Investigating Changes in Chlorophyll *a* and Other Water Chemistry Variables in Response to Global Environmental Change

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ABSTRACT

Changes in water quality are influenced by climate change and other anthropogenic stressors. We 1) assessed changes in water quality in lakes in the Laurentian Great Lakes region, and 2) compiled water quality data for lakes across the world to assess global patterns in chlorophyll *a*. We found that at the regional scale water quality (specifically chlorophyll *a*, total phosphorus, total nitrogen, and dissolved organic carbon) were influenced by temperature, precipitation, morphology, and the presence of dreissenids. We also compiled chlorophyll *a* and water chemistry data together with morphometric characteristics for 8557 lakes worldwide. This global dataset will allow researchers to associate global water quality patterns to different pressures such as changes climate or land use.

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Chapter 1

GENERAL INTRODUCTION

Healthy freshwater ecosystems are essential for human survival and play an integral role for millions of species worldwide (Michalak 2016). Further, freshwater lakes provide an extensive range of ecosystem services ranging from clean drinking water and food security to recreation and transportation (Williamson et al. 2009). However, climate change and anthropogenic stressors, such as agriculture, urbanization, and industrialization, are changing the physical, chemical and biological properties of aquatic ecosystems (Michalak 2016). Multiple stressors often combine to create conditions that may further degrade water quality. For example, Lake Erie has experienced record breaking harmful algal blooms that coincided with long-term phosphorus loading from agricultural practices, warming temperatures and changes in precipitation patterns (Paerl and Huisman 2008; Michalak et al. 2013). Impaired water quality can cause millions of dollars of damage and leave many communities without a clean, usable water source (Michalak 2016). Therefore, understanding how climate change and other human stressors may influence water quality remains an important topic of research.

Climate change, including warming temperatures and associated hydrological changes, is affecting the biotic and abiotic components of lake ecosystems. Increased temperatures may lead to the excessive proliferation of phytoplankton species that can cause harmful algal blooms (Paerl et al. 2001; O'Reilly et al. 2015). Variability in precipitation patterns can cause increased runoff from surrounding catchments. For example, increased dissolved organic carbon input can lead to a decline in water clarity (Mormul et al. 2012). Further, increased land use intensity is changing water quality in many freshwater systems. For instance, agriculture and urbanization have altered natural landscapes via fertilizer run-off, increased wastewater discharge, and changes in overall surface permeability, which have all contributed to excess phosphorus and nitrogen loadings into lakes (Bennett et al. 2001). Lastly, the introduction of invasive species, such as zebra and quagga mussels continue to have negative consequences on aquatic ecosystems by altering water transparency and nutrient cycling (Leach 1993; Conroy et al. 2005). Therefore, it is evident that freshwater lakes are extremely sensitive to global environmental change having direct and/or indirect impacts on the physical, chemical and biological lake parameters, corresponding to water quality degradation.

My thesis aims to examine the effects of climate change and other anthropogenic stressors on water quality, specifically chlorophyll levels, dissolved organic carbon, total phosphorous, and total nitrogen concentrations. I explore these effects at two spatial scales in two chapters: first by focusing on freshwater lakes situated within the Laurentian Great Lakes watershed changing through time, and second by employing a broader examination of global patterns in water quality. In the first chapter, we examined water quality trends between 1976-2016 for 36 lakes in the Laurentian Great Lakes area. Few studies have incorporated numerous water quality variables, including the physical, chemical and biological properties of a lake, and fewer have broad spatial scales, generally focusing on a single region. Here, we examine ≥20-year time-series data for total phosphorus (TP; µg/L), total nitrogen (TN; µg/L), dissolved organic carbon (DOC; mg/L), chlorophyll a (Chla; µg/L) and climate of lakes with varying geomorphometric characteristics across the Great Lakes watershed. We hypothesize that water quality is changing in the north temperate region because of climate change, and the introduction of invasive species and differences in lake morphometry. In my second chapter, we broadened our study region to include data from 8557 lakes across 44 countries. With this broader geographic dataset, we aim to identify lake Chla and other water chemistry patterns, relating them to climate and land use across a global scale. Largescale Chla datasets have received little attention in the literature, especially at the global scale, despite the close relationship between chlorophyll concentrations and water quality in freshwater systems. Using the geospatial coordinates of an individual lake, researchers will be able to relate chlorophyll patterns in this publically available dataset to global environmental pressures such as climate and anthropogenic disturbances.

Citations for MSc thesis:

Over the course of the MSc degree, I have submitted one paper related to the impacts of climate change on lake water quality to *Limnology and Oceanography*. The second chapter will be submitted as a data paper to Scientific Data.

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Chapter 1: Drivers of water quality changes in North American lakes over the past 40 years

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MY CONTRIBUTION

The manuscript titled, “Drivers of water quality changes in North American lakes over the past 40 years” was submitted to the journal Limnology and Oceanography. The authors of this publication include Alessandro Filazzola, Lewis Molot, Derek Gray, and Sapna Sharma. I analyzed all the data, and wrote the Abstract, Introduction, Methods, Results, and Discussion. I also created all figures and tables, and supplementary figures and tables.

SUMMARY

Water quality of freshwater lakes in North America is vulnerable to degradation owing to multiple environmental stressors including climate change, alterations in land use, and the introduction of invasive species. Our research questions were two-fold: 1) Is water quality in north temperate lakes changing? and 2) Are climate and invasive species contributing to these changes in water quality and how are they affected by lake morphology? Our study incorporated time-series data for at least 20 years from 36 lakes in Ontario and Wisconsin sampled between 1976-2016. First, we evaluated trends in water quality (total phosphorus (TP), total nitrogen (TN), dissolved organic carbon (DOC), and chlorophyll a (Chla)), and climate (temperature and precipitation) using Sen slopes analysis. Generally, across lakes over the past 40 years, lake TP and Chla have significantly declined, whereas DOC has increased. Mann-Whitney tests revealed that TP and Chla were decreasing at significantly faster rates in the Great Lakes compared to smaller inland lakes. Second, we conducted a redundancy analysis (RDA) to identify how climate, lake morphology, and the presence of invasive dreissenid mussels contributed to changes in water quality. The RDA revealed that precipitation, temperature, morphology, and occurrence of mussels explained 73.1% of the variation in water quality trends for the Great Lakes and 45.6% of the variation for inland lakes. The results suggest that water quality changes in the Laurentian Great Lakes region could increase the risk of algal blooms, impaired water quality for aquatic species, and limit freshwater resources for human use.

INTRODUCTION

Clean freshwater is an essential resource for human survival, ecosystem health, and sustainable economic development as it is used daily for drinking, fishing, irrigation, transport, and recreation (Beeton 2002; McMichael et al. 2006). However, water quality is becoming increasingly degraded owing to anthropogenic stressors including climate change, urbanization, agriculture, and the introduction of invasive species (Khalanski 1997; Peters and Meybeck 2000; Foley et al. 2005). North American lakes are already experiencing the combined effects of warming temperatures, changes in hydrology, inputs of excess nutrients, and non-native species invasions (Schindler 2009). Consequences of multiple stressors on water quality include a higher risk of algal blooms, changes in water chemistry, and unprecedented disturbances to biodiversity in aquatic ecosystems (Yan et al. 2001). Further, the structure and function of aquatic ecosystems may be altered as water quality could be directly or indirectly influence a lake’s response to environmental changes (Alberti 2005; Vincent 2009). For example, less favorable water quality conditions may result in changes in life history traits in fish, such as smaller body sizes, that could ultimately effect the composition of fish assemblage and food web dynamics which may lead to negative impacts on not only fisheries but entire biological communities (Jeppesen et al. 2010; Wrona et al. 2016). Lastly, climate change has been identified as one of the most influential stressors affecting water quality in North American lakes (Adrian et al. 2009). In particular, warming air temperatures have produced some of the most severe water quality impacts to date (Michalak 2016; Murdoch et al. 2000; O’Reilly et al. 2015).

Increasing temperatures have been consistently found to promote the intensity, frequency, and duration of harmful algal blooms which yield harmful toxins, release noxious taste and odor compounds, and ultimately disrupt overall lake production (Winter et al. 2011; Paerl et al. 2016). For example, in the Laurentian Great Lakes watershed, increasing air temperatures have led to shorter or no ice cover duration (Hewitt et al. 2018; Sharma et al. 2019), warmer water temperatures (O'Reilly et al. 2015), increased stratification (Stainsby et al. 2011), decreased dissolved oxygen concentrations (Magnuson et al. 1997) and favorable environments for toxic phytoplankton blooms (Anderson et al. 2002). Climate change further affects water quality by altering regional hydrological patterns. Increased variability in precipitation influences the amount and frequency of nutrients being flushed into lakes from surrounding catchments. For example, Hudson et al. (2003) found that more rainfall delivers an excess amount of terrestrial-derived organic matter, specifically dissolved organic carbon (DOC), into lakes. This introduction of DOC, which is also referred to as brownification, may lead to adverse water quality conditions including color change, decreased light attenuation, and anoxia (Kritzberg and Ekström 2012; Brothers et al. 2014). To better estimate future changes in water quality, there is a need to describe the historical relationship between water quality and climate across a gradient of lake types.

In addition to changing climates, anthropogenic stressors such as land use changes (e.g., urbanization and agriculture) may increase nutrient loadings into aquatic systems and lead to a degradation of water quality. Natural vegetation surrounding lakes all over North America have been replaced by constructed impervious surfaces, or areas equipped for irrigation and livestock (Morgan et al. 2004; Ramankutty et al. 2018). Changes to these once natural landscapes results in lands that are treated with fertilizers and pesticides and produce more sewage and waste that can enter waterways (Paerl et al. 2016). Fortunately, over the past few decades, many initiatives have been implemented to reduce the amount of nutrients being discharged into lakes in the Laurentian Great Lakes watershed. For example, large decreases in TP and total nitrogen (TN) occurred in Lake Erie and Lake Ontario after the implementation of the 1972 US-Canada Water Quality Agreement (Dove and Chapra 2015). Further, North et al. (2013) showed that over time there have been declines in total phosphorus (TP) concentrations in Lake Simcoe as a result of better management practices. Yet, the new threat of climate change in addition to nutrient levels, may be sufficient to tip the scales towards adverse water quality conditions and may promote harmful phytoplankton production (Paerl and Huisman 2008).

