Impact of Lake Recovery on Agricultural Ecosystem Services

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Nova Scotia Federation of Agriculture
Mitacs

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1.0 Project Rationale

Combustion of high sulfur fossil fuels results in the formation of sulfur dioxide that combines with atmospheric water to form acids that are deposited on the surface of the earth through both wet (precipitation) and dry (particulate) deposition. The acidification of surface water has been an area of intense research (Cosby et al. 1985; Reuss and Johnson 1986; Gorham 1989; Gorham 1998), and much work has been done to assess the impacts of sulfate deposition in NS (Gorham et al. 1986; Underwood et al. 1985; Watt et al. 1979), a region that is acid-sensitive due to poorly weathering bedrock which provides little buffering capacity to surface water.

Changes to emission policies in Canada and the United States have greatly reduced acid deposition in Nova Scotia. Similar conditions in Europe and certain regions of North America have allowed lakes to recover from acidification, evidenced by decreasing sulfate concentration, increasing pH, and increasing alkalinity (Skjelkvåle et al. 2005; Stoddard et al. 1999). It has also been found that reduced sulfate deposition is associated with increases in natural organic matter (NOM) content in lakes (Monteith et al. 2007).

Research done in Nova Scotia has found substantial decreases in lake sulfate concentration and increases in lake NOM (Clair et al. 2011), however increases in alkalinity and pH have been limited (Clair et al. 2011). More recent work done by the Center for Water Resources Studies (CWRS) indicates that lakes across the province are experiencing increasing pH, alkalinity, as well as continued increases in NOM concentration (e.g., Anderson et al., 2017). These chemical changes are positive signs that lakes are recovering from acidification, but may also have implications for ecosystem services such as water treatment and recreation.

Increasing frequency and duration of harmful cyanobacterial harmful algal blooms (CyanoHABs) in Nova Scotia suggest that physical and/or chemical changes in lakes are creating favorable conditions for cyanobacterial dominance. CyanoHABs are of concern because they are unsightly, cause taste and odor issues, and are capable of releasing cyanotoxins (Chorus and Bartram 1999). Factors affecting cyanoHAB formation include: nitrogen and phosphorus availability, temperature, organic matter, light regime, iron and other trace elements, and hydraulic conditions (Paerl et al. 2001). Control of cyanoHABs has typically focused on phosphorus and nitrogen inputs (Paerl et al. 2001), however given that cyanobacteria are nitrogen fixers, controlling phosphorus input is critical in preventing eutrophication and cyanoHABs (Schindler et al. 2016). Moreover, in a modelling study using data from 20 lakes, Rigosi et al. (2015) found temperature to be at least as important as phosphorus in predicting cyanoHAB formation.

Recently, the Centre for Water Resources Studies (CWRS) has reviewed historical and current data from two potable water supplies for Halifax Regional Municipality (i.e., Pockwock Lake and Lake Major) that show decreasing sulfate concentration in conjunction with evidence of biological (i.e., increasing organic carbon, increasing colour) and chemical (i.e., increasing pH) recovery (Anderson et al., 2017). While it is a positive sign that lakes are showing signs of returning to their natural state following years of chronic acidification, this recovery may impact how people can use these lakes for ecosystem services such as drinking water supply and recreation. For example, potentially in response to recovery, Pockwock Lake, the drinking water source for peninsular Halifax, experienced detectable levels of geosmin (an algal metabolite) for the first time in 2012, causing drinking water to have an earthy-musty taste and odour (Anderson et al., 2017). Lake Torment, a popular lake for recreation in Nova Scotia, experienced a blue green algae bloom in August 2015, prompting the province to issue an advisory to not swim in or drinking from the lake due to the toxins that some algae can produce.

Other ecosystem services could also be impacted by lake recovery. Many Nova Scotians rely on lakes to provide nutrient cycling of domestic wastewater and agricultural wastewater and run-off. CWRS has preliminarily reviewed data from several lakes in Kings County. In 2014, many of these lakes (10 of 11 lakes), showed evidence of chemical recovery through an increase in pH above 1997 through 2013 levels. This same time period also corresponded to a reduction in total phosphorus (all 11 lakes) and total nitrogen (10 of 11 lakes) concentrations. Despite this apparent general decrease in nutrient loading, chlorophyll-a (an indicator of algal biomass and lake productivity) was higher in 2014 than the 1997-2013 average in 10 of the 11 lakes. This observation indicates that, even though nutrient inputs decreased, lake productivity is increasing. This could potentially make lakes more susceptible to algal blooms as a result of nutrient enrichment from agricultural practices. Lakes that could previously subsist nutrient enrichment from agriculture wastewater and run-off may no longer be able to receive nutrient enrichment at the same flux as before without experiencing algal blooms or other negative outcomes.

2.0 Project Description

The Centre for Water Resource Studies was contracted by Nova Scotia Federation of Agriculture to review and assess water quality of lakes with varying anthropogenic impacts, to improve understanding of the implications of lake recovery on ecosystem services. A short term study of four Nova Scotian lakes was conducted during the summer months of 2017. The main objectives of the study were to assess lake-water quality and to investigate lake recovery in anthropogenically impacted Nova Scotian lakes to understand how lake recovery affects the ability of lakes to provide the ecosystem service of nutrient cycling. The findings will help the Nova Scotia Agriculture Federation and associated community plan and adapt their water management processes for changing atmospheric conditions.

