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Seasonal and inter-annual variability of phytoplankton in central Lake Diefenbaker (Saskatchewan, Canada) proximal to a large commercial aquaculture farm

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ABSTRACT

Lake Diefenbaker, Saskatchewan, is a large reservoir (392 km^2) with multiple end users, including a commercial aquaculture farm, which rely on sustainable water quality. Phytoplankton samples were taken monthly at upstream, aquaculture, and downstream locations during August 2008 to November 2011. The phytoplankton community was primarily diatoms and cryptophytes. Diatom biomass was correlated with greater mixing depth, while cryptophyte biomass was correlated with higher dissolved nutrients. Phytoplankton biomass was characterized by date, season and year, and this information was used to test spatial differences between upstream, farm and downstream locations. There was no significant difference in chlorophyte, chrysophyte or dinoflagellate biomass spatially. Upstream sites (US) had higher diatom biomass in the fall (US-DS = 329 mg/m^3). Downstream sites (DS) had higher cryptophyte biomass in the summer (DS-US = 241 mg/m^3) and higher cyanobacteria biomass in the fall (DS-US = 15 mg/m^3). Spatial trends in diatoms, cryptophytes, and cyanobacteria between upstream and downstream locations were found to be significantly related to distance downstream, but failed to provide evidence of a fish farm effect. There was far greater inter-annual variability than spatial variability in phytoplankton biomass of Lake Diefenbaker, a lake prone to flooding and drought. For instance, flooding in 2011 resulted in elevated suspended solids, nutrient concentrations, and algal biomass (particularly cryptophytes and dinoflagellates) due to a La Niña winter. Flood inputs of suspended solids to Lake Diefenbaker favour low-light adapted taxa (e.g., *Rhodomonas minuta* Skuja) over potentially toxic cyanobacteria.

Introduction

Lake Diefenbaker, SK, a large reservoir (184 km length, 392 km^2 surface area at full supply level) formed in 1967 by the impoundment of the South Saskatchewan and Qu'Appelle Rivers, is currently facing increased demand by end users. This reservoir provides multiple services to the region, including water for municipal (potable), industrial (hydroelectricity and potash), agricultural (irrigation and livestock watering), and aquacultural (trout production) purposes, as well as for flood protection and recreation. Water availability and quality are a concern to all users, and Lake Diefenbaker may be particularly susceptible to pollution considering the large catchment size of 150,000 km^2 (Water Security Agency, 2012).

Pollutants entering a reservoir are challenging to measure directly because most are nonpoint sources and are transported from the catchment during spring melt and rainfall events (Carpenter et al., 1998). The headwaters of the South Saskatchewan River originate in the Rocky Mountains of Alberta and Montana. Most of the water reaching Lake Diefenbaker is from snowpack melt, which reaches a peak flow in July (Water Security Agency, 2012). Quantification of loadings are further complicated because reservoir water discharge rates and water level changes vary greatly over the open water season, ±500 m^3/s and ±6 m, respectively (Saskatchewan Environment and Public Safety, 1988; Water Security Agency, 2012). Adding to the vulnerability of reservoirs over the long term is that typically, except during the initial stages of flooding, reservoirs trap suspended sediments and nutrients in the backwaters of impoundments (Elser and Kimmel, 1985).

In 1994, Wild West Steelhead, a commercial aquaculture operation, began operations in Cactus Bay, Lake Diefenbaker, and today is one of Canada's largest freshwater rainbow trout (*Oncorhynchus mykiss* Walbaum) producers. Trout are reared in cages suspended in the open water until of harvestable size, 0.5–2.75 kg (Anonymous, 2014). Freshwater rainbow trout cage aquaculture results in the release of faeces, urine, mucus, and small amounts of feed waste into the lake. These wastes represent a point source of nitrogen (N) and phosphorus (P) to the reservoir. Estimates of nutrient loading from this facility from 2008 to 2012 range from 18.9–23.2 MTA (metric tonnes per annum) of total phosphorus (TP) and 97.3–120.4 MTA of total nitrogen (TN;