The introduction of invasive species into the Great Lakes basin has had a profound impact on lakes in the region (McKenna 2019). The establishment of non-native zebra (*Dreissena polymorpha*) and quagga (*Dreissena bugensis*) mussels in North American lakes has caused notable water quality and ecosystem modifications (Coleman and Williams 2002; Ricciardi and MacIsaac 2000). Zebra and quagga mussels can form thick colonies on aquatic plants and hard and soft surfaces which may interfere with water supplies for drinking, irrigation, and hydropower (Ricciardi et al. 1998; Stokstad 2007). Waterbodies occupied by invasive dreissenid mussels have been associated with changes in nutrient cycling, increased water clarity (Leach 1993; Lowe and Pillsbury 1995; Conroy et al. 2005), and improved deep water dissolved oxygen (Li et al. 2017). The filter feeding abilities of these invasive mussels have been shown to deplete chlorophyll, particulate nutrients, and food availability for other aquatic species (Beeton 2002; Stefanoff et al. 2018). Nutrient dynamics may also be altered which can promote harmful algal blooms. For example, Vanderploeg et al. (2001) demonstrated that *Microcystis*, a species of toxic phytoplankton, was selectively rejected by zebra mussels. Simultaneously, the same mussels were reducing levels of competing algae, resulting in more available nutrients in the water column that formed noxious cyanobacterial blooms of *Microcystis*. The effects of dreissenid mussels in the Great Lakes have been extensively studied (Ludyanskiy et al. 1993; Lowe and Pillsbury 1995; Ricciardi and MacIsaac 2000; MacIsaac 1996), but their impacts on smaller inland lakes in relation to algae blooms and climate are less understood.

This study aimed to assess changes in water quality, defined here as Chla, TP, TN and DOC concentrations, for lakes in the Great Lakes basin, and to identify how climate change and other anthropogenic pressures may be driving those changes. To do this, we assessed water quality trends over the past 40 years in the Laurentian Great Lakes watershed and examined how they were related to a diverse set of physical, chemical, and biological variables (Table 1). By considering a suite of variables that may be influencing water quality, we specifically addressed the following questions: (1) How has water quality changed over time? (2) Are there spatial patterns in water quality trends? and (3) Are climate, surface area, and invasive dreissenid species associated with changes in water quality?

METHODS

Study Area

Our study region includes lakes in Ontario and Wisconsin that are found within the Great Lakes basin or in neighbouring watersheds. The Great Lakes basin is the largest freshwater system in the world, accounting for one-fifth of the freshwater surface on the planet (Van Der Leeden et al. 1990), and is home to millions of Canadian and U.S. residents who rely on the system for drinking water, recreation, industrial, and agricultural uses (Ducey et al. 2018). However, over the past few decades, lakes in this region have been experiencing increased anthropogenic pressures as population growth expanded from 46 to 52 million (Pendall et al. 2017). Land use around the small inland lakes in the Dorset, Turkey, Sudbury and Experimental Lakes Area regions in Ontario were limited to forestry and cottages, while lakes in the Wisconsin region experienced increased urban development (Wolter et al. 2006; Ducey et al. 2018). Lake Simcoe has experienced multiple pressures from increasing human activities over the past 200 years, including logging, damming, canal construction, agriculture, urban development, species invasion, and recently climate change (Hawryshyn et al. 2012). Further, Lake Ontario, Erie, Huron, Superior, and Simcoe assimilate wastewater from numerous municipal water pollution control plants. Although our study includes only a small fraction of the tens of thousands of lakes in Ontario and Wisconsin, our study lakes represent a broad gradient of lake morphology and a range of north temperate climates allowing the exploration of water quality patterns and drivers in diverse lake typologies.

Data acquisition

Long-term temporal data

Long-term morphological (surface area and mean depth), chemical, and biological data were retrieved for a total of 45 sampling sites from a set of 36 lakes in Canada and the United States for periods ≥20 years between 1976-2016 (Table 2). Water quality variables included TP (µg/L), TN (µg/L), dissolved organic carbon (DOC; mg/L), and chlorophyll a (Chla; µg/L). Long-term data available for this region were amalgamated in this study resulting in an extensive dataset available for examining long-term changes. Data for each lake were consistently and continuously collected from year to year during the ice-free season (May-October). Methods of data collection were consistent at each individual lake but may have differed among lakes depending upon the data source. Specific sampling details can be found in Center for Limnology 2012; desc.ca/; Hampton et al. 2017; iisd.org/ela/;. We were not concerned about inconsistencies in sampling and analytical methods among lakes, as water quality trends were calculated for each lake individually.

Historical Meteorological Data

Climate data were obtained from the Climate Research Unit (CRU) at the University of East Anglia (Harris et al. 2014). Monthly surface air temperature and precipitation means were downloaded from version 4.01 gridded time-series dataset (covers the period 1901-2016) covering all land areas at a spatial resolution of 0.5°. Data were subsequently imported into *R* using the "ncdf4" package (https://CRAN.R-project.org/package=ncdf4; R Development Core Team 2019). Using monthly climate means, we calculated seasonal means for each lake with seasons defined as winter (December-February), spring (March-May), summer (June-August), and fall (September-November).

Data analysis

Temporal trends in water quality

For each lake, we calculated a Sen slope (Sen 1968) to measure trends in TP, TN, DOC, Chla, air temperature, and precipitation between 1976 and 2016. Sen slopes analysis is a non-parametric method that calculates the median of all pairwise slopes within a dataset to statistically test trends. Sen slopes are resistant to outliers and non-normality and have been used in previous work to assess trends in water quality (Wilcox 2011; O'Reilly et al. 2015; Rose et al. 2016; Strock et al. 2017). Sen slope values and their statistical significance were calculated in *R* using the package "openair" (Carslaw and Ropkins 2012; R Development Core Team 2019). Missing data, owing to instances where some observational years where not sampled, made up <5% of all data points. In these cases, missing data were imputed using a Multiple Imputation by Chained Equation approach using the "mice" package (Van Buuren and Groothuis-Oudshoorn 2011) to obtain a full dataset. The Sen slopes calculated for each lake over the selected timeframe were subsequently used as the response variables for investigating spatial patterns in water quality trends as well as the associations between water quality and climate, lake morphology, and dreissenid species.

Following our quantification of water quality trends by lake, we separated lakes into two groupings with "the Great Lakes" comprised of Lake Ontario, Lake Huron, Lake Erie, and Lake Superior, and "inland lakes" comprised of all remaining smaller inland lakes. This separation was implemented because large and small lakes behave quite differently owing to their difference in water volume (Moses et al. 2011). For example, Lake Ontario is the smallest of the Great Lakes, but was larger than all the small inland lakes in our dataset combined, and therefore we expected it to exhibit different limnological responses (Beeton 1984). We compared the rate of change for the water quality of large versus small lakes by assessing TP, TN, DOC and Chla Sen slope values for each grouping using the Mann-Whitney (MW) test. The non-parametric MW test is a common method to determine if there is a difference in medians between two groups when the data are not normally distributed (Ruxton 2006).

Spatial patterns in inland lakes in water quality

We identified if changes in water quality over time were spatially autocorrelated in the small inland lakes by calculating Moran's I statistic (Odland 1988) using the Moran I function in the "ape" package in R Studio (Paradis and Schliep 2018; R Development Core Team 2019). Significant spatial autocorrelation values indicated the degree to which one value, at a given location, was similar to other values within a defined spatial radius. To calculate Moran's I, matrices of inverse distance weights of TP, TN, DOC and Chla trend values were generated where pairs of points closer together (using site spatial coordinates) were weighted higher than points farther apart. The inverse of the matrix values was taken, and diagonal entries were replaced with zeros. Moran's I was not performed on the Great Lakes as they cover a considerably larger surface area yet had fewer sampling points.

Drivers of water quality trends

We investigated drivers of water quality trends in the Great Lakes and small inland lakes using a redundancy analysis (RDA) implemented in the rda function found in the "vegan" package for R (https://CRAN.R-project.org/package=vegan; R Development Core Team 2019). RDA (package vegan, function rda) is a direct gradient ordination analysis which summarizes the linear relationship between a multivariate set of response variables to explanatory variables (Legendre and Legendre 2012). We used an RDA rather than other ordination techniques, such as a Canonical Correspondence Analysis, because the response variables had a linear distribution that was identified from a detrended correspondence analysis with a gradient axis of less than 2 (Legendre et al 2011). The Sen slopes for TP, TN, DOC, and Chla calculated for each lake were used as the response variables. The data were standardized to provide a comparable unitless scale to compare lake morphology with water quality and climate variables. Explanatory variables for both RDAs included morphological characteristics (surface area, mean depth and elevation) and climatic variables (winter, spring, summer and fall temperature and precipitation), whereas dreissenid mussel invasion was only included for the small inland lakes RDA as all the Great Lakes are already invaded. Prior to analyses, we assessed potential multicollinearity between seasonal climate and morphometric variables using a Spearman rank correlation matrix in R (package corrplot). Climate and morphometric variables that were highly correlated ($r > 0.7$) were removed from the RDA.

RESULTS

Temporal trends in water quality

In the Laurentian Great Lakes, TP and Chla concentrations decreased over time and DOC increased over time (Table 3; Figure 1). Some of the strongest decreases in TP were observed in the Great Lakes, whereas the more northern inland lakes experienced a less intense decrease in TP (Figure 1a). The response of TN was mixed, with increases and decreases at various magnitudes with no spatial pattern (Figure 1b). DOC showed an increasing trend through most of the landscape, however, there were no significant trends in DOC in the Great Lakes or lakes in the Turkey Lakes Watershed (Figure 1c). Trends in Chla decreased overall, except for some lakes in the Wisconsin region that increased (Figure 1d). Over the entire Great Lakes watershed temperature increased throughout all seasons. In most regions, winter precipitation increased and spring precipitation decreased. Climatic trends by region can be found in Table S1.

The rates of change in TP and Chla were significantly different in the Great Lakes than in small inland lakes (MW test: $p_{TP} = 0.01$, $p_{Chla} = 0.03$). TP and Chla decreased at a faster rate in the Great Lakes ($\bar{X}_{TP}= -0.25$, $\bar{X}_{Chla}= -0.2$) than in inland lakes ($\bar{X}_{TP}= -0.05$, $\bar{X}_{Chla}= -0.02$).

Spatial patterns in water quality

Results from the Moran’s I statistic indicated that DOC was the only water quality variable that had a statistically significant degree of positive spatial autocorrelation in small inland lakes (Moran’s I = 0.45, p = <0.001; Table S2). This suggested that there was spatial structure in DOC as neighbouring small lakes experienced increases in DOC at similar rates. There was no spatial structure in TP, TN, and Chla (p>0.05 for all comparisons).