This project consisted of three tasks:

Task 1: Collection and Review of Historical Data

Task 2: Lake Monitoring Program

Task 3: Data Analysis and Modelling

3.0 Project Approach

3.1 Task 1: Collection and Review of Historical Data

Task 1 included a review of historical water quality data (e.g., nutrient concentrations) with the objective of determining if the proposed study lakes exhibit signs of chemical and/or biological recovery. The historical data review included a review of published research as well as information gathered from water utilities, government, and community groups. Water and air quality databases maintained by Nova Scotia Environment and Environment Canada were also reviewed.

3.2 Task 2: Lake Monitoring Program

Task 2 involved water quality monitoring of each lake. Monitored parameters will included nutrients (e.g., total phosphorus, total nitrogen), organic matter (e.g., dissolved organic carbon [DOC], colour, and oxygen demand), productivity (e.g. chlorophyll a) and a number of physical/chemical parameters (e.g., pH, alkalinity, sulfate).

3.3 Task 3: Data Analysis and Modelling

In Task 3, analysis of available historical data and data generated from the monitoring program were combined to determine if and how lake recovery is impacting each lake. Recommendations with respect to threshold nutrient loading, given changing atmospheric conditions and reduction in acid deposition were developed.

4.0 Findings

4.1 Task 1: Collection and Review of Historical Data

Changes in water chemistry due to decreased acid deposition occur on decadal time-scales. Short term sampling programs do not provide the temporal coverage required to observe recovery from acidification. Sources of longer term data were sought to provide context for results from this study.

Figure 1 shows trends in wet deposition of nitrate and sulfate measured at two precipitation monitoring stations in NS. Deposition of both analytes has decreased substantially since the 1980s. Sulfate deposition has declined steadily over the past several decades, whereas decreases in nitrate deposition began around 2000.

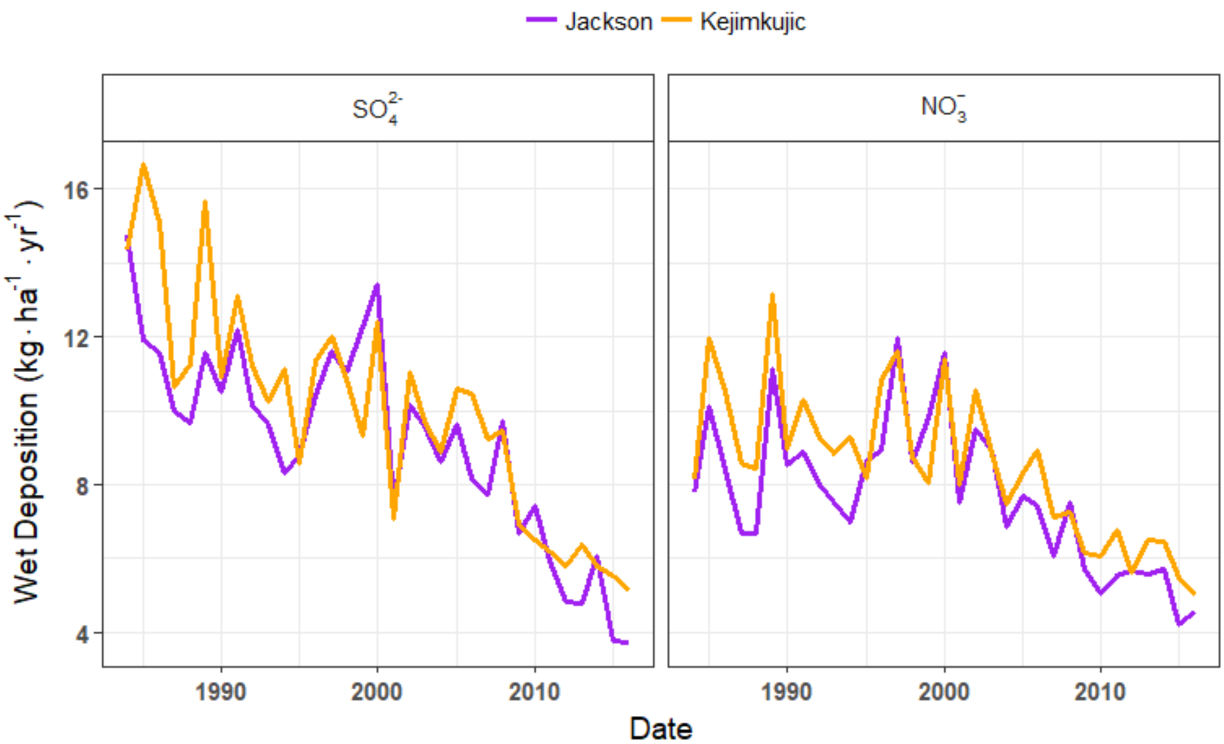

Figure 1 - Wet deposition of sulfate and nitrate measured at two precipitation monitoring stations in Nova Scotia.

Historical data for Aylesford Lake and Lake Torment were provided by the King's County Lake Monitoring Program. Sparse historical data for Nowlan's Lake was found in reports prepared for Nova Scotia Environment. Data for Lake Torment was limited to CWRS data collected in the past several years. Historical data from 10 lakes in King's County was obtained from the King's County Lake Monitoring Program and used to create figures S1 to S4 in the Appendix. Major trends include higher levels of chlorophyll-a, an indicator of algal growth, in most of the lakes (8 of 9 with complete chlorophyll-a data) after 2010 than before 2000 (Figure S1) and gradual increases in pH and colour in many of the lakes (Figure S2). No statistically significant trends in either total phosphorus or total nitrogen concentrations were found between 1995 and 2005 (Appendix Figure S3 and S4). Additional discussion about the significance of these parameters and their current levels in the lakes sampled during this study is provided in Section 4.2 and Section 4.3.

