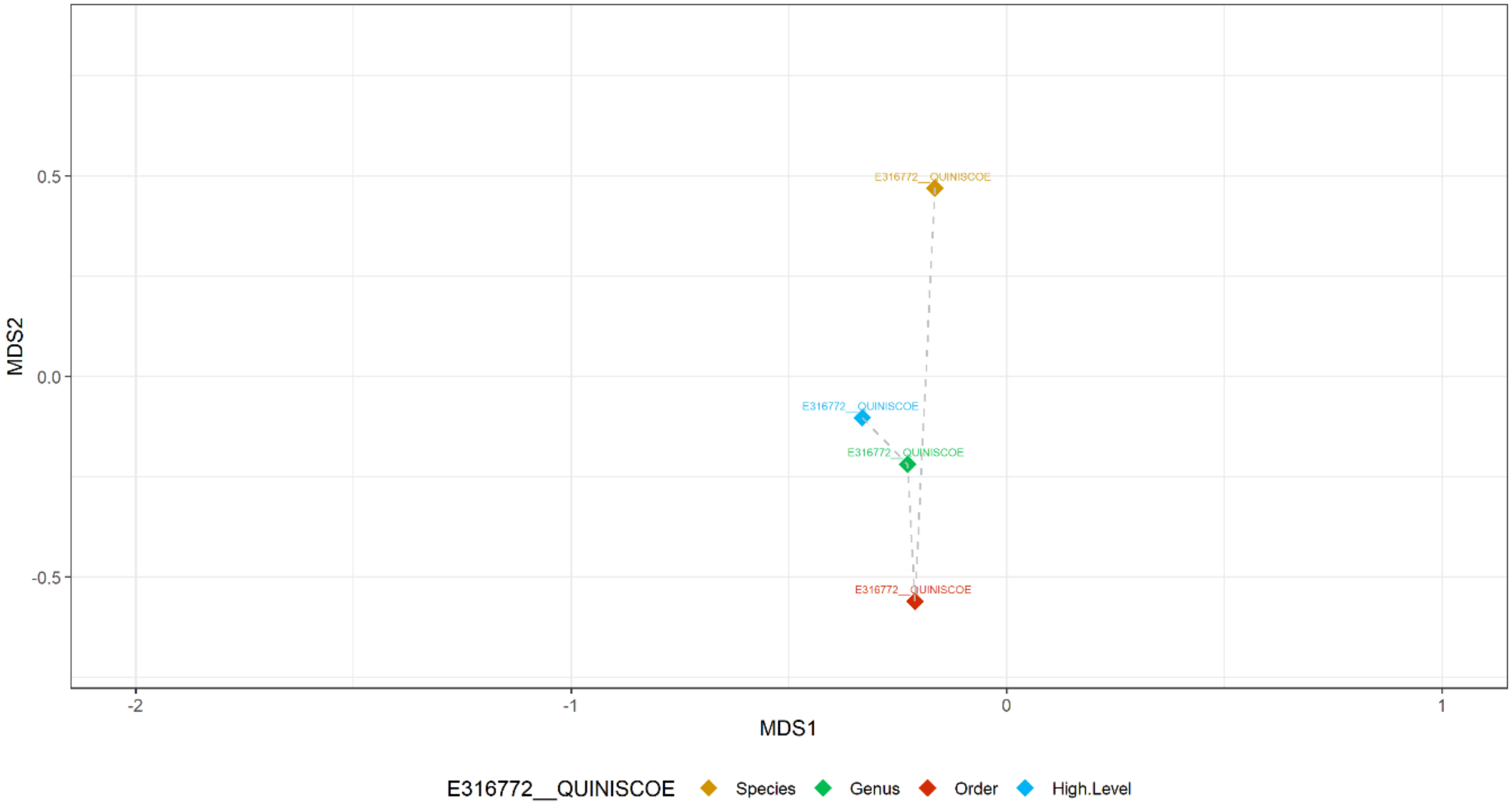


Figure A4- 10: Comparison of NMDS results at species and high level taxonomic groups for Quiniscoe Lake

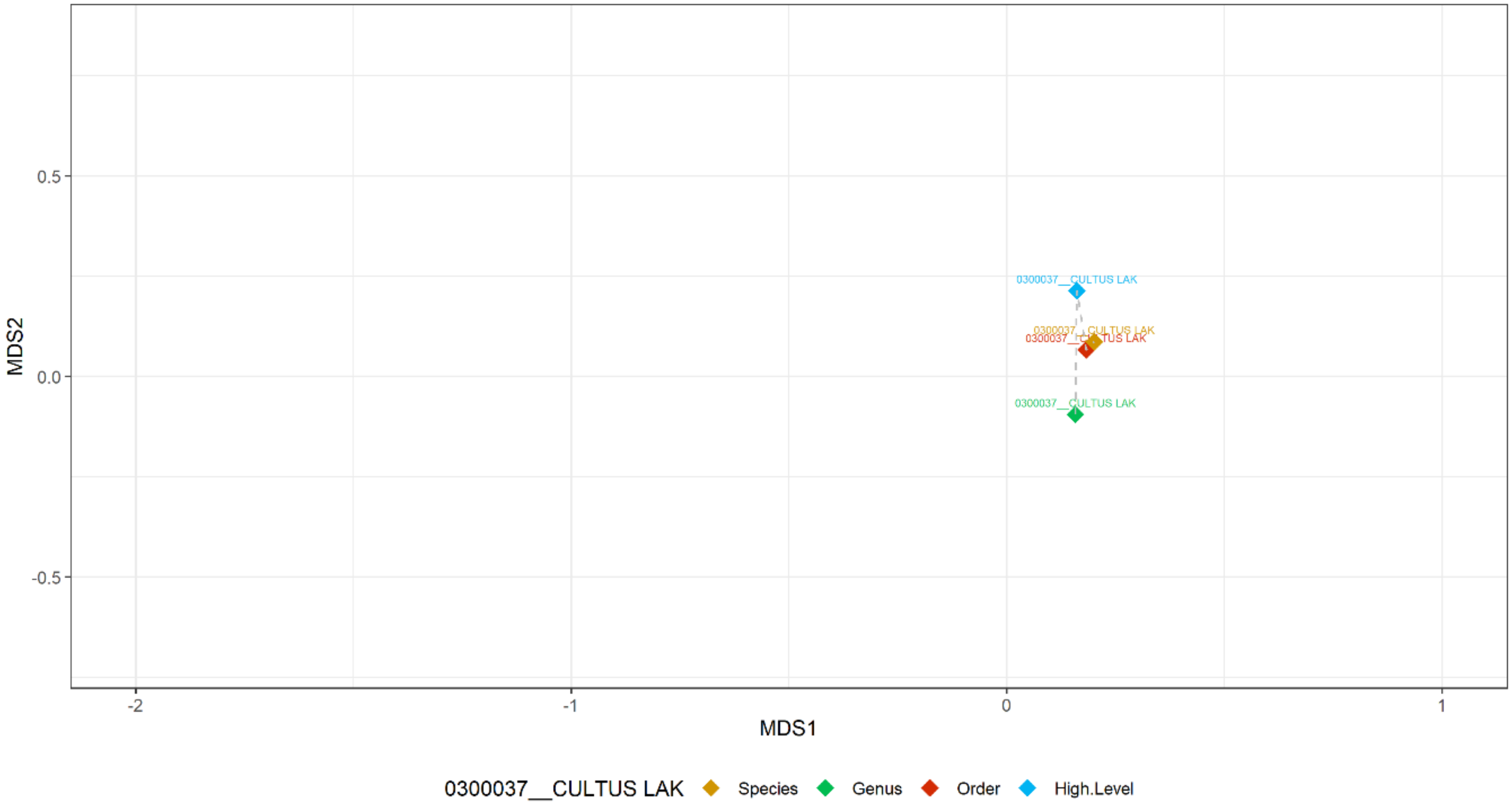


Figure A4- 11: Comparison of NMDS results at species and high level taxonomic groups for Cultus Lake