Drivers of trends in water quality

The RDA explained 73.1% of the variation in changes in water quality over time for the Great Lakes (Figure 2a). The first axis explained the most variation at 48.2%, and the second axis explained an additional 31.9%. In the Great Lakes, wetter springs were associated with increases in Chla, whereas higher DOC was correlated to warmer spring and winter temperature. The percentage of variation explained by the RDA for small inland lakes was 45.6% (Figure 2b,c). The first axis accounted for most of the variation (39.5%) and the second axis accounted for 15.9% of the variance. The presence of dreissenids combined with cooler winter and spring temperatures was associated with increasing Chla in inland lakes. Lower altitude inland lakes receiving less fall precipitation were associated with decreases in DOC and TP. TN was not influenced by climate, lake morphology, or dreissenid invasion in both the Great Lakes or small inland lakes in this study region.

DISCUSSION

Our study provides an overview of the spatial and temporal trends and drivers of water quality for north temperate lakes of North America. In this study, we examined 20 to 40-year time series from 36 North American study lakes with a broad range of morphometric characteristics to document how multiple environmental stressors have affected water quality. We found that water quality has changed over time, with increasing DOC levels in most lakes. TP and Chla were mostly decreasing in the Great Lakes region, although Chla has been increasing in the most southern inland lakes in our study. Climate, temperature and precipitation, in addition to surface area and dreissenid presence were all found to be important drivers for DOC and Chla concentrations in the Laurentian Great Lakes watershed. Our results show that there have been significant changes in water quality over time which can potentially influence key limnological processes and ecosystem services.

Trends in water quality over the past 40 years

We observed significant declines in TP concentrations in 20 of our study lakes over time. TP decreased in Lakes Erie, Huron, and Ontario at a significantly faster rate than in small inland lakes coinciding with multiple initiatives that targeted the reduction of TP entering the Great Lakes over the past four decades (De Pinto et al. 1986; Baker et al. 2019). The 1972 Great Lakes Water Quality Agreement aimed to reduce the amount of TP loadings from direct sources by improving sewage treatments and from indirect sources by reducing TP inputs associated with urban development and agriculture (De Pinto et al. 1986; Carpenter et al. 1998; Winter et al. 2011). Many smaller lakes, regardless of human activity (e.g. Dickie and Harp lake having high cottage densities while Plastic lake has none) or undisturbed forested watersheds (e.g. the Turkey

Lakes), also experienced decreasing trends in TP. Eimers et al. (2009) found that lower TP concentrations in streams during the spring resulted in decreased TP exports to lakes found in the Dorset region suggesting these major changes in TP exports to inland lakes are governed by terrestrial processes (Palmer et al. 2011). However, long term declines in TP were not consistent with expectations based on redox processes involving Fe (e.g., due to dry lands) (Eimers et al. 2009), less fertilizer runoff and local waste production (Dillon et al. 1993), decreases in wetland cover (which is not consistent with increases in DOC over time) (Dillon and Molot 1997; O'Brien et al. 2013), or changes in cottage density (Quinlan et al. 2008). Consequently, the causes of long-term TP decline in this region are uncertain and should remain the focus of future research.

Nutrient loading, invasive species, and climate change are factors affecting chlorophyll production in lakes (Richardson et al. 2018). We observed decreases in Chla at 30 study sites across the entire study region. Declines in the Great Lakes may be explained by improved waste water treatment and aquatic mitigation measures (Smith et al. 1981). Whereas Chla decreases in small inland lakes were due to changes in terrestrial export mechanisms. Declining trends in Chla may also be a result of the introduction of invasive species, such as zebra and quagga mussels, into North American freshwaters in the mid 1980's (Ludyanskiy 1993). High densities of these non-native species allow them to filter-feed large volumes of water decreasing nutrient availability and phytoplankton biomass (and Chla) in the water column (Qualls et al 2007). This could be contributing to the faster decrease in Chla occurring in the Great Lakes relative to the smaller inland lakes which lack dreissenids. However, our observed trends in Chla may not accurately represent conditions in individual lakes at any given point in time because chlorophyll levels can be spatially and temporally heterogeneous. For example, despite the decreasing trends in Chla in Lake Huron over the study period, there have been several reports of toxic phytoplankton blooms in select locations, resulting in temporary high concentrations of Chla in some locations (Vanderploeg et al. 2001; Fahnenstiel et al. 2008).

In the Laurentian Great Lakes region, changing climate and hydrologic conditions have been suggested as drivers explaining extensive increases in DOC and brownification of lakes (Williamson et al. 1999; Williamson et al. 2015). We found that 17 of our study lakes showed significant increasing trends in DOC, which was consistent with previous findings reporting increasing DOC in lakes in the regions of Sudbury, Dorset and ELA, and in numerous lakes throughout Quebec (Keller et al. 2008; Zhang et al. 2010; Couture et al. 2012). Keller et al. (2008) demonstrated that higher temperatures may increase DOC export from catchments substantially given that the supply of DOC in lakes generally reflects temperature related processes of organic matter production and decomposition. In combination with warming temperatures, trends in DOC may depend on hydrological conditions. For example, Hongve et al. (2004) found that altered hydrological pathways, during periods of increased or intensive rainfalls, may increase DOC concentrations by flushing accumulated DOC from organic-rich matter from the upper soil. Further, changes in DOC may also be linked to a complex combination of regional variables such as longer ice-free periods, a reduction in solar radiation, or decreasing trends in precipitation sulfate concentrations (Zhang et al. 2010; Couture et al. 2012; Marcarelli et al. 2019).

We observed a considerable amount of temporal variation in TN trends over the study period. These variable trends in TN may correspond to changes in surrounding terrestrial catchments. For example, trends in non-point sources of nitrogen, specifically agricultural fertilizer use (Williamson et al. 2008), and point sources from human waste water treatments (Peierls et al. 1991) will affect TN in surface waters. TN levels in smaller, less disturbed lakes are influenced by the extent of surrounding wetlands (Dillon et al. 1991; Gren 1995).

Spatial patterns in water quality

Our results indicated that the only water quality variable that was spatially autocorrelated in small lakes was DOC. This could be a result of large-scale climate changes, such as changes in precipitation patterns and warming temperatures (Hudson et al. 2003). Interestingly, the lack of significant spatial autocorrelation for trends in TP, TN and Chla suggests that broadscale changes in variables such as precipitation might be outweighed by watershed and lake-specific changes in drivers such as shoreline development, wetland restoration, and point and non-point sources of nutrients. In the small inland lakes, trends in TP, TN and Chla might reflect watershed-specific responses to climate change.

Drivers of water quality trends

Impact of lake morphology on water quality trends

A lakes morphology, specifically surface area, can alter the primary mechanisms by which climate and other stressors affect water quality, and must be taken into consideration when making broad statements about a lakes ability to integrate its surrounding environment (Adrian et al. 2009). Surface area has the potential to affect responses of internal variables in lakes to external drivers. As a result, a variable that exhibits a specific response in one lake may experience a difference response in another lake depending on morphological characteristics. Generally, lakes with smaller surface areas are linked to shallower waters which and may experience increased temperatures, longer ice-free periods, and richer algal biomass, lower dilution potential (Staehr 2012, Xie 2006; Nõges 2009). Further, the physical characteristics of a lake can affect nutrient and organic matter throughout the water column as smaller lakes can mix more easily during wind events, allowing more sediment resuspension, whereas deep lakes are more likely to undergo thermal stratification (Newman and Reddy 1992). In these smaller lakes, resuspension events have been shown to act as a source of nutrients for phytoplankton growth (Li et al. 2008). Finally, smaller lakes are more susceptible to climate changes, such as increased rainfall and droughts, as water level fluctuations can modify lake depth (Nõges 2009).

Great Lakes water quality

In the Great Lakes, increased DOC concentrations were positively associated with warming seasonal temperatures. Previous studies have demonstrated that warmer geographic regions in the northern hemisphere were more likely to experience accelerated changes in DOC (Monteith et al. 2007; Weyhenmeyer and Karlsson 2009). In our study, winter temperature emerged as a significant driver governing DOC concentrations in large lakes (Figure 2a). The importance of winter climate for DOC dynamics in lakes has been repeatedly documented and concludes that increases in DOC are expected with warmer winters (Belzile et al. 2002; Park et al. 2005; Karlsson et al. 2008). It is important to note that many potential causes of variability of DOC concentrations in lakes have been proposed in the literature. Contradictory results among studies conducted at different spatial and temporal scales suggest that the methodological approach may be a critical confounding factor. For example, Preston et al. (2001) demonstrated the difficulty of identifying possible mechanisms for DOC increases at various scales in a well-studied catchment, therefore, future studies identifying a common driver behind the widespread increase of DOC must extrapolate results with caution.

Our results showed a significant decline in TP in Lake Erie, Huron, and Ontario which parallels with previous records which found similar TP declines in the Great Lakes (Dove and Chapra 2015). At present, two sources of TP are considered: natural TP from deposition and local weathering, and imported TP from fertilizers and human waste. However, human and natural TP sources are subject to different controls. Initial improvements in TP levels in the Great Lakes were brought about due to mandated changes in point source discharges, such as sewage treatments improvements, and phosphate reductions in detergents (Steven and Neilson 1987; Chapra and Dove 2015). Later declines were hypothesized to have originated from the dreissenids filtering lake water after colonization (Chapra and Dolan 2012). For example, similar to our findings, Dove and Chapra (2015) found declines in TP in Lake Erie and Ontario over a 42-year period to be 8 and 11 µg/L, respectively. It is evident that lake TP has been declining in the Great Lakes, and addressing whether natural or anthropogenic TP have responded differently over time in terms of absolute amount and rates is a notable question to further explore.

Small inland lake water quality

Fall precipitation was strongly and positively associated with DOC in small inland lakes which also influenced TP and TN (Figure 2b). Hudson et al. (2003) found that DOC concentration in boreal lakes was negatively correlated with solar radiation and prior winter precipitation and positively correlated with summer precipitation although summer precipitation was not a significant variable in a regression analysis. An increase in precipitation is anticipated to increase export of terrestrial DOC into an aquatic system, as DOC mass export and runoff are tightly coupled (Dillon and Molot 2005). However, as shown in inland lakes in the Great Lakes region, increased spring precipitation did not correspond to an increase in lake DOC (Figure 2b). In early spring, when soils and peat are still frozen, heavy precipitation may fail to export DOC locked in frozen soil and wetland and in fact may dilute lake DOC to some extent (Hudson et al. 2003; Heinz and Zak 2018).