4.2 Task 2: Lake Monitoring Program

The water quality parameters measured in this study included indicators of trophic status (nutrients, chlorophyll-a, transparency, and microcystin-LR) as well as parameters related to lake recovery (pH, alkalinity, TOC, DOC, and colour).

4.2.1 Methodology

Four lakes were selected for this study: Aylesford Lake, Lake Mattatall, Nowlan's Lake, and Lake Torment. CyanoHABs have occurred in all lakes but Aylesford, and these lakes represent a range of anthropogenic impacts. Aylesford Lake has high recreational value with a public beach and boat launch, as well as seasonal and permanent residences. Lake Mattatall and Lake Torment are not public access lakes, but both have seasonal and permanent residences. Nowlan's Lake does not have either permanent or seasonal residences; there is however, a fur farm on the southeast shore.

4.2.1.1 Surface Water Quality Monitoring Program

A sampling program was conducted during summer 2017 to document the physical and chemical characteristics of each lake. The focus of the study was the potential impacts of increasing NOM, with special interest in lake eutrophication and trophic status. Water quality parameters measured included pH, conductivity, colour, total and dissolved organic carbon (TOC and DOC), UV absorbance (254ηm), nutrients, chlorophyll-a, microcystin-LR, and metals. Laboratory analysis was both conducted by CWRS, with the exception of chlorophyll-a analysis, which was performed at the Dalhousie University Department of Oceanography.

Each study lake was sampled twice - in early and late summer, in the location of the deepest basin and locations used in previous studies. When multiple deep basins were identified, samples were taken from each. Samples were collected 0.5 meters (m) from the surface and 1.0 m above the lake bottom - hereafter referred to as surface and bottom samples respectively, using a horizontal Van Dorn water sampler. In-situ measurements included temperature, dissolved oxygen, conductivity, pH - measured using a YSI-sonde, and transparency - measured using a 20 centimeter (cm) Secchi disk.

4.2.1.2 Water Sampling Procedure

Samples for metals analysis were collected in HPDE bottles that had been bathed in 10% (v/v) nitric acid for 24 hours, rinsed in triplicate with ultra pure water, and capped. Samples for physical/chemical analysis were collected in HDPE bottles that had been hand washed and rinsed in triplicate with ultra pure water. All samples were kept cool and in the dark during transport to CWRS or Department of Oceanography laboratories.

4.2.2 Results

4.2.2.1 Nutrient Concentrations

Both total phosphorus and total nitrogen are important nutrients for biological productivity in surface water, but management of total phosphorus has the greatest impact on controlling eutrophication (Schindler et al. 2016). Concentrations of total phosphorus and total nitrogen measured in this monitoring program were consistent with historical data (Lake Aylesford and Lake Torment). Mean total phosphorus and total nitrogen concentrations were of similar magnitude in Aylesford Lake, Lake Torment, and Lake Mattatall with total phosphorus ranging from 23.0 µg/L in Lake Mattatall to 32.7 µg/L in Lake Torment, and total nitrogen ranging from 140.4 µg/L in Aylesford Lake to 257.2 µg/L in Lake Mattatall. In Nowlan's Lake mean total phosphorus and total nitrogen values were 226.5 µg/L and 496.4 µg/L, respectively. Figure 2 shows mean total phosphorus and total nitrogen concentrations in each lake.

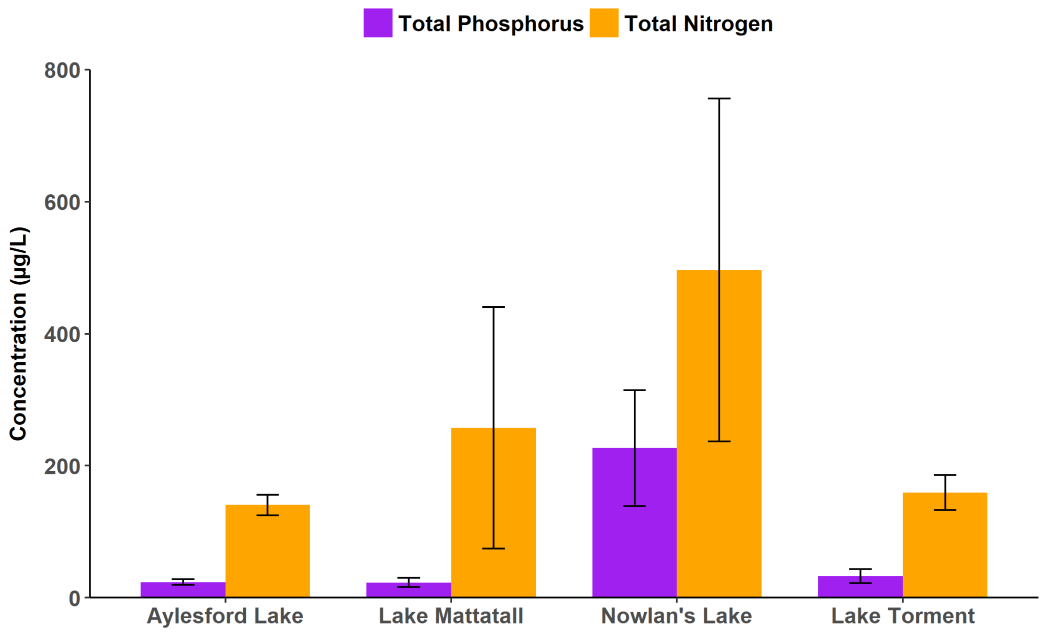

Figure 2 - Mean total phosphorus and mean total nitrogen concentrations in each study lake