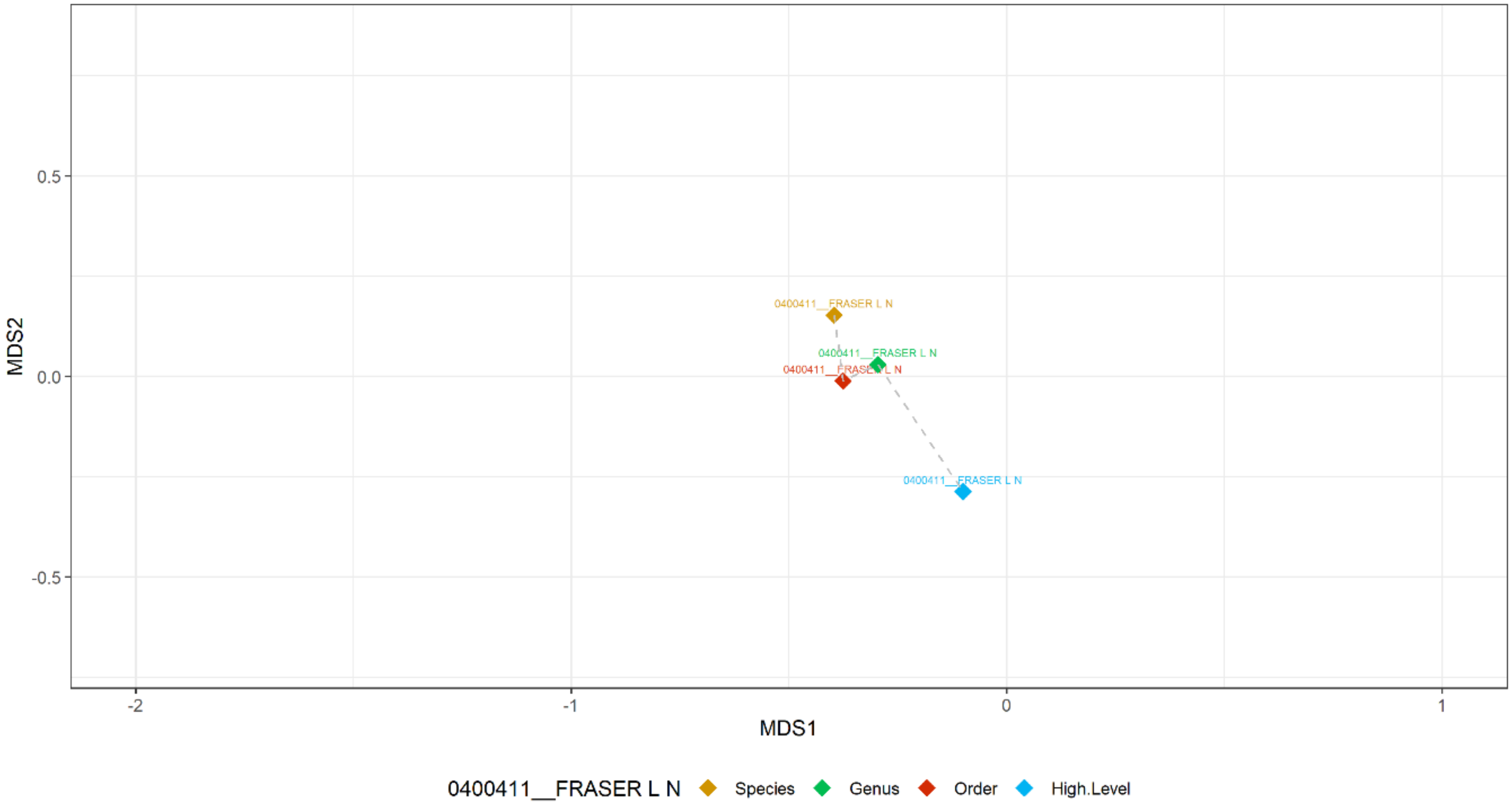


Figure A4- 12: Comparison of NMDS results at species and high level taxonomic groups for Fraser Lake

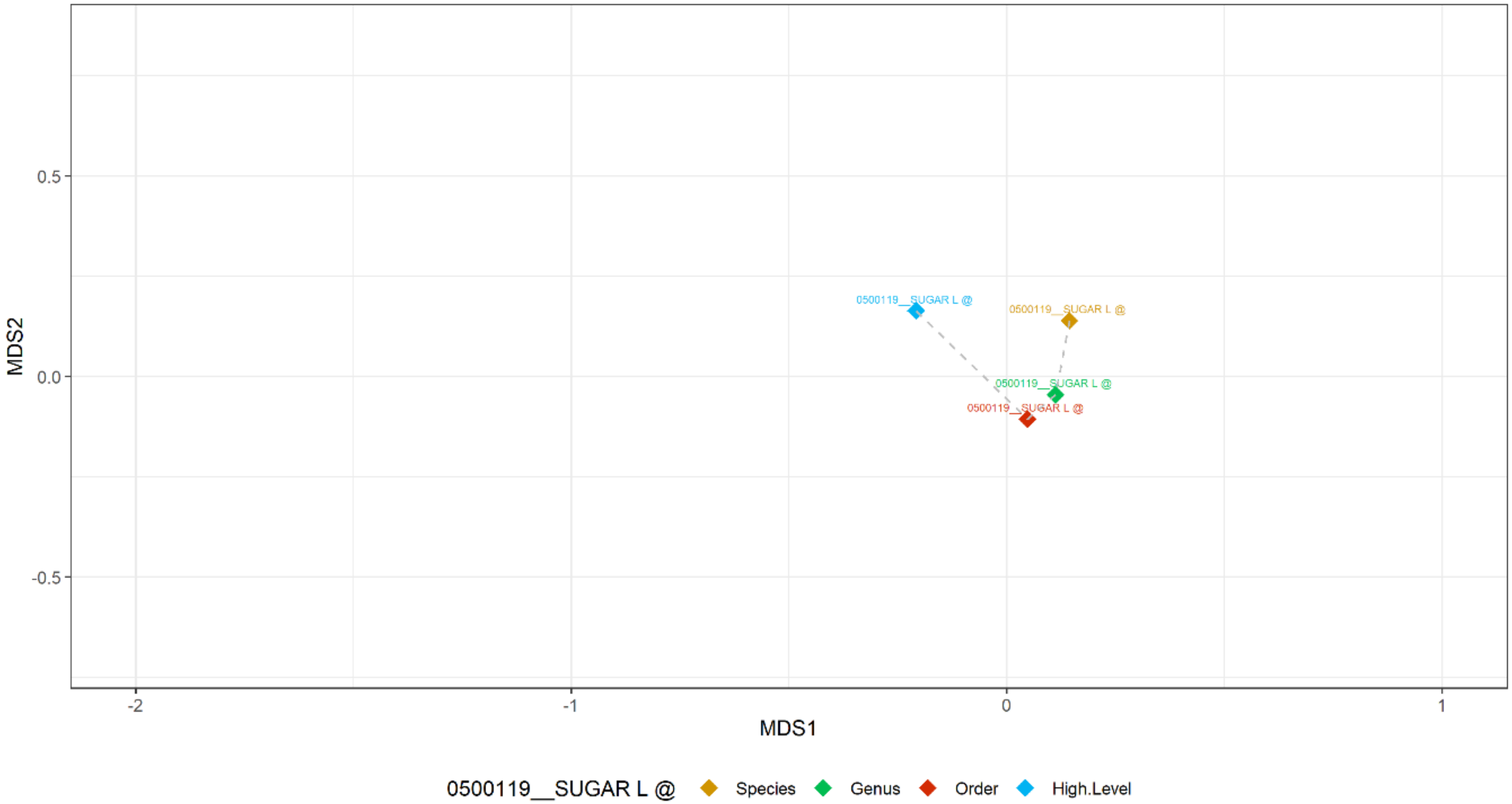


Figure A4- 13: Comparison of NMDS results at species and high level taxonomic groups for Sugar Lake