Not all of the small lakes in our dataset followed the broad patterns we found for Chla. Interestingly, our analysis showed that Chla increases were common in dreissenid invaded lakes in Wisconsin. It has been established that dreissenids are effective ecosystem engineers, and have altered the cycling of nutrients in the nearshore zone creating a new littoral material processing function termed “the nearshore shunt” (Heckey et al. 2004; Stefanoff et al. 2018). It has been hypothesized that dreissenids redirect organic matter and nutrients to the nearshore benthic zone (Holland et al. 1995), improve nearshore water clarity (Leach 1993; Lowe and Pillsbury 1995), and increase the surface area available for benthic algal attachment (by altering the roughness of the substratum and through accumulation of hard substrate). Therefore, Chla concentrations in southern Wisconsin may have simply been an outcome of landscape interactions. Regions such as Madison, WI, are highly developed and increased TP level may have led to more Chla in Wisconsin lakes, despite the dreissenid invasion.

The small lakes in southern Wisconsin (Mendota, Monona, Wingra and Fish Lake) exhibited increased variability in water quality variables, specifically Chla, compared to all other small lakes in the Great Lakes region. On a spatial basis, this might partly be explained by catchment areas being more heavily populated in southern geographic regions (when compared to the five northern Wisconsin lakes). However, since specific weather conditions vary widely between regions, the southern Wisconsin lakes may act as sentinels for future responses of degraded water quality and increased Chla as these lakes tend to experience warmer and wetter climates relative to our other study sites.

Implications of changing water quality

As shown in our study and many others, freshwater resources are experiencing significant changes with extensive implications for human and ecosystem health (Hallouin et al. 2018). Therefore, maintaining proper water quality has emerged as a key environmental issue (Michalak 2016). We observed significant changes in water quality expressed as DOC, TP, TN and Chla in nearly all lakes in our study region. We found that climate and the invasion of dreissenids were significant drivers of water quality in the Laurentian Great Lakes watershed and that lake morphology (surface area and mean depth) influenced lake responses to the drivers. Our water quality analysis revealed that there have been improvements in water quality in some lakes with declines in TP and subsequently Chla concentrations, owing to better water management strategies over the past 40 years (De Pinto et al. 1986). However, we still do not know how climate, warming temperatures, and other anthropogenic factors will affect effect water quality in the future. In response to global environmental changes, shifts in thermal habitats, precipitation patterns and nutrient availability may alter the interaction of response variables with the potential of influencing entire aquatic comminutes, starting with primary producers (Williamson et al. 2008). Further, the occurrence of more frequent extreme events such as intense rain, prolonged drought and abnormally high temperatures may promote degradation of water quality (Benson et al. 2012). Extreme events can lead to warmer and more turbid waters, less ice-cover, an alteration in the availability of nutrients and may promote a higher risk of toxic algal blooms (Murdoch et al. 2000; Winter et al. 2011; Benson et al. 2012; Sharma et al. 2019).

Maintaining water quality conditions provides extensive ecosystem services with vast socio-economic implications. Freshwater lakes in the Great Lakes region provide clean drinking water to millions of people in Canada and the United States and support multi-billion-dollar industries including fisheries, recreation, transportation, and tourism (Krantzberg and De Boer 2008). For example, water quality changes are predicted to impact commercial and sport fishing by creating a new set of environmental challenges for non-generalist species, and by shifting the ranges of highly valued cold water fishes, such as lake trout, northward (Ficke et al. 2007; Sharma et al. 2007; Van Zuiden et al. 2016). While there have been some successes over the past 40 years in understanding and mitigating the effects of numerous stressors on freshwater lake ecosystems, further research, monitoring, and restoration efforts are greatly needed in order to safeguard our vital freshwater resources for future generations.

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TABLES

Table 1. Summary of key response variables to climate change for various physical, chemical, and biological parameters as well as any underlying mechanisms and climate drivers with explanations on external pressures and comments on our current understanding with advantages (A), and disadvantages (D). PP=precipitation, AT=air temperature, WS=wind speed, CC=cloud cover, SR=solar radiation, EV=evaporation.

Lake properties	Physical, chemical and biological variables	Mechanisms	Climate drivers	External pressures	Comments	References
Morphology	Surface area	Influenced by hydrology (drought and/or flood conditions), flow regulation (input/output and surface/ground waters)	PP, AT, EV	Surrounding catchment (land use change and development)	Influences temperature effects, wind conditions and dilution capacity A: Easily measured D: Cannot draw many conclusion solely based on surface area	Whitehead et al. 2009
	Mean depth	Dependent on water volume	PP, EV	Hydrological changes, wind mixing depending on depth	A: Distribution, biomass and productivity of species D: May affect turnover potential, depth may determine degree of deep water mixing (possible anoxic conditions)	Dennison 1987; Ding et al 2002
Chemistry	Phosphorus & Nitrogen	Terrestrial runoff, anthropogenic inputs, internal reservoirs	PP, AT, atmospheric deposition	Current trophic status and nutrient availability, surrounding terrestrial catchment (farming, urbanization) and	A: Limiting nutrient for primary producers, regulates species composition and richness D: Multiple stressors	Guildford et al. 2000; Xu et al. 2010

				waste systems (sewage plants and treatments) yielding nutrients into lakes	interacting, site-specific	
	DOC	Relative contribution determined by allochthonous (from catchment) and autochthonous (within system) sources	AT, PP, SR, CC, atmospheric deposition	Modified by acid deposition, ultraviolet radiation, fluxes of DOC from catchment (e.g. runoff), water residence time, trophic status	A: Multiple effects on the physical, chemical, and biological lake processes D: Highly determinant of transparency, dependent on local and system-specific factors	Curtis et al. 1995; Williamson et al. 1999; Hudson et al. 2003; Zhang et al. 2010; Hanson et al. 2011
Community structure	Primary production	Ice-off/ice-on, stratification (intensity/duration), nutrient loadings, trophic state, transparency	AT, PP, SR, CC	Characterized by interacting physical, chemical and biological sources	A: Used as a measure of lake quality (e.g. chlorophyll *a* concentrations), D: Site-specific	Nürnberg et al. 2002; Elser et al. 2007
	Algal blooms	Period of stratification, nutrient loadings, trophic state, water residence time, lake mixing	AT, PP, SR, CC, WS	Cultural eutrophication, climate change	A: Seasonal, easily detectable D: Intensity and frequency highly dependent on when/where the sample was taken	Pearl et al. 2001; Pearl et al. 2016
	Invasive species	Energy flow, nutrient dynamics, species assemblages, community structures	AT	Anthropogenic change to environment, new networks of travel, transport and trades, climate change	A: Detect change over large special scale D: Ability to predict outcomes of invasions are limited (generally negative)	Moyle et al. 1996; Simon et al. 2003; Johnson et al. 2009; Keller et al. 2011
Temperature	Mean water temperature	Total lake heat budget	AT, SR, PP, AV, CC	Influenced by hydrology, ice phenology, morphology and	A: Easily and consistently measured, overall net temperatures of	Juday 1940; Edinger et al. 1968; Bai et al. 2012

				transparency, climate change	lake D: Dependent on geomorphometric factors and mixing regimes, seasonal/interannual variability	
	Surface water temperature	Net heat energy input and losses across the air-water interface (latent and sensible heat fluxes)	AT, WS, SR, PP, EV, CC	Nutrient loadings, turbidity, forest cover/state of riparian zone, transparency	A: Easily and consistently measured D: Depends on seasonal variations (date of spring/fall overturn), lakes with different morphometric characteristics act in distinct manners	Edinger et al. 1968; Hondzo et al. 1993; Venäläinen et al. 1999; Sharma et al. 2008; O'Reilly et al. 2015
	Stratification	Seasonal turnover events, vertical distribution of heat	AT, WS, PP	Influenced by ice phenology, mixing regimes, warmer and longer summers	Dependent on thermal stability and influences community structures A: Integrates climate changes of local region D: Requires high-resolution spatial and temporal data	Kling 1988; Livingstone 2003, Richardson et al. 2017
Ice phenology	Ice cover duration	Thawing in the spring and freezing in the fall, variations in ice structure, thickness, and decay	AT, SR, CC, PP	Complex interplay of meteorological and limnological factors, influenced by latitude, interannual variability, climate change	A: Sensitive indicator of climate (highly correlated to local weather) D: Ambiguous definition of ice-on/ice-off, interannual variability	Magnuson et al. 2000; Bonsal et al. 2006; Duguay et al. 2006; Nghiem et al. 2007; Livingstone et al. 2009; Adrian et al. 2009

Table 2. Lake characteristics and data source of 36 lakes in the Laurentian Great Lakes watershed, with water chemistry and chlorophyll variables (with standard deviation in parentheses) being mean values for the study period. TP = total phosphorus, TN = total nitrogen, DOC = dissolved organic carbon, Chla = chlorophyll a.

Lake	**Latitude, Longitude (decimal degrees)**	**Lake Surface Area (ha)**	**Mean Depth (m)**	**Maximum Depth (m)**	**Elevation (m above sea level)**	**TP* (µg/L)**	**TN* (µg/L)**	**DOC* (mg/L)**	**Chla* (µg/L)**	**Source** **Dreissenids presence/absence (P/A)**
Dorset, Ontario, Canada										Dorset Environmental Science Center
Blue Chalk Lake	45.20, -78.94	52.4	8.5	23	344	6.1 (0.6)	204.1 (18.9)	2 (0.2)	1.8 (0.4)	A
Chub Lake	45.30, -79.23	34.4	8.9	27	344	8.6 (0.9)	334.9 (31.3)	5.4 (0.8)	2.9 (0.9)	A
Crosson Lake	45.08, -79.04	56.7	9.2	25	332	9.7 (1.4)	343 (29.1)	4.6 (0.5)	4 (3.1)	A
Dickie Lake	45.15, -79.09	93.6	5	12	341	9.7 (1.4)	343 (29.1)	4.6 (0.5)	4.3 (2.0)	A
Harp Lake	45.38, -79.14	71.4	13.3	37.5	327	9.4 (1.5)	323.1 (21.5)	5.4 (0.7)	2.6 (0.9)	A
Heney Lake	45.13, -79.10	21.4	3.3	5.8	346	6 (0.7)	261 (23.3)	3.4 (0.6)	2.2 (0.6)	A
Plastic Lake	45.18, -78.82	32.1	7.9	16.3	379	4.9 (1)	197 (27.5)	2.3 (0.3)	2 (0.6)	A
Red Chalk East	45.19, -78.94	13	5.7	343	45.19	6.6 (0.8)	305 (22)	3.2 (0.4)	2.6 (0.7)	A
Red Chalk Main	45.19, -78.95	44.1	16.7	38	343	4.7 (0.4)	273.1 (18.2)	2.8 (0.4)	2.1 (0.7)	A
Wisconsin, USA										North Temperate Lakes Long Term Ecological Research Network
Allequash Lake	46.04, -89.62	1.6	2.9	8	500	16.3 (4.6)	301 (51.6)	4.2 (0.3)	12.5 (8.6)	A
Big Muskellunge Lake	46.02, -89.61	3.6	7.5	21.3	500	9.7 (4.8)	345.2 (56.4)	3.9 (0.2)	3.8 (1.3)	A
Crystal Lake	46.00, -89.61	0.4	10.4	20.4	500	7.6 (2.6)	181.8 (28.7)	2 (0.2)	3.5 (1)	P
Fish Lake	43.29, -89.65	0.8	6.6	NA	18.9	18 (4.6)	812.3 (154.2)	8 (1.9)	6.9 (3)	A