4.2.2.2 Chlorophyll-a

Chlorophyll-a is a pigment contained in chloroplasts of photosynthetic organisms and is a commonly used indicator for phytoplankton biomass (Desortova 1981). Chlorophyll-a concentrations were highest in Nowlan's Lake which was consistent with the high nutrient concentrations in that lake. Surface chlorophyll-a concentrations ranged from 4.1 µg/L in Aylesford Lake to 19.8 µg/L in Nowlan's Lake. Bottom chlorophyll-a concentrations ranged from 1.2 µg/L in Lake Torment to 17.6 µg/L in Nowlan's Lake. Figure 3 shows the mean chlorophyll-a concentration measured in the surface and bottom of each lake.

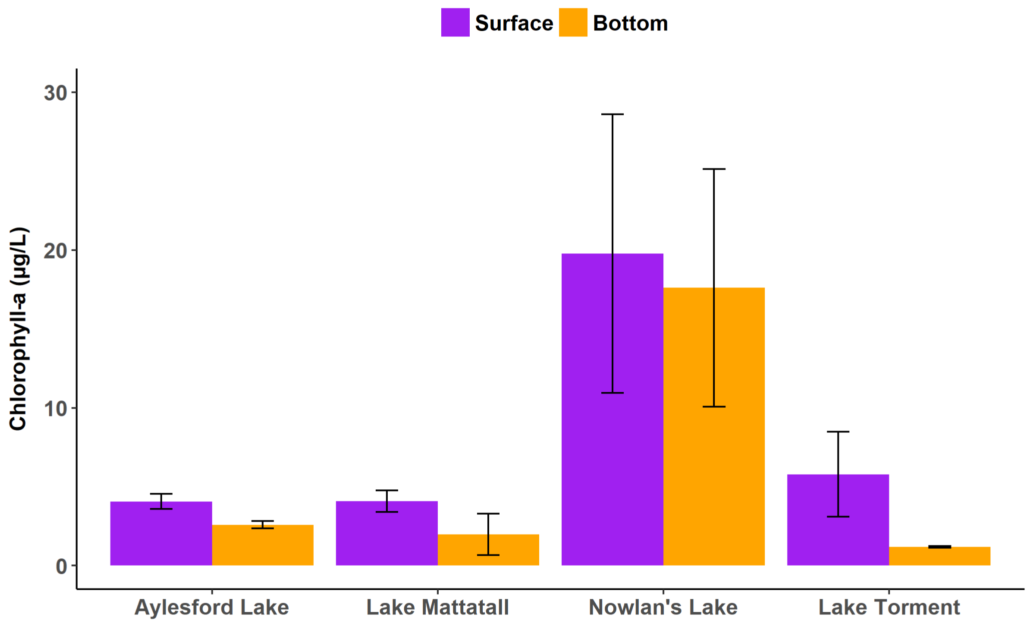

Figure 3 - Mean chlorophyll-a concentrations at the surface and bottom of each study lake (2017)

4.2.2.3 Water Transparency

The Secchi disk has long been used to measure water transparency. Secchi depth is affected by both algal and non-algal turbidity (Lind 1986), and in dystrophic lakes, may be affected by coloured organic matter (Brylinsky 2011). Secchi depth was highest in Aylesford Lake and lowest in Nowlan's Lake with depths of 2.6 and 1.4m respectively. Figure 4 shows the mean Secchi depth measured at each of the study lakes.

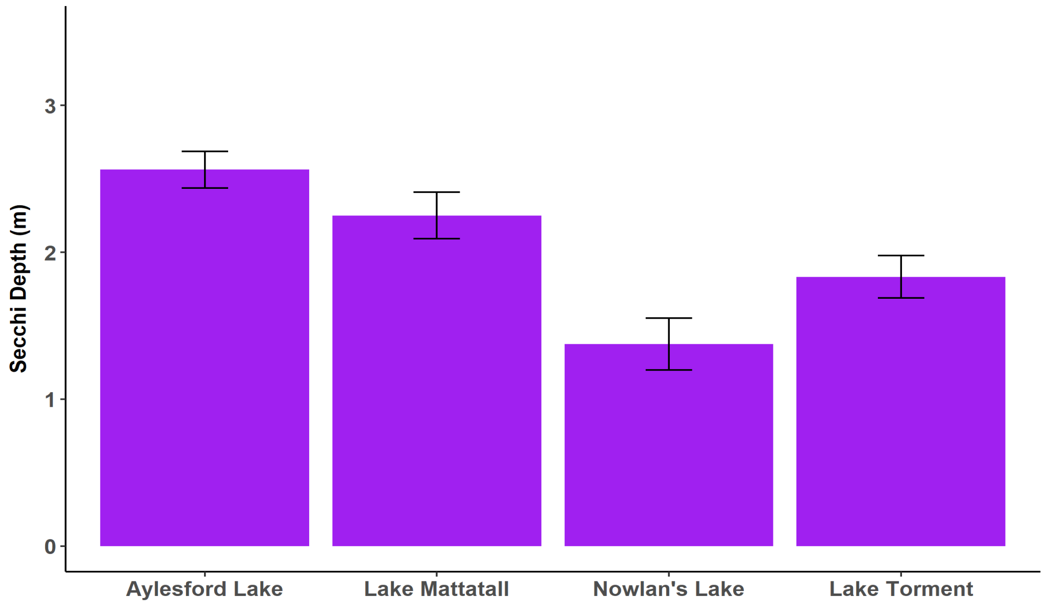

Figure 4 - Mean Secchi depth of each lake.