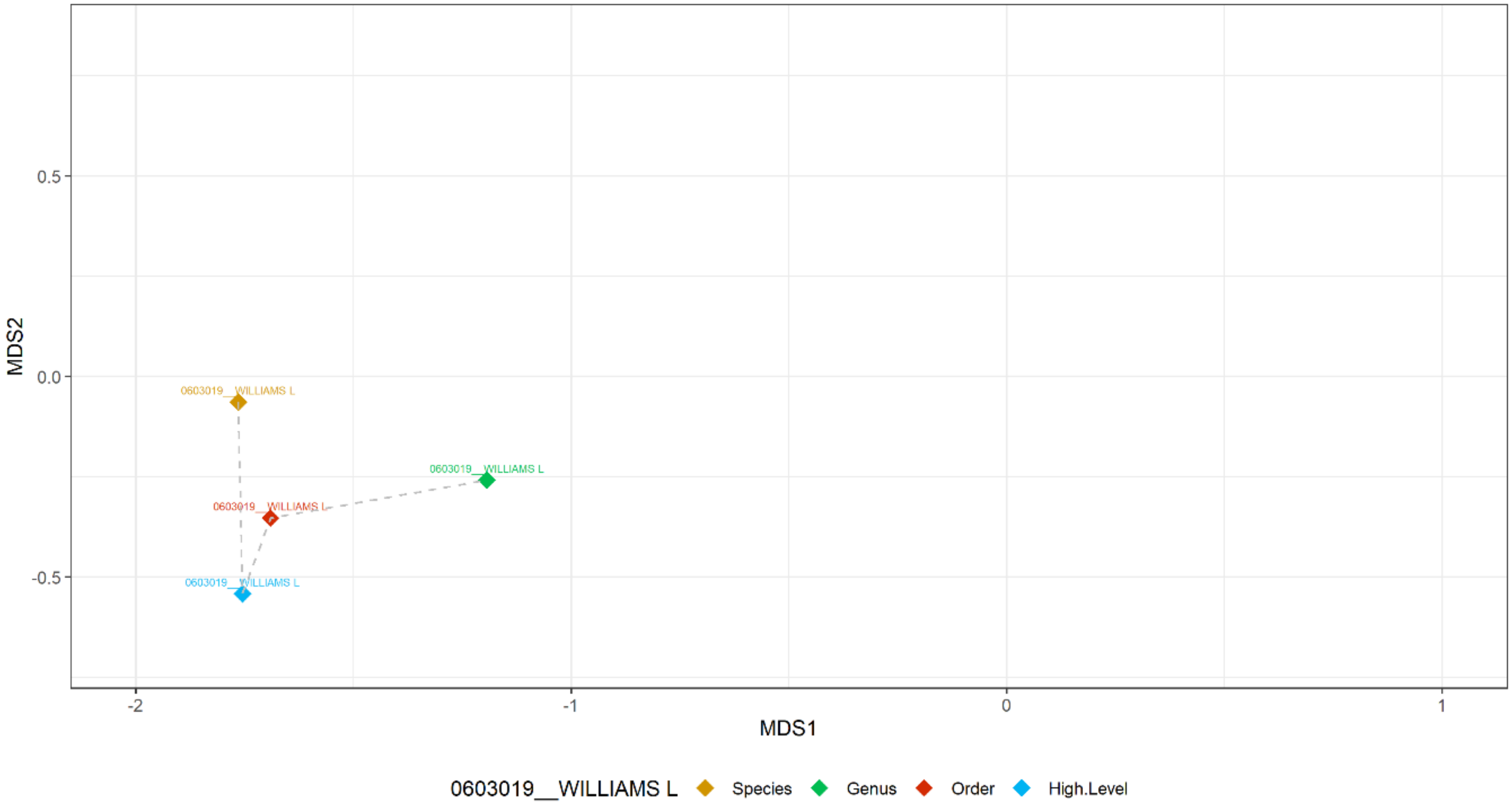


Figure A4- 14: Comparison of NMDS results at species and high level taxonomic groups for Williams Lake

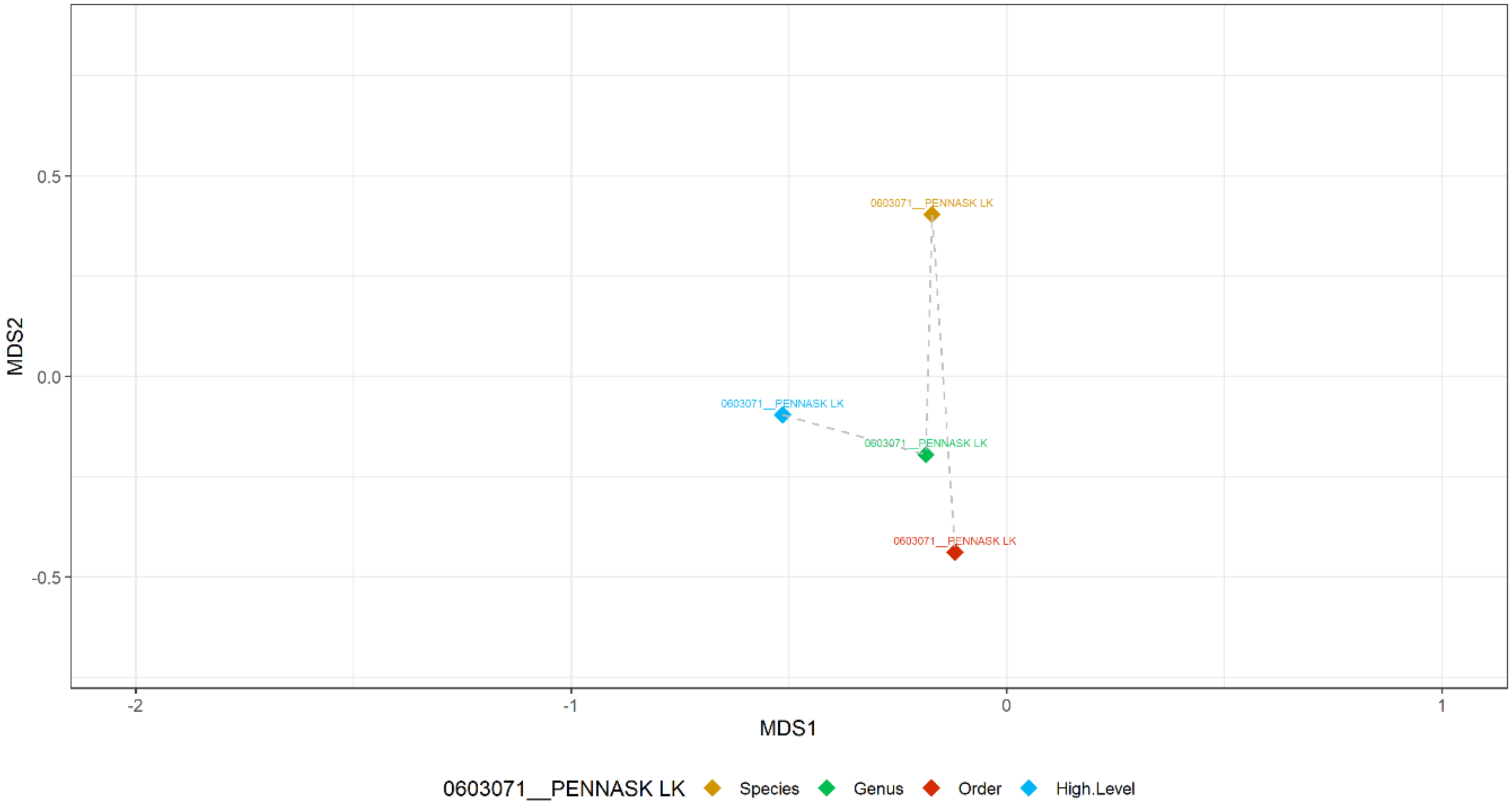


Figure A4- 15: Comparison of NMDS results at species and high level taxonomic groups for Pennask Lake