Lake Mendota	43.10, -89.41	39.6	12.8	25.3	260	47 (19.1)	996.1 (204.5)	5.9 (1)	7.4 (3)	P
Lake Monona	43.06, -89.36	13.6	8.2	22.5	260	45.6 (10.3)	880.6 (131.8)	6.1 (0.8)	8.8 (3.8)	P
Lake Wingra	43.05, -89.43	1.4	2.7	6.7	260	47.3 (20.1)	868 (138.8)	6.4 (1.5)	13.6 (5.2)	A
Sparkling Lake	46.01, -89.7	0.6	10.9	20	500	7 (2.3)	229.6 (39.7)	3.2 (0.2)	3.8 (1.3)	A
Trout Lake	46.03, -89.67	15.7	14.6	35.7	500	6.1 (1.9)	209.3 (46.7)	3.1 (0.2)	3.1 (0.8)	A
Simcoe, Ontario										Center for Environmental Research
Lake Simcoe	44.44, -79.17	722	14.6	42	219	13.4 (3.8)	421 (52.4)	4.1 (0.3)	1.1 (0.7)	P
Turkey Lakes Watershed, Ontario, Canada										Environment and Climate Change Canada
Batchawana Lake North	47.07, -84.39	5.9	3.9	11.3	370	5.6 (1.6)	420 (87.1)	4.1 (0.4)	NA	A
Batchawana Lake South	47.06, -84.38	5.8	3.3	10.9	370	6.1 (2)	395.8 (65.1)	4.8 (0.5)	NA	A
Little Turkey Lake	47.04, -84.41	19.2	6	13	370	5.4 (1.8)	505.9 (119.8)	3.9 (0.5)	NA	A
Turkey Lake	47.05, -84.42	52	12.2	37	370	5.4 (2.7)	430.1 (76)	3.6 (0.5)	NA	A
Wishart Lake	47.05, -84.4	19.2	2.2	4.5	370	8.9 (15.9)	429.7 (114.4)	4.5 (0.5)	NA	A
Sudbury, Ontario										Ministry of Environment, Conservation and Parks
Aurora Whitepine Lake	47.38, -83.63	84.3	7	21.3	422	4 (1.5)	165.8 (33)	3 (0.6)	0.001 (0)	A
Clearwater Lake	46.37, -81.05	75.9	8.4	21.5	267	5.1 (7.8)	218.7 (48)	2.3 (1)	0.002 (0)	A
Sans Chambre Lake	46.72, -81.12	14.5	5.6	15	385	9.7 (15.2)	242.4 (69.3)	2.7 (0.5)	0.002 (0)	A
Laurentian Great Lakes, Canada/USA										Center for Environmental Research
Lake Erie	42.13, -83.11	25700	19	64	173	24.7 (11)	539.7 (108.2)	2.1 (0.2)	2.4 (1.8)	P

Lake Huron	43.75, -81.73	59565	59	229	117	11.2 (8.3)	529.5 (96.7)	1.6 (0.1)	1.2 (0.9)	P
Lake Ontario	44.15, -77.39	19009	86	244	74	13 (6.6)	484.2 (68)	2.1 (0.1)	1.3 (0.8)	P
Lake Superior	48.48, -89.16	82097	149	406	180	4.8 (1.5)	440.6 (27.9)	1.7 (0.1)	1.1 (0.3)	P
Experimental Lakes Area, Ontario, Canada										International Institute for Sustainable Development
Lake 114	49.67, -93.76	12.1	1.7	5	418	14.2 (3.6)	655.3 (181.9)	8 (1.2)	5.4 (3)	A
Lake 224	49,69, -93.72	25.9	11.6	27.4	409	7.7 (1.5)	260.5 (33.7)	3.1 (0.4)	NA	A
Lake 373	49.74, -93.72	27.3	11	20.8	424	8.8 (2.1)	272.5 (29.7)	4 (0.2)	NA	A
Lake 442	49.78, -93.82	16	9	17.8	411	14.7 (3)	469.4 (67)	6.7 (0.3)	NA	A
Lake 239	49.66, -93.72	54.3	10.5	30.4	386	7.3 (1.8)	316.2 (34.6)	6.6 (0.6)	NA	A

*Ice-free means (for available data between 1976-2017)

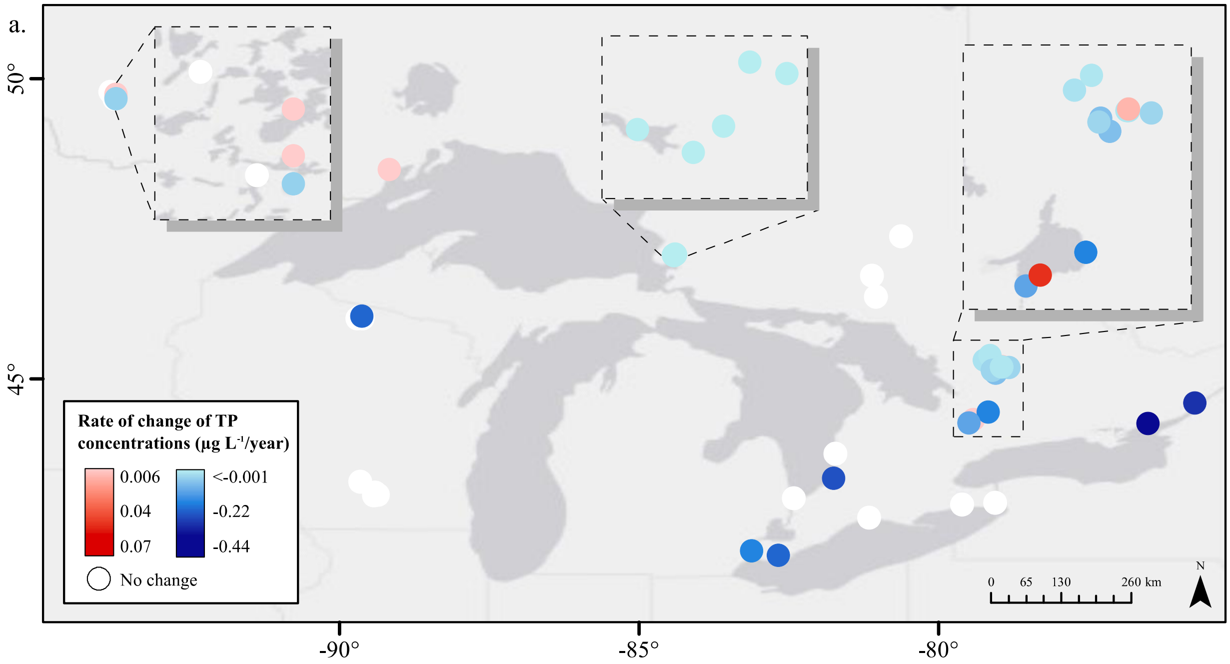
Table 3. Summary of mean Sen slope values for chemical and biological variables by region (with sample size in parentheses). Lakes with <20-year time-series were not included in total mean values.

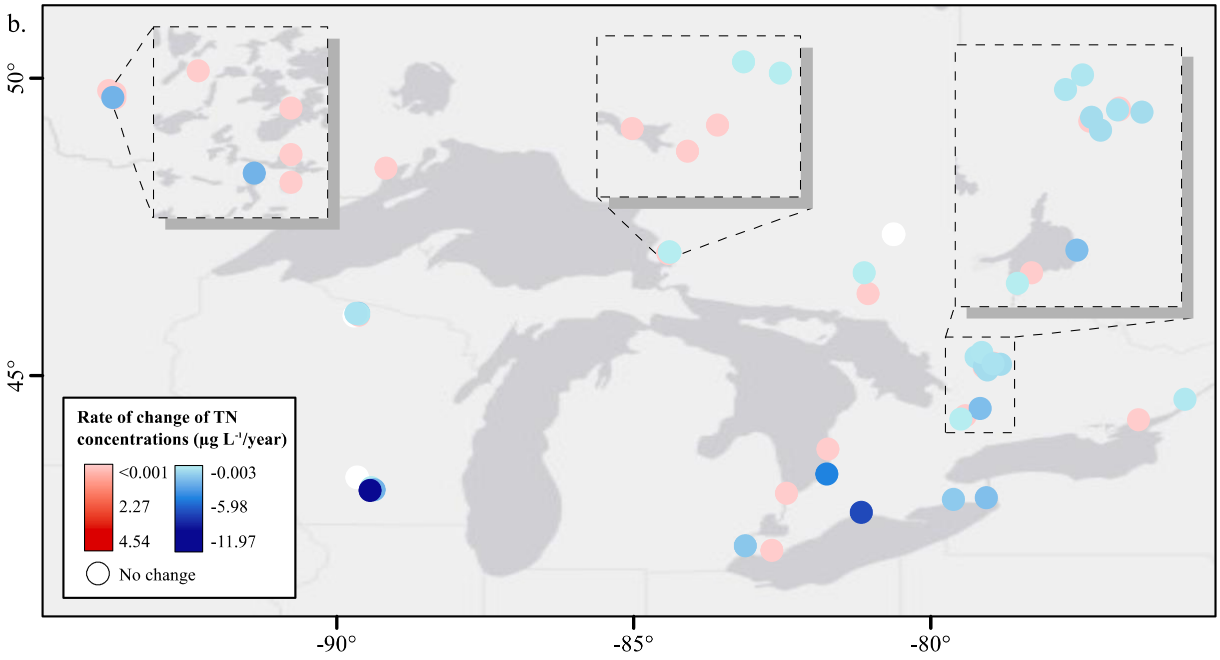
Water quality variable	**Dorset**	**ELA**	**Great Lakes***	**Lake Simcoe***	**Sudbury**	**Turkey Lakes**	**Wisconsin**
Mean TP (µg L$_{-1}$ year$_{-1}$)	-0.04 (n=9)	0.03 (n=3)	-0.27 (n=6)	-0.1 (n=3)	0 (n=3)	-5.86$_{-5}$ (n=5)	-0.05 (n=5)
Mean TN (µg L$_{-1}$ year$_{-1}$)	-0.28 (n=9)	1.17 (n=3)	-0.25 (n=7)	0.32 (n=3)	7.77$_{-4}$ (n=3)	7.48$_{-4}$ (n=5)	-0.58 (n=5)
Mean DOC (mg L$_{-1}$ year$_{-1}$)	0.04 (n=9)	0.01 (n=3)	-	0.02 (n=3)	0.06 (n=3)	7.91$_{-4}$ (n=5)	-0.001 (n=5)
Mean Chla (µg L$_{-1}$ year$_{-1}$)	-0.02 (n=9)	-	-0.05 (n=6)	-0.04 (n=3)	-2.05$_{-5}$ (n=3)	-	-0.005 (n=5)

*Region where individual lakes had numerous sampling sites.