4.2.2.4 Total Nitrogen to Total Phosphorus Ratios

The ratio of total nitrogen (TN) to total phosphorus (TP) is used to determine which nutrient is limiting productivity. A molar TN:TP ratio greater than 17:1 indicates that phosphorus is limited, whereas a ratio less than 17:1 indicates nitrogen limitation (Vallentyne 1974). Cyanobacteria are favored by low TN:TP ratios (WHO 1999), because as nitrogen fixing bacteria, they are able to out-compete non-nitrogen fixers (Schindler 1977; Schindler 2012). Liu et al. (2011) showed that low TN:TP was correlated with increasing microcystis biomass. Table 2 shows the mean TN:TP ratios found at each lake for each sampling event. TN:TP ratios were less than 8 for both sampling events at Nowlan's Lake and for the August sampling event at Lake Torment.

Table 2 - Mean molar total nitrogen to total phosphorus ratio (TN:TP) for each sampling event at each study lake. Bolded TN:TP indicates conditions that may be favorable for cyanobacteria

	Date	TN:TP
Aylesford Lake	2017-06-01	13.7
	2017-08-01	13.3
Lake Mattatall	2017-06-19	19.6
	2017-07-13	24.5
Nowlan's Lake	2017-05-16	**3.7**
	2017-07-03	**5.7**
Lake Torment	2017-06-26	15.6
	2017-08-01	**7.3**

4.2.2.5 Microcystin-LR

Microcystin-LR is a toxin produced by several genera of cyanobacteria, and may be present in surface water even in the absence of bloom conditions (WHO 1999). WHO guidelines for microcystin-LR in recreational water are based on probability of adverse health effects, and are separated into three ranges:

- Low probability: 2 to 4 μg/L - potential for skin irritation following contact
- Moderate probability: <20 μg/L - potential for hepatotoxic effects following accidental ingestion
- High probability: Visible scum - potential for serious adverse effects following accidental ingestion

Microcystin-LR was detected in Nowlan's Lake in both sampling events at concentrations of 0.1 to 0.4 µg/L (0.1 µg/L MDL). At such low levels there is minimal risk of adverse health effects, but these results provide evidence of cyanobacterial presence in Nowlan's Lake. No microcystin-LR was detected in the other study lakes.

4.2.2.6 pH and Alkalinity

pH and alkalinity describe the acid-base status and buffering capacity of water, and both of these parameters have increased in NS lakes in response to reduced sulfate deposition (CWRS unpublished). Review of long term water chemistry data provided by the King's County Lake Monitoring Program indicates that pH has increased in lakes in that region, but alkalinity remains relatively unchanged (Appendix Figure S2).

Comparability of the results of the current monitoring program with historical data is difficult to assess, but the pH and alkalinity values measured during the summer of 2017 are of similar magnitude with recent historical results. Both pH and alkalinity were lower in Aylesford Lake and Lake Torment than in Nowlan's Lake and Lake Mattatall. Mean pH ranged from 5.80 in Aylesford Lake to 6.8 in Nowlan's Lake. Mean alkalinity ranged from 2.6 in Aylesford Lake to 14.6 mg/L as $CaCO_3$ in Lake Mattatall.

4.2.2.7 Organic Carbon and Colour

Increases in organic carbon concentration have been observed across North America and Europe (Monteith et al. 2007). Recent work done by CWRS, using colour as a proxy for organic carbon, found the same trend to be true in Nova Scotia. Data from the King's County Lake Monitoring Program indicates that colour has generally increased in lakes in that region as well (Appendix Figure S2).

Figure 4 shows mean organic carbon (both total and dissolved) concentrations at each of the study lakes. Dissolved organic carbon concentrations ranged from 4.7 mg/L in Lake Mattatall to 6.7 mg/L in Lake Torment. Differences between dissolved and total organic carbon for individual lakes were not statistically significant, indicating that the majority of organic carbon is in the dissolved form. Constituents of DOC impart colour to surface water, and colour is often used as a proxy for organic matter in surface water. Colour in the study lakes coincided with organic carbon concentrations, with the lowest colour in Lake Mattatall and the highest in Lake Torment (results not shown).