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Podemski et al., submitted for publication). External P loads to Lake Diefenbaker were estimated to be 1533 MTA of TP in 2011 (North et al., 2015) from upstream sources; thus the aquaculture facility contributes 1.5% of total P loading. No estimate of external N loads has been completed for Lake Diefenbaker. Dissolved and particulate concentrations of N and P were slightly elevated at the edge of the commercial aquaculture cages than at the upstream site 200 m away (Podemski et al., submitted for publication). The P loads from aquaculture were typically less dispersive than N because of the high proportion of particulate bound P (74%), compared to particulate bound N (18%; Podemski et al., submitted for publication). The distribution of nutrients in reservoirs like Lake Diefenbaker, including sites near the fish farm, follow a trend from higher TP concentrations at the inflow of the South Saskatchewan River to lower TP concentrations downstream (Abirhire et al., 2015; Kennedy and Walker, 1990). The trend in decreased TP downstream, as well as decreased chlorophyll *a* concentrations and increased Secchi depth (Abirhire et al., 2015) may play a role assessing the spatial and temporal phytoplankton trends around the fish farm.

Recently, public interest in Lake Diefenbaker has been generated by the reports of algal blooms (Giesy et al., 2009; Li et al., 2008), total coliform exceedances (North et al., 2014), and reduced water clarity (Yip et al., 2015). Algal blooms, particularly those composed of cyanobacteria, are a common indicator of water quality deterioration and may pose a threat to the potability of water, with taste and odour issues and toxicity all being potential concerns. For this reason, toxicologists have examined cyanobacteria strains from Lake Diefenbaker in the laboratory, with particular interest in *Anabaena circinalis* Rabenhorst ex Bornet and Flahault (Hecker et al., 2012). However, the seasonal occurrence and abundance of these blue-green algae and the environmental conditions that influence toxin-producing species were not addressed by the authors.

Seasonal phytoplankton populations in reservoirs typically consist of a sequence of dominant and co-dominant groups that employ different life strategies from opportunistic-, competitive-, and stress-tolerant forms (Reynolds, 1989). In spring after ice off, phytoplankton in temperate reservoirs often have diatom dominant communities because they outcompete other taxa in cold water temperatures when soluble reactive silica is available and deep thermal mixing can resuspend viable silica frustules. When thermal stratification is established in the summer time, cyanobacteria and chlorophytes can become dominant in temperate reservoirs. Cyanobacteria outcompete other taxonomic groups under higher water temperatures through rapid growth rates and buoyancy control during periods of enhanced stratification (O'Neil et al., 2012), and limited N availability relative to P (Becker et al., 2010; Kim et al., 2007; Pålsson and Granéli, 2004). The recent perception of a community composition shift towards more nuisance cyanobacteria in Lake Diefenbaker (Giesy et al., 2009; Hecker et al., 2012) suggests increased nutrient loads and/or water temperatures in the reservoir of late (Barbiero et al., 1997).

There are a few publications on Lake Diefenbaker phytoplankton that address the role environmental variables play on community composition (Abirhire et al., 2015; Dubourg et al., 2015; McGowan et al., 2005; Saskatchewan Environment and Public Safety, 1988). The phytoplankton composition from July 1984 to June 1985 was characterized by cyanobacteria dominance (79% of total biovolume) and high chlorophyte diversity (Saskatchewan Environment and Public Safety (SEPS), 1988). More recent estimates of phytoplankton community composition from pigment analysis of water samples during 1995–2003 by McGowan et al. (2005) and from taxonomic identifications during 2011–2012 by Abirhire et al. (2015) indicate a community consisting primarily of cryptophytes and diatoms. In 1984 and 1985, the phytoplankton were believe to be P-limited, as drought conditions had reduced nutrient loads to 814 MTA of TP and TN:TP molar ratios averaged 90 (Saskatchewan Environment and Public Safety, 1988). More recently, TP loads were estimated to be 1533 MTA TP in 2011 and 616 MTA TP in 2012 (North et al., 2015), and studies suggest phytoplankton dynamics (biomass, physiology, and gross primary production) may not be P-limited (Dubourg et al., 2015; Yip et al., 2015).