Red = increasing rate of change, blue = decreasing rate of change, - = no significant change or not enough data available.

FIGURES


a.
50°
45°
Rate of change of TP concentrations (μg L⁻¹/year)
0.006
0.04
0.07
<-0.001
-0.22
-0.44
No change
0 65 130 260 km
N
-90°
-85°
-80°


b.
50°
45°
Rate of change of TN concentrations (μg L⁻¹/year)
<0.001
2.27
4.54
-0.003
-5.98
-11.97
No change
-90°
-85°
-80°

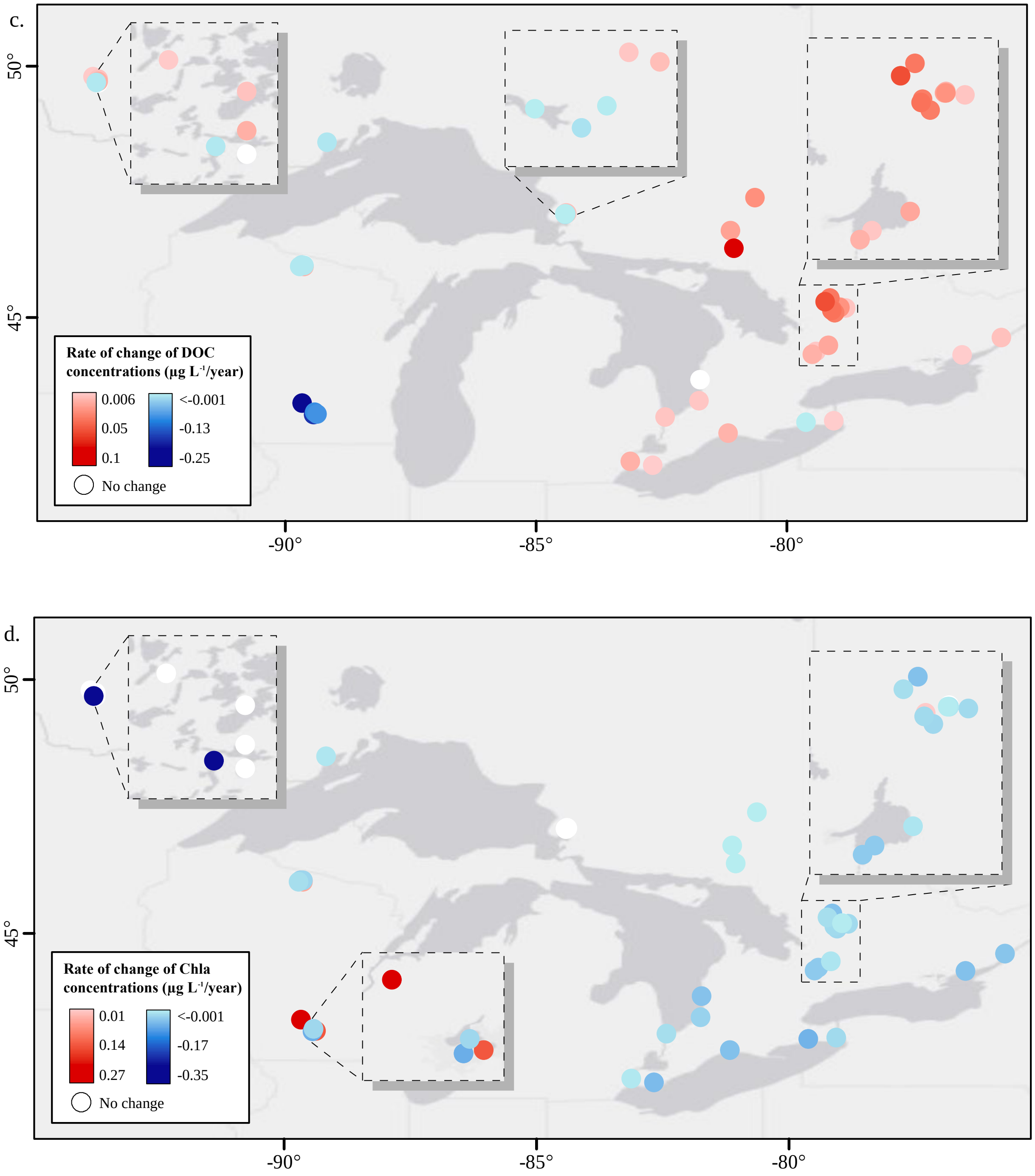
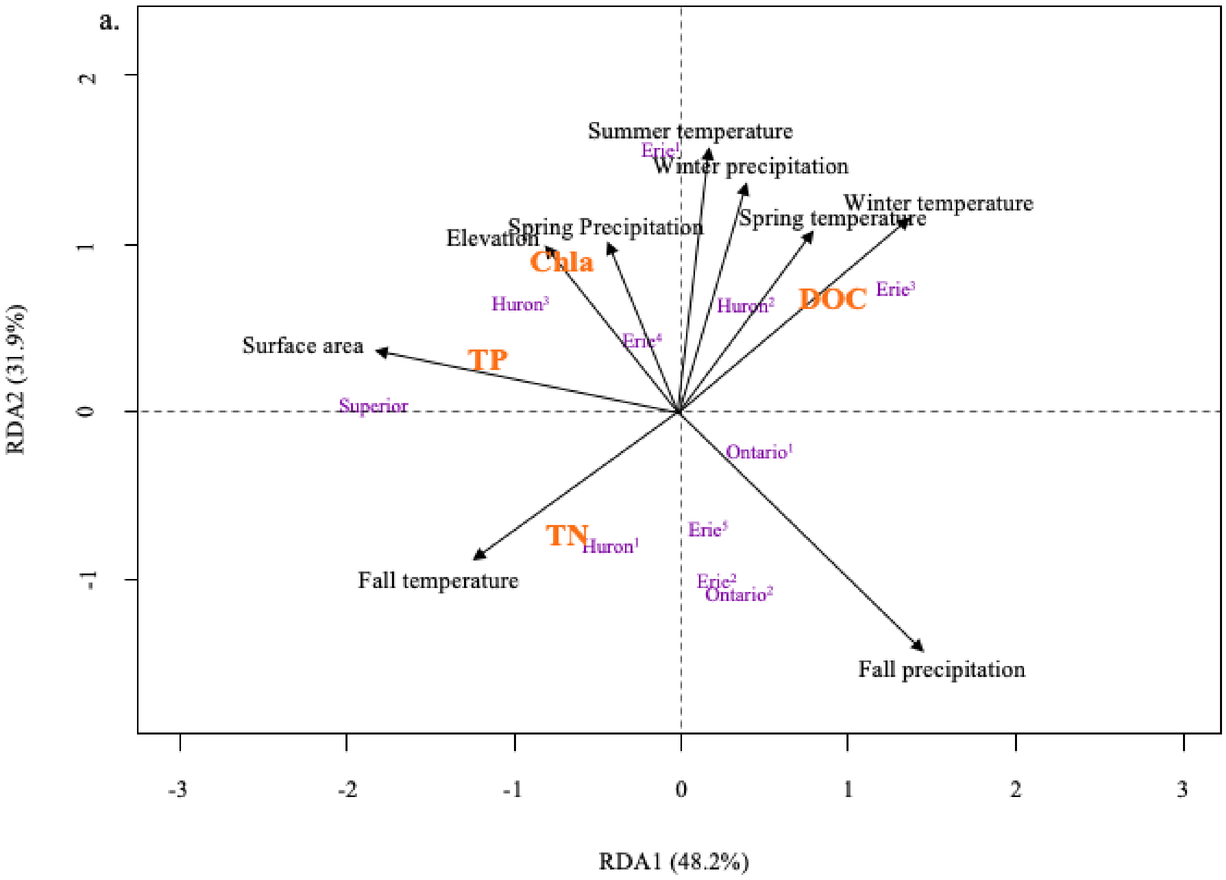
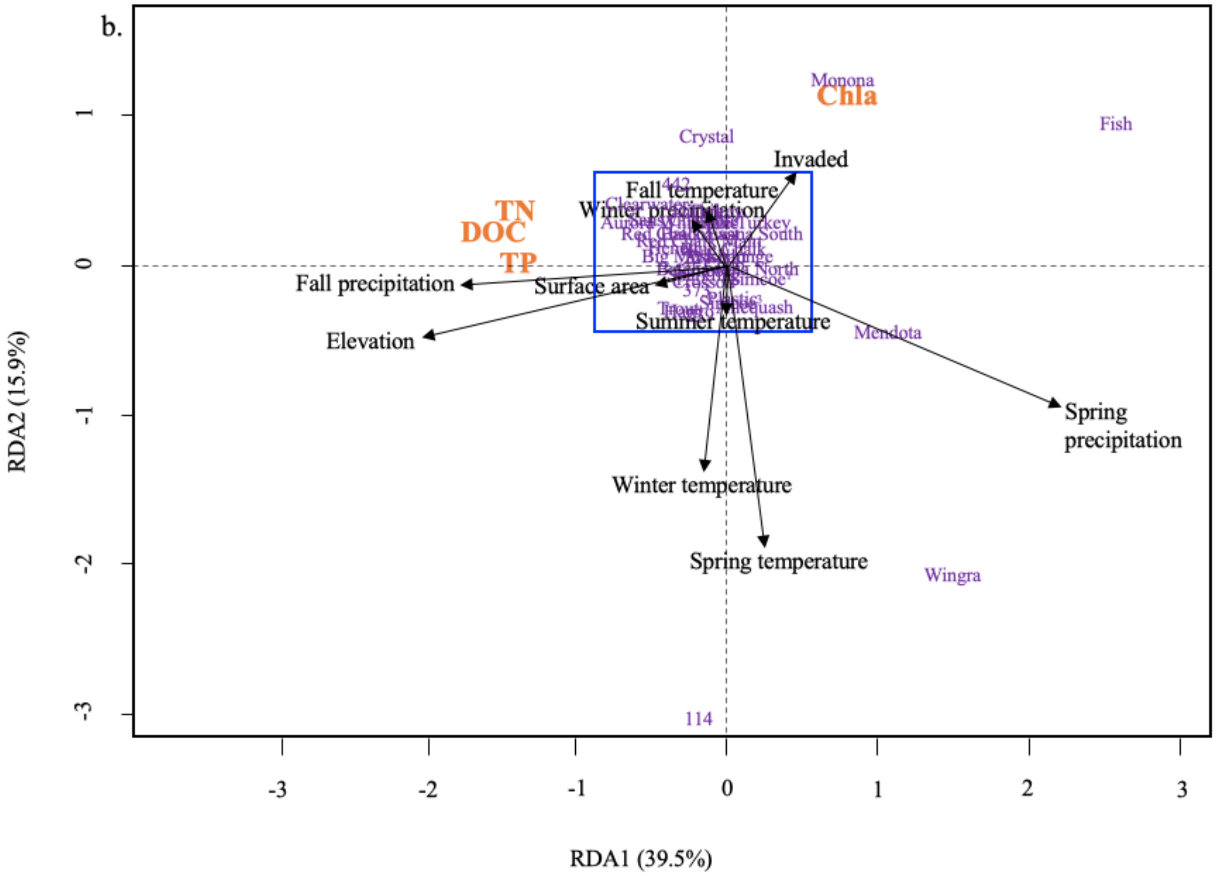