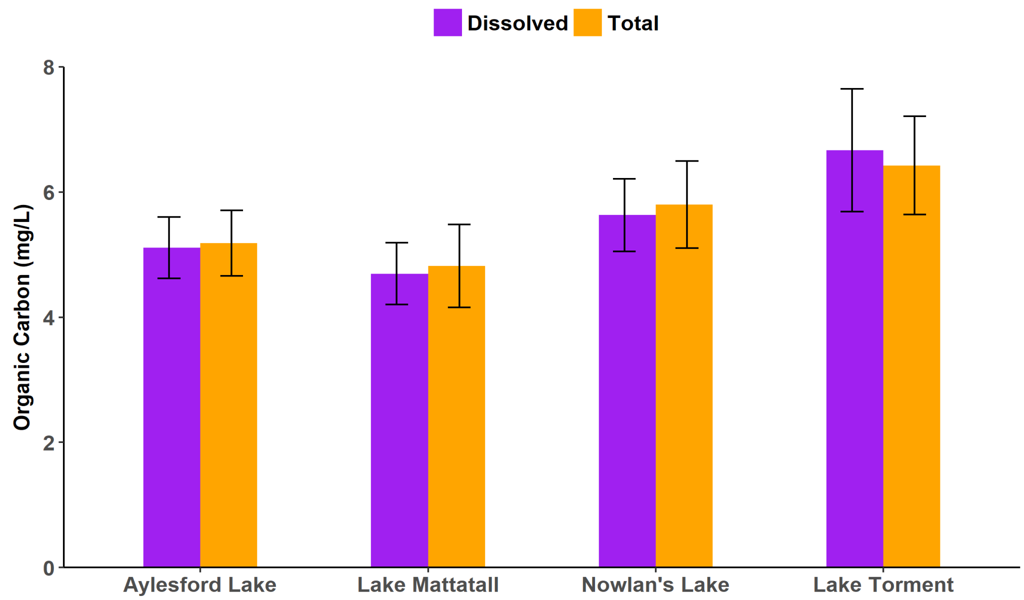

Figure 4 - Mean total and dissolved organic carbon concentrations in each study lake.

4.3 Task 3: Data Analysis and Modelling

4.3.1 Long Term Trends

Review of long term data shows that lakes in Nova Scotia are responding to reduced sulfate deposition with increases in pH and NOM. These improvements in acid-base status have been accompanied by increases in organic carbon and colour – findings that are consistent with trends in other parts of North America and Europe. Increases in chlorophyll-a concentrations in King's County Lakes, despite no observed increases in nutrient concentrations suggests a change in the sensitivity of lake biological productivity to nutrient loads. Potential causes of this include changing temperature (warmer water, longer ice-free season, changes in thermal stratification) and changing light regime. Recent work by Seekel et al. (2015) found that a threshold DOC exists, below which the increases in DOC improve primary production by increasing nutrient availability, and above increases in DOC inhibit primary productivity by decreasing light availability. It is evident that organic matter is increasing in lakes across Nova Scotia, but the impact of this change on biological function, and thereby sensitivity to nutrient loading, remains to be elucidated.

4.3.2 Lakes in King's County, NS

Of the four study lakes included in this monitoring program, only one lake – Aylesford Lake – has not experienced cyanoHABs. Given that water chemistry in Aylesford Lake and Lake Torment are relatively similar, and they are in the same region, lake morphology (i.e. depth, volume, flushing rate) might play a role in explaining the apparent lack of susceptibility of Aylesford Lake to cyanoHABs. During the August sampling event at Lake Torment TN:TP ratios were such that cyanobacteria would be favored, and it is possible that over the course of the summer, phosphorus loading increases due to recreational activity on the lake.

The occurrence of cyanoblooms in Nowlan's Lake is very likely the result of high nutrient loading to that lake. Phosphorus concentrations in excess of 250 µg/L were measured in this monitoring program, and similar (and greater) concentrations have been measured in previous studies (Bylinski 2011). Low total nitrogen to total phosphorus ratio in this lake favors cyanobacterial proliferation, and the detection of microcystin-LR, albeit at low concentrations, highlights the importance of controlling nutrient inputs to this lake.

4.3.3 Trophic Status

Trophic status refers to the biological productivity of a lake, and ranges from oligotrophic (unproductive) to eutrophic (very productive). Historically, nutrient concentrations (total phosphorus and total nitrogen), chlorophyll-a concentration, and water transparency (Secchi depth) have been used as indicators of trophic status (Vollenweider and Kerekes 1982). The Organization for Economic Cooperative Development (OECD) provides ranges used to determine trophic status as shown in table 3. In Canada, a guidance framework based on OECD ranges is used to assess phosphorus concentrations. This framework views the upper value of phosphorus concentration for a given trophic status as a "trigger value". If phosphorus concentrations in a water body are more than 50% greater than the trigger value for its baseline trophic status, action may be required (Environment Canada 2004). This framework relies upon knowledge of baseline trophic status.

Table 3 - OECD ranges for trophic status categories

	Parameter		
	Total Phosphorus (μg/L)	Chlorophyll-*a* (μg/L)	Secchi Depth (m)
Ultra-oligotrophic	< 4	< 1.0	≥ 6.0
Oligotrophic	≥ 4 - < 10	≥ 1.0 - < 2.5	≥ 3.0 - < 6.0
Mesotrophic	≥ 10 - < 35	≥ 2.5 - < 8.0	≥ 1.5 - < 3.0
Eutrophic	≥ 35 - < 100	≥ 8.0 - < 25.0	≥ 0.7 - < 1.5
Hyper-eutrophic	≥ 100	≥ 25.0	< 0.7

Many lakes in Nova Scotia are dystrophic, meaning that they are highly colored due to relatively high inputs of humic and fulvic acids (Brylinsky 2011). As a result, dystrophic lakes may have low transparency that would typically be associated with biological productivity. In these lakes however, low transparency is not solely the result of algal biomass (Brylinsky 2011).