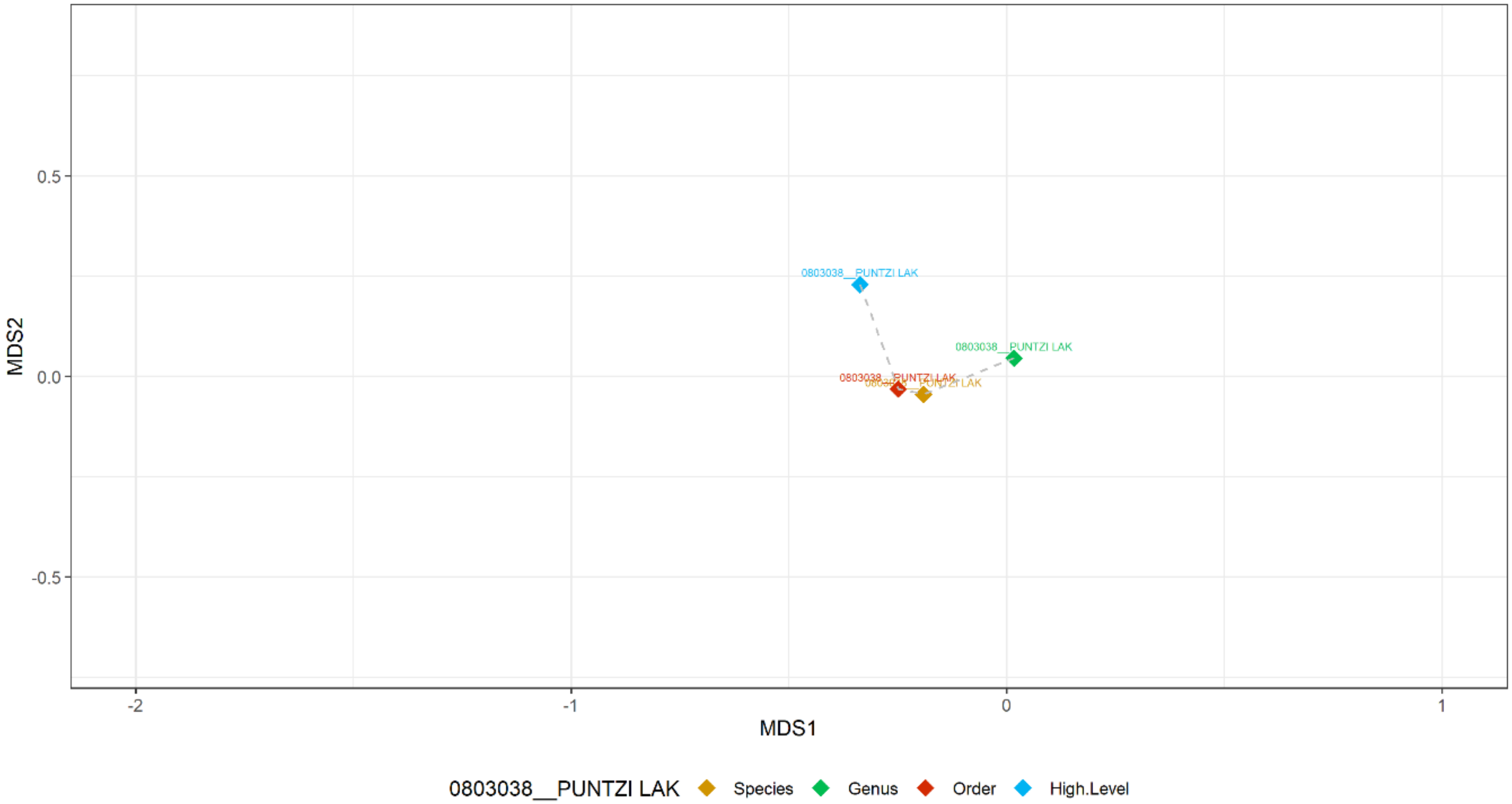


Figure A4- 16: Comparison of NMDS results at species and high level taxonomic groups for Puntzi Lake

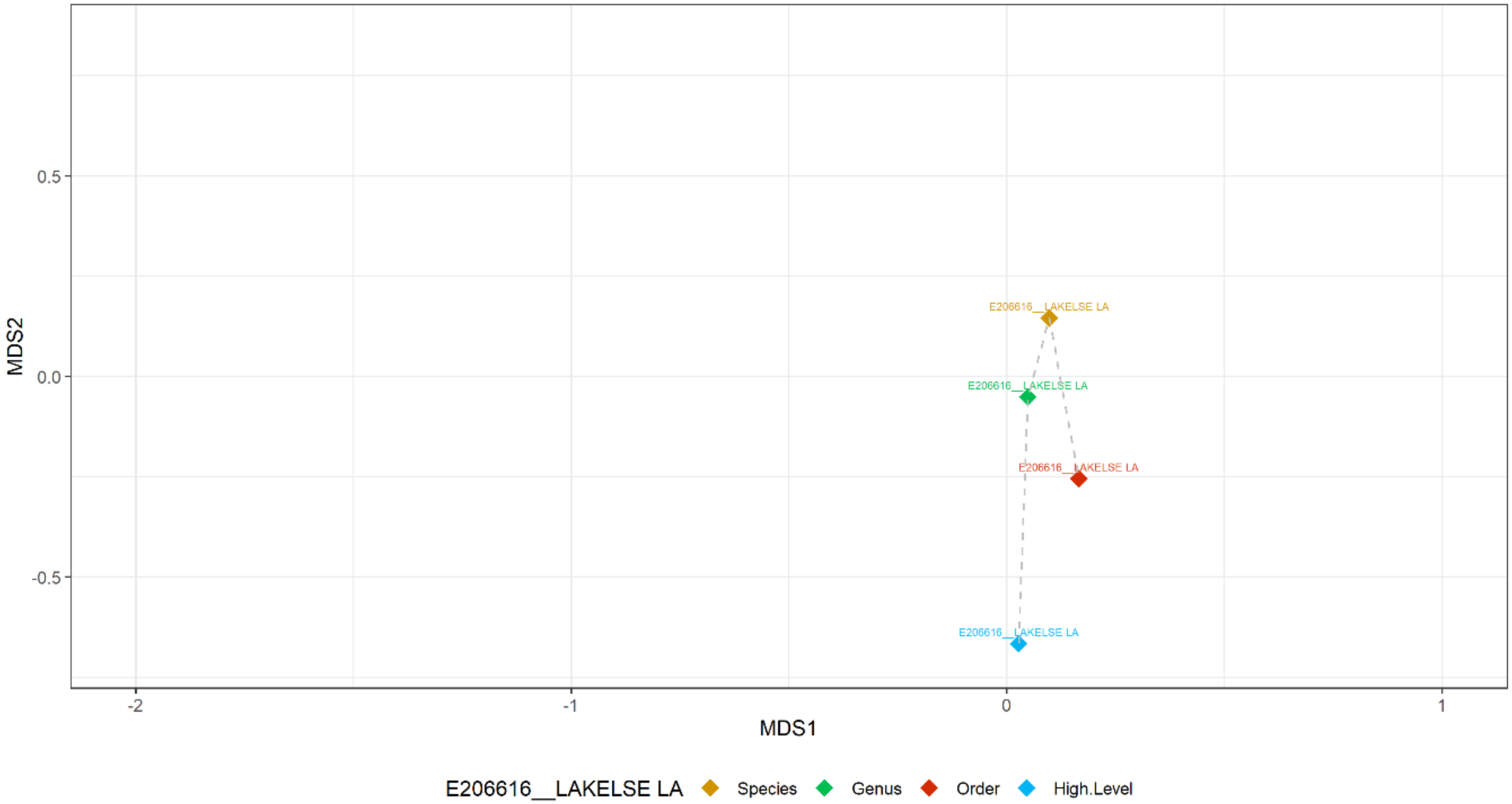


Figure A4- 17: Comparison of NMDS results at species and high level taxonomic groups for Lakelse Lake