Figure 1. Lake specific trends in a) TP, b) TN, c) DOC and d) Chla concentrations during the study period (1976-2017). Positive temporal trends are depicted using shades of red and negative trends are depicted using shades of blue. A stronger shade in either trend direction denotes a faster trend regionally. White circles indicate no significant trends or no data available.


a.
Summer temperature
Erie^1
Winter precipitation
Winter temperature
Spring Precipitation
Spring temperature
Elevation
Chla
DOC
Erie^3
Huron^3
Huron^2
Erie^4
Surface area
TP
Superior
Ontario^1
Erie^5
TN
Huron^1
Erie^2
Ontario^2
Fall temperature
Fall precipitation
RDA2 (31.9%)
2
1
0
-1
-3
-2
-1
0
1
2
3
RDA1 (48.2%)


b.
Monona
Chla
Fish
Crystal
Invaded
442
Fall temperature
Winter precipitation
Clearwater
Aurora
Turkey
South
TN
DOC
TP
Big
North
Simcoe
373
Plastic
Trout
Fall precipitation
Surface area
Summer temperature
Elevation
Mendota
Spring
precipitation
Winter temperature
Spring temperature
Wingra
114
RDA2 (15.9%)
1
0
-1
-2
-3
-3
-2
-1
0
1
2
3
RDA1 (39.5%)

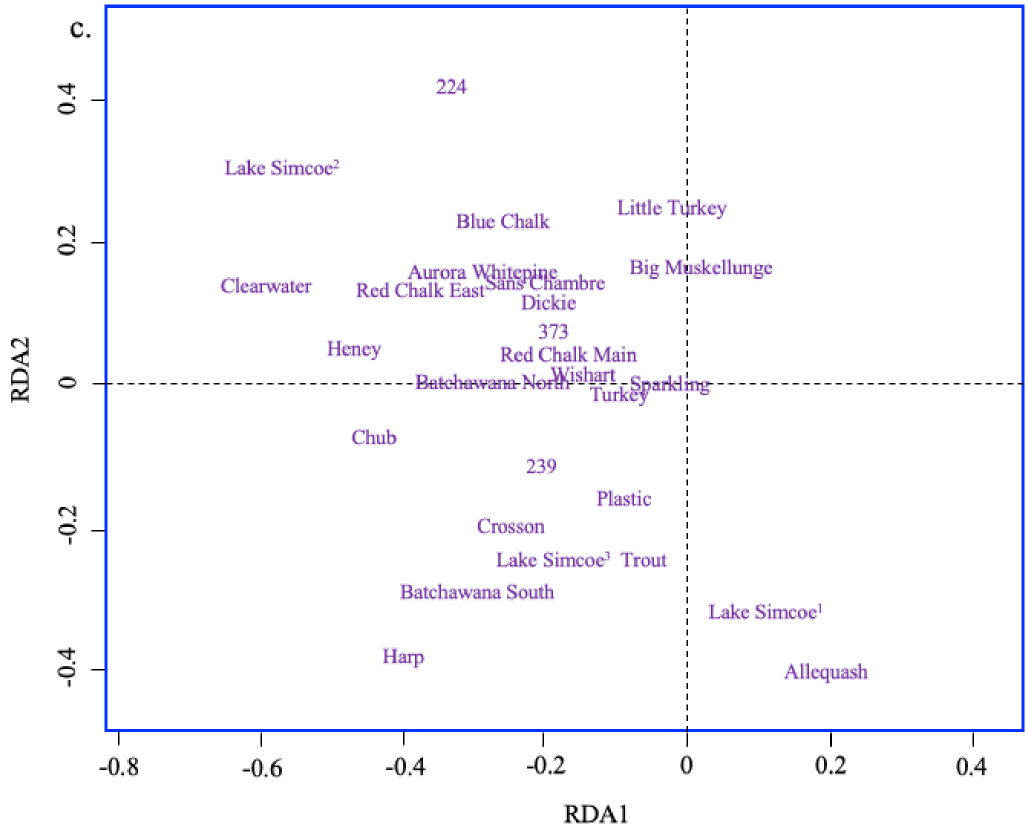


Figure 2. Redundancy analysis (RDA) of changes in lake variables over time for a) the Great Lakes and b) inland lakes. Only the first two axes are shown which explain 73.1% and 45.6% of the variation for the large and small lakes, respectively. c) Magnified portion of the RDA of inland lakes to better depict the location of lakes in figure b). Climate variables are represented by arrows and water quality data is bolded. Superscripts (1-5) denote different sampling locations within the same lake.

SUPPLEMENTARY MATERIALS

Table S1. Summary of mean Sen slope values for climate data by region (with sample size in parentheses). Lakes with <20-year time-series were not included in total mean values. Temperature (tmp) was measured in °C/year and precipitation (ppt) was measured in mm/year.

Seasonal climate variable	**Dorset** (n=9)	**ELA** (n=3)	**Great Lakes*** (n=7)	**Lake Simcoe*** (n=3)	**Sudbury** (n=3)	**Turkey Lakes** (n=5)	**Wisconsin** (n=9)
Winter tmp	0.048	0.038	0.048	0.001	0.031	0.027	0.04
Spring tmp	0.019	0.014	0.013	0.018	0.0068	-0.0037	0.0051
Summer tmp	0.032	0.0088	0.03	0.014	0.028	0.029	0.031
Fall tmp	0.041	0.05	0.044	0.05	0.047	0.024	0.046
Winter ppt	0.76	0.017	0.28	0.32	0.23	-0.069	0.2
Spring ppt	-0.11	0.45	0.19	-0.032	-0.016	-0.046	0.55
Summer ppt	0.086	0.13	-0.043	0.25	-0.022	0.014	-0.032
Fall ppt	0.098	0.095	-0.2	-0.36	-0.039	0.081	-0.81

*Region where individual lakes had numerous sampling sites.

Red = increasing rate of change, blue = decreasing rate of change.

Table S2. Moran's I statistic determining the degree of spatial autocorrelation for water quality variables in small lakes across the Laurentian Great Lakes watershed.

Water quality variable	**Moran's I**	***P* value**	**SD**
TP	-0.066	0.76	0.1
TN	-0.076	0.7	0.11
DOC	0.45	<0.001	0.11
Chla	-0.07	0.57	0.063

Chapter 2: A global database of chlorophyll and water chemistry in freshwater lakes

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Keywords: Chlorophyll, lakes, global, water chemistry, geomorphology

MY CONTRIBUTION

The authors of this publication include Alessandro Filazzola, Arnab Shuvo, Carolyn Ewins, Luke Moslenko, Khondoker Sadid, Kevin Blagrave, Derek Gray, Roberto Quinlan, Catherine O'Reilly, and Sapna Sharma. I contacted authors and collected, extracted, checked, and compiled data from various institutions and organizations. I was also involved in producing metadata, performing analysis, creating tables and writing the Abstract, Introduction, and Methods.

SUMMARY

Measures of chlorophyll represent the primary production in freshwater lakes that is often used by managers as a proxy for water quality. However, chlorophyll concentrations in lakes are dependent on many interacting factors, including nutrient inputs, time of year, spatial heterogeneity (within and among lakes), climate, and anthropogenic development. Therefore, integrating a global dataset of lake physical, chemical, and biological characteristics can help elucidate patterns and trends in freshwater resources. We synthesized a global database of measured chlorophyll *a* (Chla) values, associated water chemistry variables, and lake morphometric characteristics for 8557 freshwater lakes distributed across 44 countries. Data were collected based on a systematic review examining 3322 published manuscripts that measured lake Chla and supplemented this data with online repositories such as KnB, Dryad, and Pangaea. Using the geospatial coordinates of the lakes, researchers are now able to relate measures of chlorophyll to climate and other anthropogenic disturbances. This publically available database can be used to improve our understanding of how chlorophyll responds to global environmental change and provide baseline comparisons for environmental managers responsible for maintaining water quality in lakes.

INTRODUCTION

Freshwater lakes are vulnerable to the effects of water fouling, nutrient enrichment, and alterations in climate and land use owing to their sensitivity to local and global environmental changes (Meyer 1999; Wrona et al. 2006; Adrian et al. 2009). Lakes provide key social, economic, and ecological resources (Beeton 2002), while accounting for less than 1% of the world's surface freshwater supply (Shiklomanov 1993). Lake water provides critical ecosystem services including consumption, transportation, agriculture, and recreation, in addition to habitat for over 100,000 species of invertebrates, insects, animals, and plants (Beeton 2002; McMichael et al. 2006; WWF 2018). However, alterations in biological and chemical lake processes can impact how and when freshwater resources can be used. Particularly, increases in lake chlorophyll levels can impact water quality through alterations in color and odor (Nürnberg and Shaw 1998), dissolved oxygen availability (Makri et al. 2019), and overall lake production (Håkanson and Boulion 2001). Therefore, it is imperative to maintain the integrity of freshwater systems to avoid further loss of ecosystem services.