Lake	Activities	Past Issues	Trophic Status (2017)	Microcystin LR (2017)
Aylesford Lake	Residential, recreational	None	Mesophilic	No
Lake Mattatall	Residential, recreational	Algae blooms	Mesophilic	No
Nowlan's Lake	Fur farming	Algae blooms	Eutrophic	Yes
Lake Torment	Residential, recreational	Algae blooms	Mesophilic	No

5.0 Conclusions and Recommendations

Increased occurrence of cyanoHABs in NS lakes is concerning for recreational water users, local residents, and policy-makers alike. Blooms are unsightly and may result in the release of cyanotoxins, and subsequent loss of aesthetic value of recreational lakes.

Lack of historical data makes it difficult to hypothesize as to drivers of the increasing frequency and duration of cyanoHABs in NS lakes. Data from King's County lakes suggest increasing biological productivity despite no apparent change in nutrient loading. Organic matter concentrations in lakes across the province are increasing and links between lake organic matter content and primary productivity have been made (Seekel et al. 2015). This represents an area for future research in Nova Scotia.

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Appendix

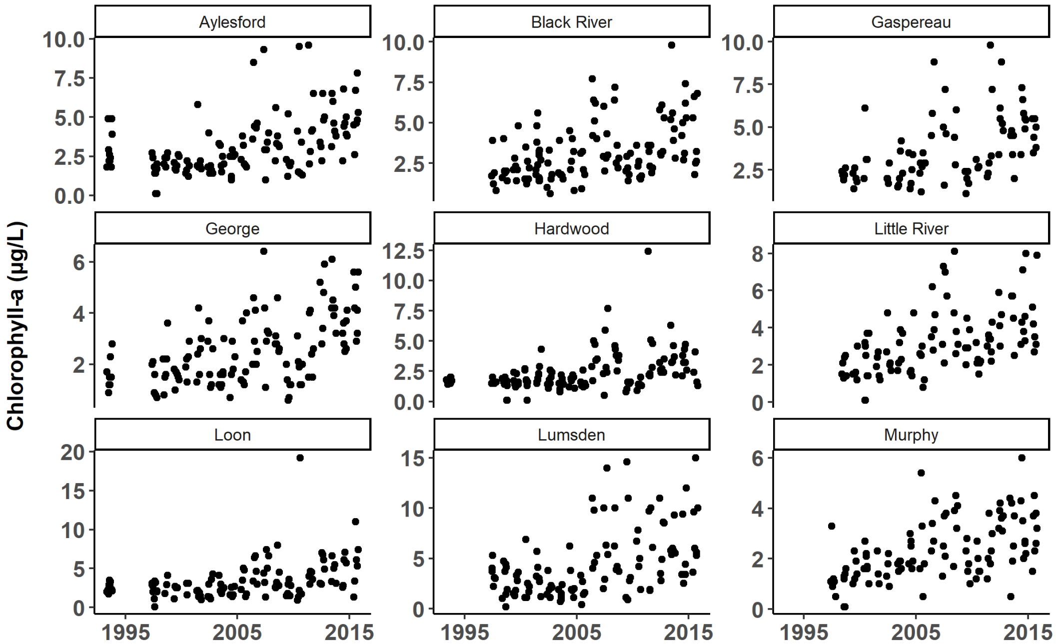

Figure S1 - Chlorophyll-a concentrations in King's County Lakes from 1995 to 2016.

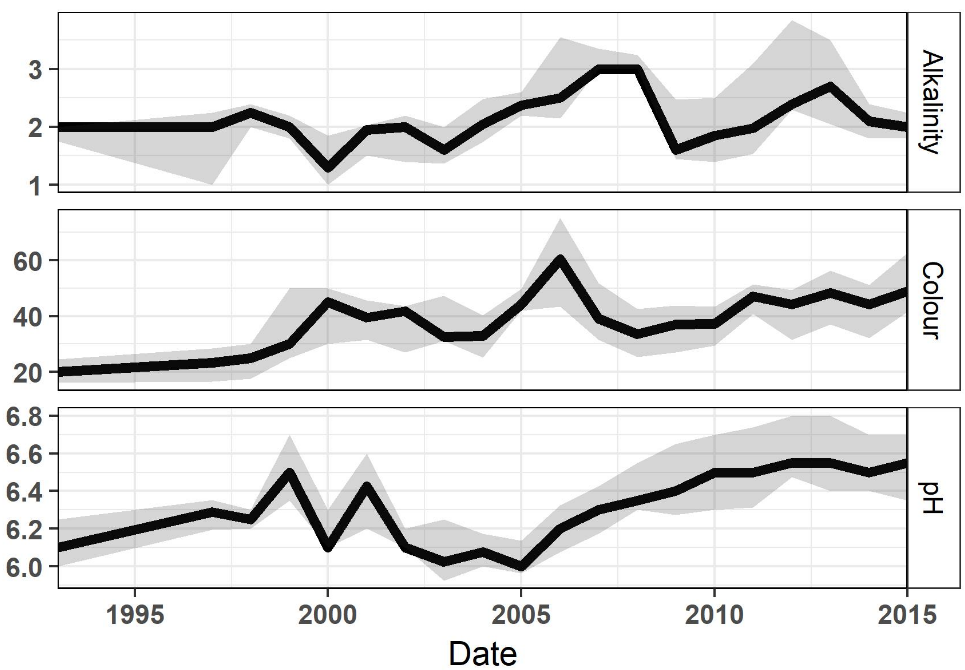

Figure S2 – Median alkalinity (mg/L $CaCO_3$), colour, and pH of King's County Lakes from 1995 to 2016 with associated 95% confidence intervals denoted by background shading