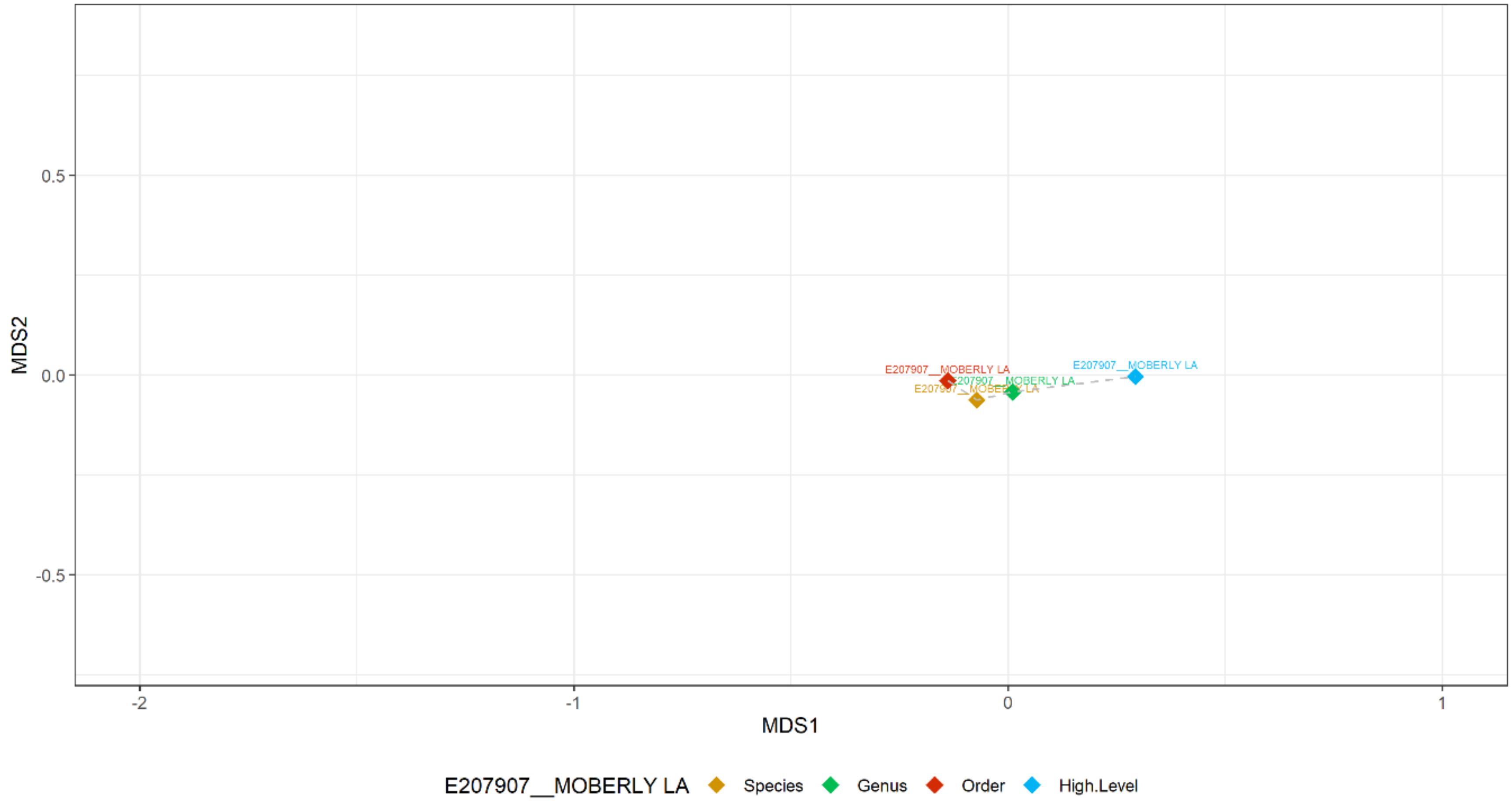


Figure A4- 18: Comparison of NMDS results at species and high level taxonomic groups for Moberly Lake

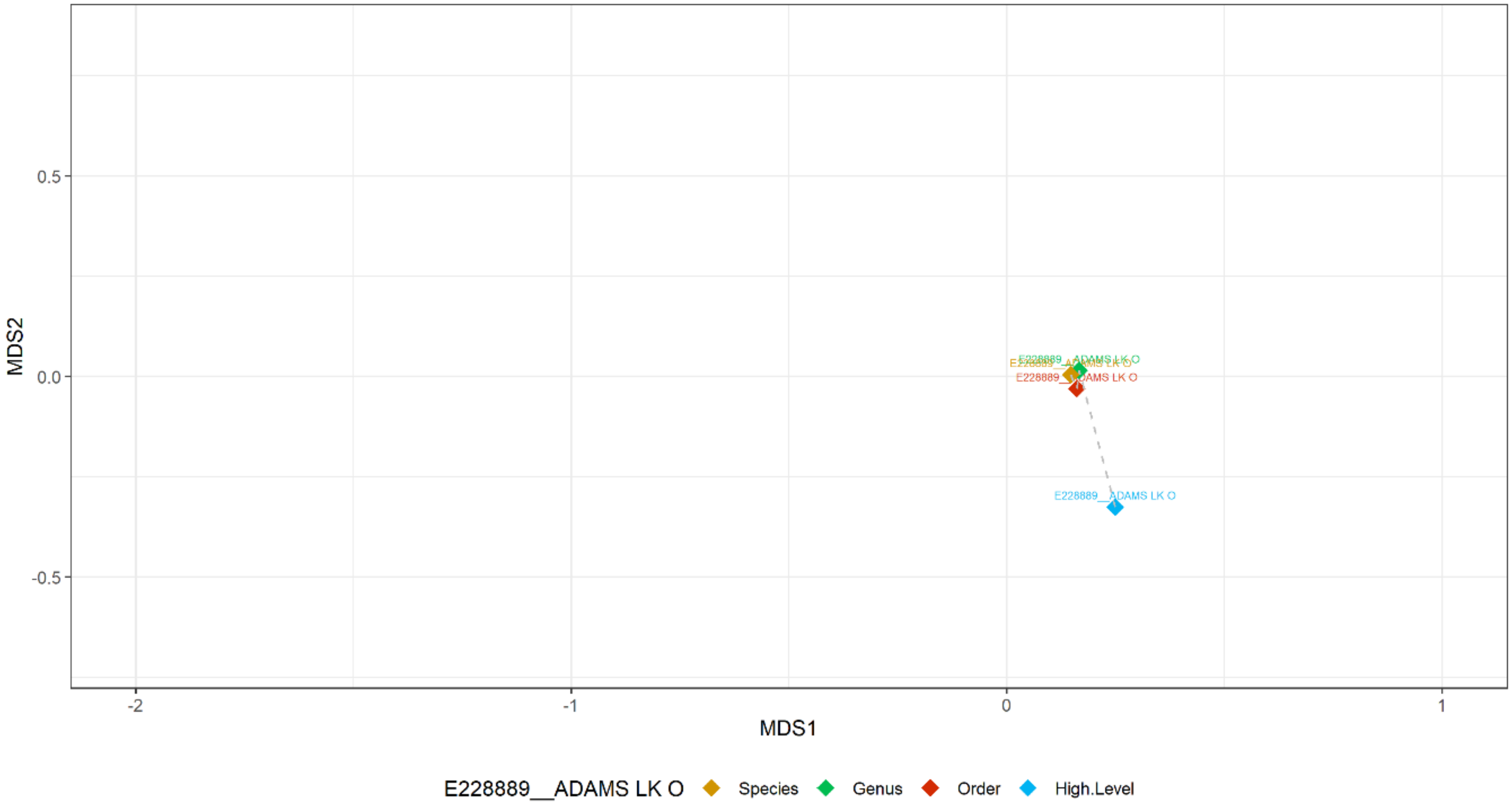


Figure A4- 19: Comparison of NMDS results at species and high level taxonomic groups for Adams Lake