Based on a Landsat imagery model, there is evidence that shoreline erosion in Lake Diefenbaker has not abated and water clarity has been in decline since 1984 (Yip et al., 2015), which may be affecting phytoplankton composition. Phytoplankton growth can frequently be limited by light as in Lake Diefenbaker and other reservoirs (Becker et al., 2010; Chellappa et al., 2009; da Silva et al., 2005; Fee et al., 1987; Hecky and Guildford, 1984). In reservoirs, large-scale water level fluctuations are known to cause shoreline erosion in boreal forest peatlands and unconsolidated prairie soils that rapidly bury organic matter and result in increased turbidity (Hecky and Guildford, 1984; Hewlett et al., 2015). Elevated turbidity and low light conditions in Lake Diefenbaker are greatest in the spring and early summer months when more particulates are in suspension (Hudson and Vandergucht, 2015). Phytoplankton best suited to these conditions are stress-tolerant centric diatoms, chrysophytes and cryptophytes (Havens, 1991; Klaveness, 1989; Pålsson and Granéli, 2004). These taxa are often co-dominant when nutrients are high, thermal mixing is deep and light availability is limited in oligo-mesotrophic reservoirs (Chellappa et al., 2009; Havens, 1991; Klaveness, 1989; Pålsson and Granéli, 2004; Phillips and Fawley, 2002).

Long-term phytoplankton population changes in Lake Diefenbaker were assessed by Hall et al. (1999) through a paleolimnological reconstruction of the fossil diatom population and preserved algal pigment concentrations. The reservoir had an initial four-year period of eutrophication following the impoundment in 1967, and then conditions gradually became mesotrophic over a decade (Hall et al., 1999). Reservoir trophic status is known to evolve over time from the initial stage of water level rise, terrain immersion and eutrophication (3–4 years); to an erosional stage and gradual increased shoreline stability (decadal); to a final oligotrophication stage (Lepistö, 1995), but at Lake Diefenbaker there have been no signs of reduced shoreline erosion or the onset of oligotrophication (Hewlett et al., 2015). Fossil pigments from diatoms, cryptophytes, and cyanobacteria were always abundant in Lake Diefenbaker sediment records, but increased trophic status with greater aphanizophyll pigment concentrations from N_2-fixing cyanobacteria was evident after 1986 in sediment records from the Qu'Appelle arm (Hall et al., 1999). Limited data exists on the water TP concentrations in the 1990s, but Hall and colleagues speculated that either internal P loading increased or the aquaculture production was responsible for this rise in lake productivity and cyanobacteria abundance. To this day, one contentious source of nutrients to Lake Diefenbaker is the large commercial aquaculture facility located midway along the length of the reservoir.

Here we present four years of phytoplankton community composition (2008–2011) collected at eight locations along a 20-km portion of Lake Diefenbaker. Sites included: three upstream of the fish farm (400 m–14 km), three at the fish farm cages (1–600 m), and two downstream of the fish farm (4 km). We present the spatial distribution, community composition, cell density, biomass, and frequency of occurrence of the phytoplankton species. Water quality monitoring of engineered water bodies like reservoirs may not receive the same due diligence as their naturally formed counterparts. Long-term monitoring of water chemistry and phytoplankton community composition is expensive and labour intensive. Our data will serve to extend the sparse dataset along a temporal and spatial scale for this reservoir, as we investigate the factors contributing to the phytoplankton biomass and community succession.

The objectives of this paper are to: 1) assess the community composition along a 20-km length of the reservoir; 2) present the phytoplankton community composition and biomass change during four open water seasons (2008–2011); and 3) assess the spatial phytoplankton community composition trends proximal to a large aquaculture operation.

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