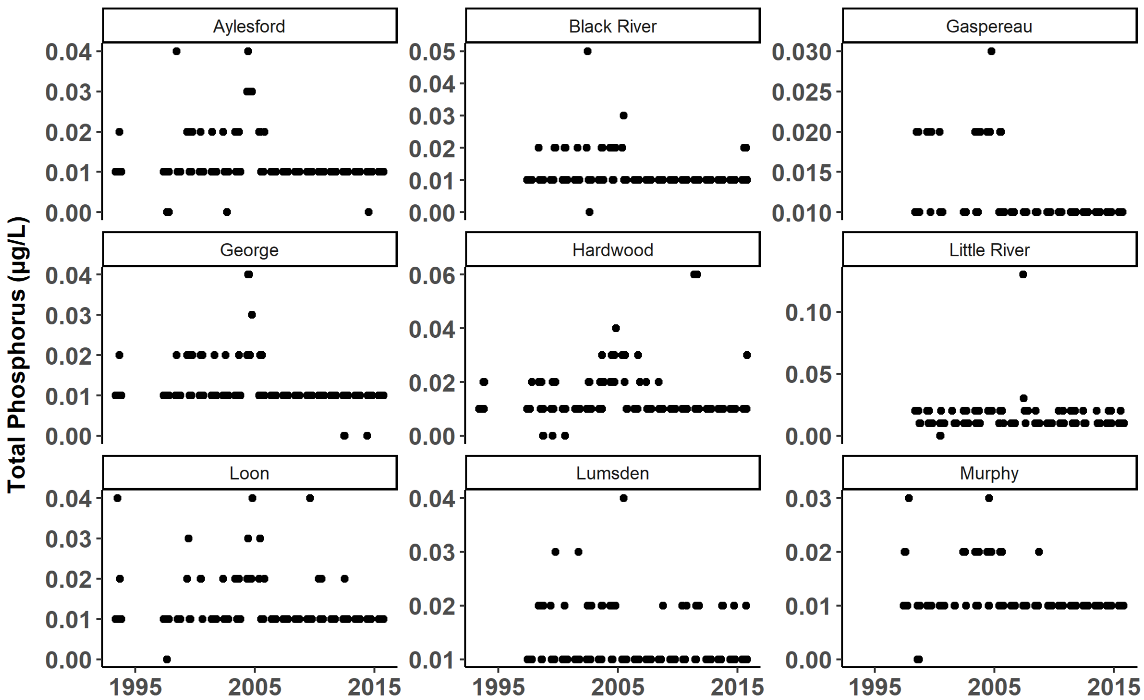

Figure S3 - Total phosphorus concentrations in King's County Lakes from 1995 to 2016.

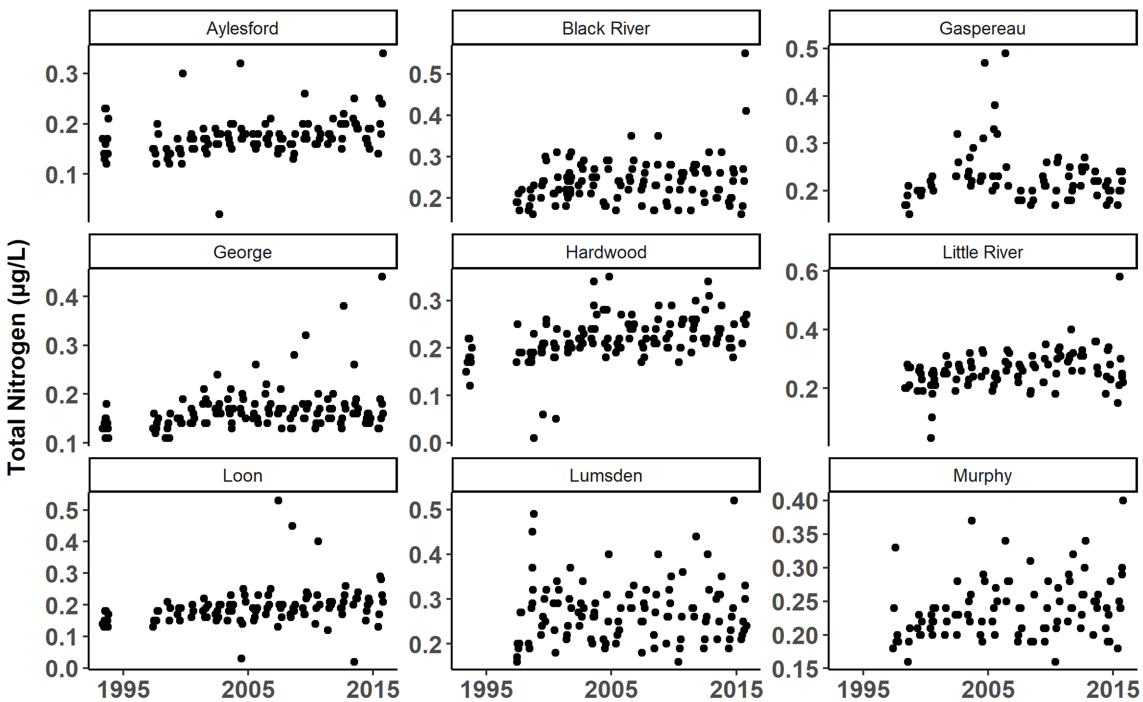

Figure S4 - Total nitrogen concentrations in King's County Lakes from 1995 to 2016.