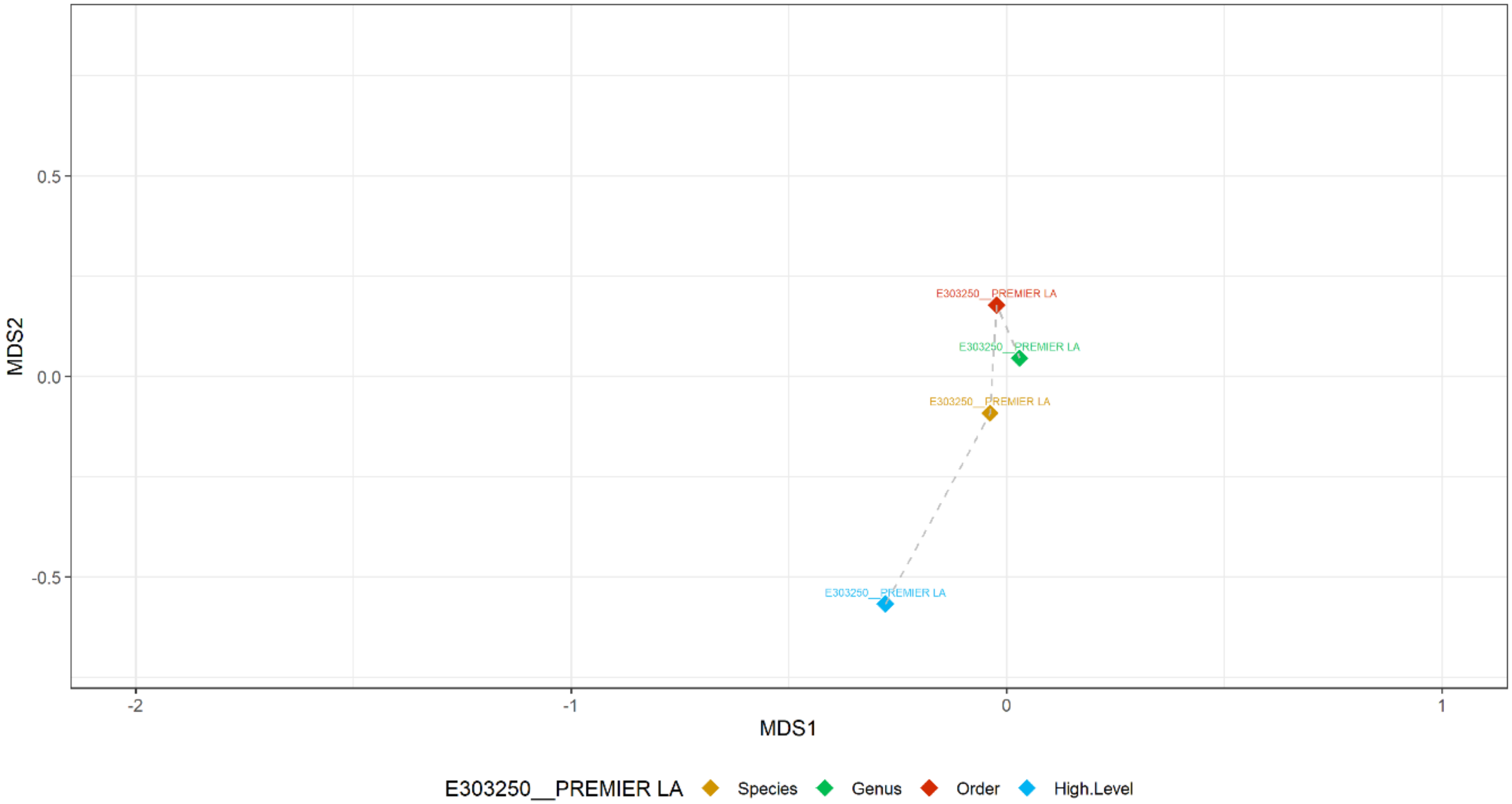


Figure A4- 20: Comparison of NMDS results at species and high level taxonomic groups for Premier Lake

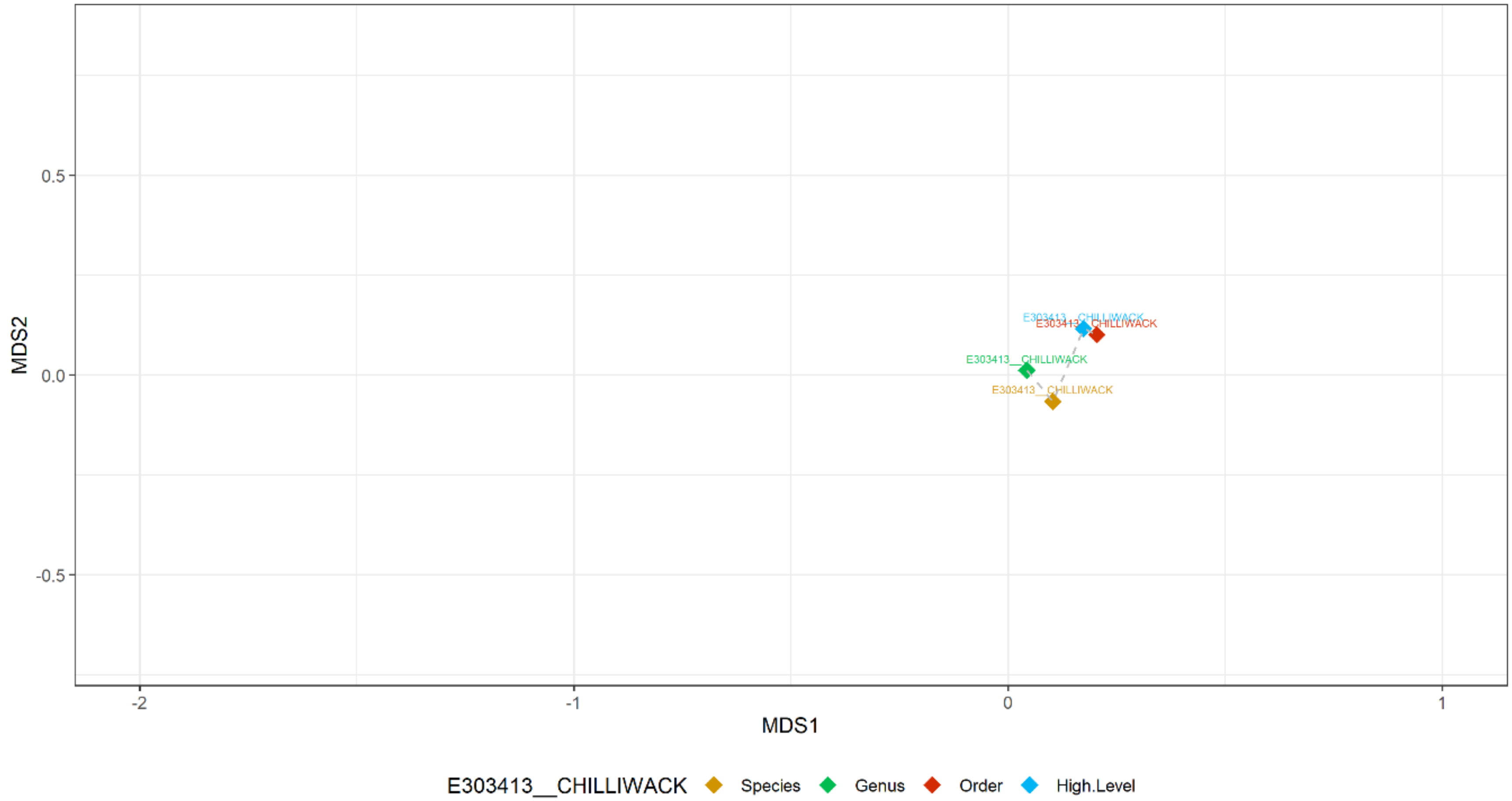


Figure A4- 21: Comparison of NMDS results at species and high level taxonomic groups for Chilliwack Lake

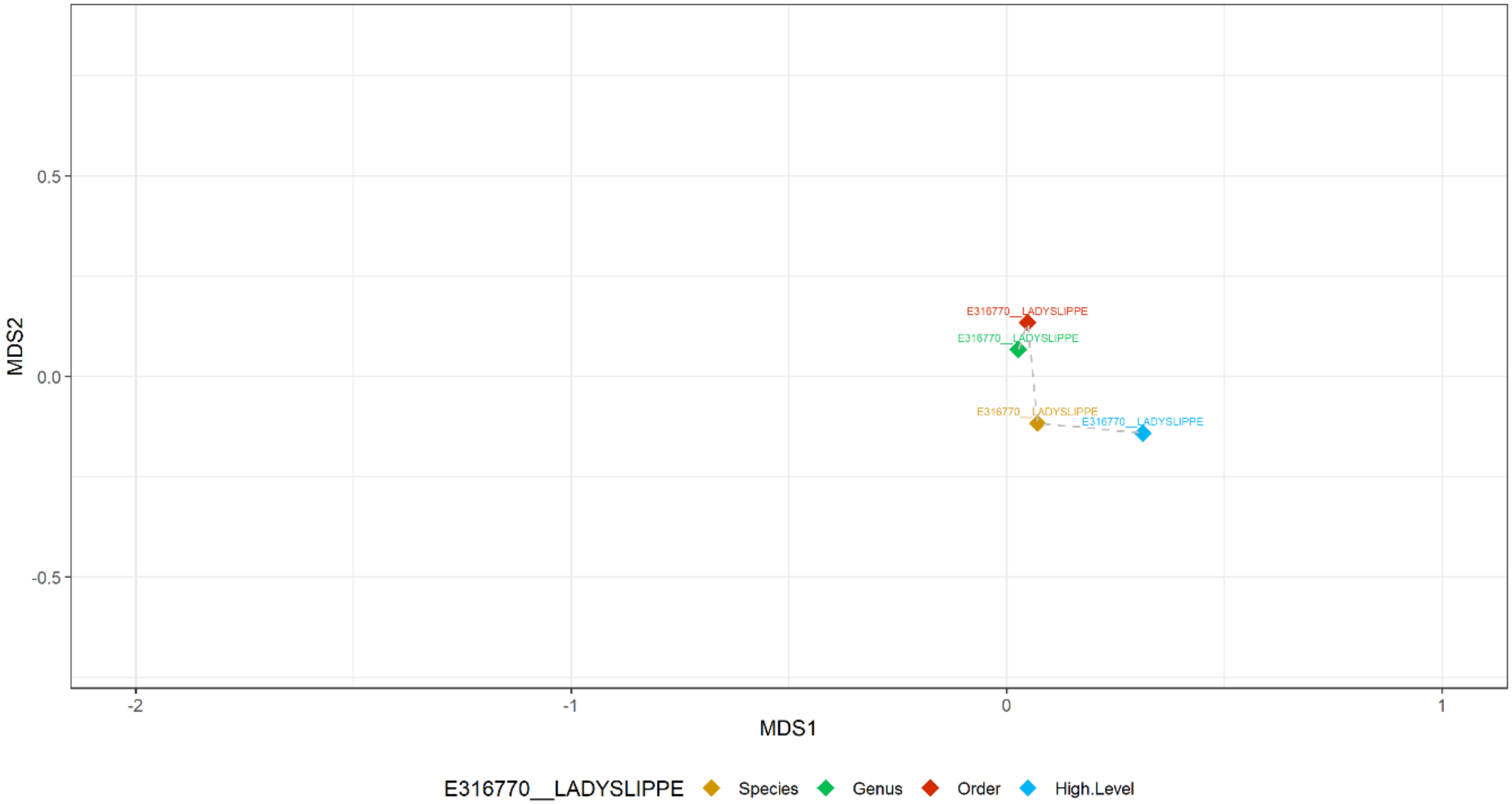


Figure A4- 22: Comparison of NMDS results at species and high level taxonomic groups for Ladyslipper Lake

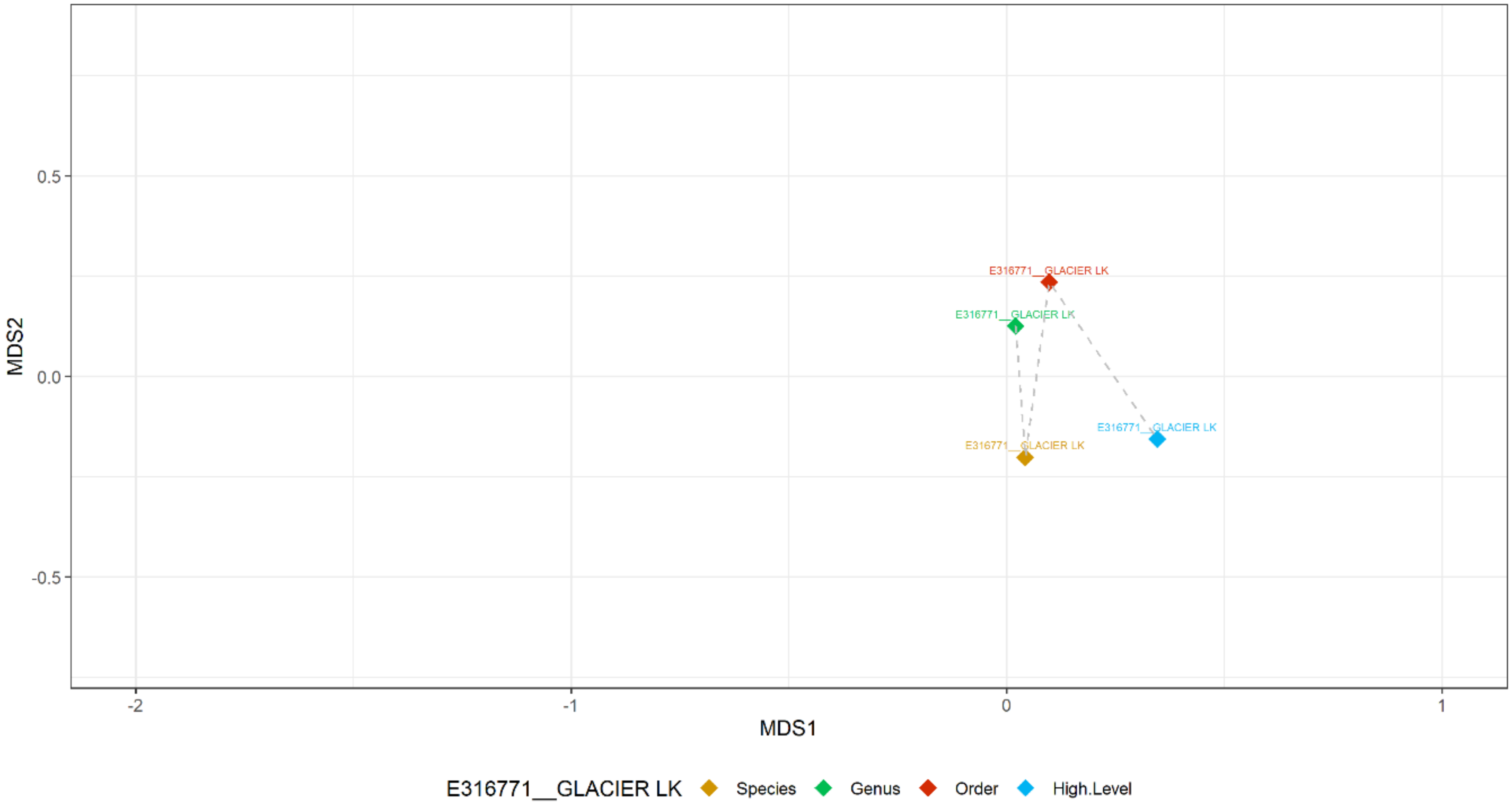


Figure A4- 23: Comparison of NMDS results at species and high level taxonomic groups for Glacier Lake

Appendix 5: Top 10 Phytoplankton Taxa at Each Lake by Percent Abundance

	0200434__COLUMBIA L		0300037__CULTUS LAK		0400411__FRASER L N		0500119__SUGAR L @		0500615__SKAHA L OP		0603019__WILLIAMS L		0603071__PENNASK LK		0803038__PUNTZI LAK		E206283__LIZARD LAK		E206616__LAKELSE LA	
1	Aphanocapsa elachista	23.4%	Chroomonas acuta	35.3%	Aphanizomenon	22.2%	Dinobryon sertularia	55.8%	Oscillatoria tenuis	29.5%	Oscillatoria tenuis	78.8%	Aphanizomenon flosaquae	34.1%	Dinobryon sertularia	28.7%	Merismopedia tenuissima	34.6%	Chroomonas acuta	27.2%
2	Scenedesmus denticulatus	7.5%	Crucigenia retangularis	15.4%	Aphanocapsa elachista	18.7%	Achnanthidium microcephalum	8.5%	Aphanizomenon	11.5%	Aphanizomenon flosaquae	5.8%	Aphanizomenon	19.4%	Anabaena flosaquae	26.7%	Asterionella formosa	10.6%	Asterionella formosa	18.5%
3	Kephyrion	7.2%	Cryptomonas ovata	6.4%	Anabaena	9.8%	Ochromonas	6.5%	Lyngbya limnetica	9.1%	Aphanizomenon	5.7%	Chroomonas acuta	13.3%	Aphanocapsa elachista	25.1%	Geminella interrupta	6.8%	Ochromonas	8.0%
4	Botryococcus braunii	7.1%	Cryptomonas	5.8%	Aulacoseira italica	7.8%	Chroomonas acuta	4.7%	Chrysophyta	8.9%	Lyngbya limnetica	5.5%	Anabaena	6.7%	Dinobryon	4.0%	Chroomonas acuta	5.4%	Cyclotella glomerata	6.4%
5	Crucigenia quadrata	6.4%	Gloeocystis ampla	5.7%	Chroomonas acuta	6.4%	Tabellaria flocculosa	2.3%	Aulacoseira italica	4.7%	Limnothrix redekei	1.8%	Aulacoseira italica	4.6%	Chroomonas acuta	3.5%	Dinobryon sertularia	3.8%	Peridinium inconspicuum	2.9%
6	Chroomonas acuta	5.1%	Crucigenia quadrata	4.6%	Asterionella formosa	6.2%	Cyclotella glomerata	1.8%	Tabellaria fenestrata	4.3%	Chroomonas acuta	1.2%	Anabaena affinis	2.4%	Dinobryon divergens	2.7%	Aphanocapsa elachista	3.7%	Cryptomonas ovata	2.8%
7	Oocystis lacustris	4.7%	Aulacoseira italica	3.7%	Fragilaria crotonensis	5.6%	Scenedesmus denticulatus	1.4%	Anabaena flosaquae	4.2%	Anabaena affinis	0.7%	Gloeocystis ampla	2.3%	Crucigenia retangularis	2.3%	Pediastrum tetras	3.6%	Fragilaria crotonensis	2.0%
8	Anacystis thermalis	2.3%	Elakatothrix gelatinosa	3.2%	Coelosphaerium naegelianum	5.2%	Peridinium inconspicuum	1.3%	Stephanodiscus niagarae	3.9%	Cryptomonas ovata	0.1%	Botryococcus braunii	2.1%	Sphaerocystis schroeteri	1.0%	Selenastrum minutum	3.5%	Cyclotella	1.9%
9	Tetraedron minimum	2.3%	Dinobryon divergens	2.7%	Coelosphaerium pallidum	4.2%	Cryptomonas ovata	1.0%	Anabaena	3.7%	Bacillariophyceae	0.0%	Cyclotella glomerata	1.5%	Anabaena	0.9%	Gloeocystis ampla	3.0%	Dictyosphaerium pulchellum	1.8%
10	Anabaena	2.2%	Anacystis thermalis	2.6%	Ochromonadales	1.8%	Elakatothrix gelatinosa	0.9%	Chroomonas acuta	3.3%	Cryptomonas	0.0%	Fragilaria crotonensis	1.3%	Stephanodiscus niagarae	0.7%	Rhabdoderma lineare	3.0%	Lyngbya limnetica	1.7%

	E207466__QUAMICHAN		E207907__MOBERLY LA		E223304__DIANA LAKE		E228889__ADAMS LK O		E303250__PREMIER LA		E303413__CHILLIWACK		E316770__LADYSLIPPE		E316771__GLACIER LK		E316772__QUINISCOE	
1	Anacystis aeruginosa	57.6%	Aulacoseira italica	40.2%	Merismopedia tenuissima	72.3%	Aphanocapsa elachista	46.9%	Gloeocystis ampla	37.3%	Sphaerocystis schroeteri	54.2%	Sphaerocystis schroeteri	36.2%	Crucigenia retangularis	27.3%	Anabaena affinis	41.1%
2	Coelosphaerium naegelianum	13.6%	Chroomonas acuta	35.9%	Gurleyi	14.3%	Chroomonas acuta	8.7%	Dinobryon divergens	26.3%	Gloeocystis ampla	17.9%	Gloeocapsa	12.4%	Chroomonas acuta	25.1%	Spondylosium planum	28.3%
3	Aphanizomenon	9.6%	Cryptomonas ovata	4.6%	Botryococcus braunii	4.1%	Aphanocapsa delicatissima	6.7%	Chroomonas acuta	8.8%	Elakatothrix gelatinosa	6.7%	Ankistrodesmus falcatus	11.5%	Sphaerocystis schroeteri	24.7%	Oocystis borgei	6.4%
4	Cryptomonas ovata	5.8%	Fragilaria crotonensis	2.5%	Crucigenia tetrapedia	1.5%	Anacystis thermalis	6.0%	Anacystis thermalis	6.2%	Chroomonas acuta	3.3%	Kephyrion	6.8%	Anabaena	6.0%	Elakatothrix gelatinosa	5.4%
5	Chroomonas acuta	2.6%	Asterionella formosa	1.6%	Ochromonas	1.4%	Asterionella formosa	5.7%	Crucigenia retangularis	4.4%	Cyclotella glomerata	2.6%	Oocystis lacustris	6.4%	Eunotia	3.9%	Oocystis lacustris	4.0%
6	Anabaena circinalis	2.4%	Dinobryon divergens	1.1%	Cryptomonas ovata	1.2%	Cryptomonas ovata	5.5%	Aphanocapsa elachista	4.2%	Kephyrion	1.8%	Nephrocytium	3.7%	Schroederia setigera	2.9%	Tabellaria flocculosa	1.4%
7	nicicola	1.5%	Oocystis	1.0%	Asterionella formosa	0.9%	Cyclotella glomerata	4.2%	Kephyrion	3.2%	Cryptomonas ovata	1.7%	Chroomonas acuta	3.7%	Ochromonas	1.4%	Sphaerocystis schroeteri	1.3%
8	Anabaena spiroides	1.2%	Gloeocystis ampla	0.8%	Dinobryon bavaricum	0.7%	Crucigenia retangularis	2.8%	Cryptomonas ovata	1.7%	Ankistrodesmus falcatus	1.2%	Botryococcus braunii	2.6%	Fragilaria crotonensis	1.1%	Dinobryon sertularia	1.3%
9	Pediastrum boryanum	0.9%	Ochromonas	0.8%	Sphaerocystis schroeteri	0.5%	Aulacoseira italica	2.2%	Cyclotella bodanica	1.0%	Scenedesmus denticulatus	1.0%	Crucigenia quadrata	2.6%	Achnanthidium microcephalum	0.7%	Asterionella formosa	1.3%
10	Stephanodiscus niagarae	0.9%	Achnanthidium microcephalum	0.8%	Peridinium inconspicuum	0.4%	Cryptomonas	1.0%	Cryptomonas	0.7%	Peridinium inconspicuum	0.8%	Bacillariophyceae	2.3%	Cryptomonas	0.6%	Bacillariophyceae	0.6%

-------------End of Report-------------