Chlorophyll *a* (Chla) is frequently used as an easy and suitable measurement of lake water quality by research and management agencies (Carlson 1977; Sterner 2010; Li et al. 2017). Many environmental assessments commonly use Chla as a biological indicator for determining lake trophic status (Carlson 1977; OECD 1982). In freshwater ecology, Chla also functions as a good proxy for other variables, such as primary production or transparency, and is often included as a covariate in limnological studies (Bennion et al. 2019). Chla is therefore routinely measured in water quality programs across the globe.

Including lake chemistry and morphometry as response variables in combination with Chla is fundamental to discern limnological processes at the individual or global scale lake level. While lakes naturally vary in their Chla concentrations owing to seasonal fluctuations and climate variability, they can also respond to anthropogenic influences such as nutrient inputs (Elser et al. 2007). Anthropogenic sources of nutrient loadings in lakes include runoff from surrounding watershed from land use changes (Hall et al. 1999; Bennett et al. 2001), atmospheric deposition (Williamson 2008), and sewage discharge (Carpenter et al. 1998). Furthermore, individual lake properties such as surface area, depth, and volume can mediate the temperature, productivity, and energy flow of a lake (Williamson et al. 2009). Accordingly, water chemistry (defined here as total phosphorus, total nitrogen, phosphate, total nitrate and nitrite, dissolved organic carbon, dissolved oxygen, and ammonia) as well as numerous morphometric characteristics were included in assembly of this dataset.

Generating a database of Chla values can be challenging because it requires *in situ* data measurements in lakes. There are Chla levels inferred from remote sensing (e.g. Li et al. 2012; Odermatt et al. 2018) that can be effective for comparisons among lakes, but are limited because there is significant error surrounding the separation of turbidity from light attenuation in the water column (Palmer et al. 2015; Salama & Verhoef 2015). Similarly, *in situ* measurements can be limited because certain lakes are difficult to access (e.g. high alpine, or arctic). Ideally, a Chla database would have both modelled and field measurements to allow users the option to trade-off coverage for accuracy. Although extensive national water quality databases exist (e.g. Soranno et al. 2017), there is evidently a need for a cohesive and broadscale database of water quality worldwide. The incentive to assemble this global database of lake Chla, water chemistry, and morphometric characteristics is to identify global and regional Chla patterns over broad spatial and temporal scales. Other applications of this dataset include and are not limited to identifying which environmental stressors (e.g. climate, nutrient or anthropogenic factors) are most important in driving changes in water quality, specifically Chla.

Using the scientific literature and online data repositories, we conducted a systematic review to acquire instances where Chla has been measured. Here, we present a database of global spatial coverage of Chla from 8557 lakes distributed across 44 countries collected in situ or by satellites. Concurrently, we also acquired information about lake morphometry and water chemistry as they are highly correlated with Chla concentrations. We provide a summary of these data and associated variables to serve as a tool in ecological research and freshwater management.

METHODS

Systematic literature review

We conducted a systematic review to identify relevant primary articles using “chlorophyll” and “lake*” as citation search terms in Web of Science between the years 2000 and 2018. Papers that were not primary articles or were not in a relevant field relating to limnology were excluded. We screened 3322 articles, beginning with those most recently published in 2018, and working backwards in time until the year 2000 (which includes most relevant data with minimal repetition). Articles were excluded from our study if the methods in which they collected water quality data violated the following criteria: i) were not sampled in the lake; ii) were collected in a manipulative study; or iii) were monitored *in situ* using sensors that were not supplemented by additional calibration techniques (Zeng and Li 1978). If an article did not violate any criteria, we extracted Chla and any other water chemistry data, sampling or lake coordinates, and geomorphometric characteristics directly from the article or the supplementary material (Figure 1; Table 1). If raw data were not presented in the article, we contacted the study authors to request their data.

Repository data

We found an additional 15 online data repositories that contained lake Chla measurement and other water chemistry data for 7665 lakes globally using the online search engines Dryad (https://datadryad.org/), KnB (https://knb.ecoinformatics.org/), and Google Dataset Search (https://toolbox.google.com/datasetsearch).

Repository 1 – Ecology under lake ice (Hampton et al. 2016)

This dataset included 118 unique sampling observations for global coverage of Chla values. Time-series data were provided for 34 lakes. 118 paired sampled Chla concentrations contributed to the ice-on (winter) and ice-free (summer stratification) yearly aggregate. Other data including physical, chemical, biological, and a suite of metadata variables were also collected.

Repository 2 – Limnological data and depth profile from Oneida Lake, New York, 1975 to present (Rudstam 2015)

This dataset contains limnological data from Oneida Lake, New York, United States. Average Chla was calculated weekly between 1975-present at 5 standard locations throughout Oneida Lake. Integrated water samples of Chla were extracted with acetone and measured spectrophotometrically. Location and attributes of sampling stations, temperature, pH, dissolved oxygen, and conductivity were also obtained from this repository.

Repository 3 – Transparency, Geomorphology and Mixing Regime Explain Variability in Trends in Lake Temperature and Stratification across Northeastern North America (1975–2014) (Richardson et al. 2017)

Metadata for 230 lakes in northeast North America were obtained from Richardson et al. (2017). Lake data were obtained from various sources including state and provincial agencies, and research stations. Chla was measured in lakes in Massachusetts, Maine, New Hampshire, New York, Ontario, Pennsylvania and Rhode Island and were sampled in 1975, 1985, or in both years. If multiple sampling values existed for an individual lake, the variable was averaged to produce a single descriptor value.

Repository 4 – The European Multi Lake Survey (EMLS) dataset of physical, chemical, algal pigments and cyanotoxin parameters 2015 (Mantzouki et al. 2018)

This dataset contains Chla data and other physical, chemical and biological parameters for 345 lakes across Europe in summer 2015. 197 scientists from 26 European countries sampled lakes during the two-week warmest period for each region (based on 10-year air temperature data). The sampling location was either a known sampling point or the center of the lake. Data collectors followed standardized sampling, sampling processing and preserving protocols to obtain an integrated water column sample from 0.5 m below the surface until the bottom of the metalimnion. Samples were shipped, stored and processed in laboratories in the Netherlands, Germany and Switzerland to minimize errors.

Repository 6 – The Lake Inventory Program (https://novascotia.ca/nse/surface.water/lakesurveyprogram.asp)

The Lake Inventory Program measured Chla and other water quality parameters for 103 lakes in Nova Scotia between 1974-2010. Samples were taken during the summer months at varying sampling depths (depending on thermal stratification) according to protocols developed by Nova Scotia Environment.

Repository 7 – National Aquatic Resource Surveys (https://www.epa.gov/national-aquatic-resource-surveys/data-national-aquatic-resource-surveys)

The National Aquatic Resource Surveys (NARS), in collaboration with the National Lakes Assessment (NLA) and the U.S. Environmental Protection Agency (EPA), conducted a national scale assessment of lakes collecting and analyzing data across the conterminous United States.

Chla samples, along with other water chemistry data, were taken in 2012 and 2007 for 2281 sampling locations. Methods were based on both the guidelines developed and followed in the Western Environmental Monitoring and Assessment Program (Baker et al. 1997) and at the local state level. An integrated sampler was used to collect index Chla data at the centre of the lake (> 50 m) or at the deepest point. Littoral Chla samples were taken 0.3 m below the water surface within the littoral area. Samples were then sent to appropriate analytical laboratories for analysis (extraction 90% acetone analysis by fluorometry).

Repository 8 – McMurdo Dry Valleys Chlorophyll-A Concentrations in Lakes (Priscu 2014)

This dataset contains Chla data at specific depths in McMurdo Dry Valley lakes in the Antarctic (part of the McMurdo Long Term Ecological Research project). The basic method of Holm-Hansen et al. (1965) and Strickland and Parsons (1972), with a few modifications, was used to analyze Chla samples starting in 1993-present.

Repository 9 – Diversity II water quality parameters from ENVISAT (2002-2012): a new global information source for lakes (Odermatt et al. 2018)

The Diversity II water quality dataset consists of Chla concentrations and other water quality parameters for lakes worldwide (based on data from the full ENVISAT MERIS operation). This modeled data consists of several monthly, yearly and 9-year average for Chla concentrations at a single lake between the years 2006-2011.

Repository 10 – Cascade Project at North Temperate Lakes LTER High Frequency Sonde Data from Food Web Resilience Experiment 2008-2011 (Carpenter et al. 2018)

Chla data was collected from surface waters from Paul and Peter lakes in the Upper Peninsula of Michigan during the summers of 2008-2011. Samples were collected at the deepest point of the lake at 5 minute intervals using in-situ automated sensors at a depth of 0.75 m below the surface.

Repository 11 – Lake Metabolism at North Temperate Lakes LTER 2000 (Bade et al. 2002)

Researchers at the North Temperate Lakes Long Term Ecological Research program obtained surface water quality data (depth of 0.5 m) of 31 lakes in the Northern Highland Lake district of Wisconsin and the Upper Peninsula of Michigan. Sondes were deployed during the months of July and August of 2000 to measure Chla and other water chemistry data. Chla was collected by filtering 200 ml of lake water, and then freezing filters, followed by methanol extraction. Fluorescence was determined before and after acidification to correct for pheopigments.

Repository 12 – Landscape Position Project at North Temperate Lakes LTER: Chlorophyll 1998-2000 (Greenfield et al. 2005)

49 Lakes located within the Northern Highland-American Legion State Forest, Vilas County, were surveyed between 1998-2000. Chla data was collected at or close to the deepest part of the lake at either one or two times or monthly throughout the summer. Further, epilimnion, metalimnion, and hypolimnion measures of chlorophyll *a* were recorded and analyzed using a spectrophotometer.

Repository 13 – Unpublished data, Massachusetts Department of Environment Protection, lake water chemistry data, 1995-2004 (Dallaire et al. 2017)

This database contains Chla data for lakes in Massachusetts between 1999-2004. Water quality surveys consist of around five sampling events interspersed throughout the water recreation season for conventional water quality analyses

Repository 14 – LAGOS-NE: Lake nutrient chemistry and geospatial data to measure spatial structure of ecosystem properties in a 17-state region of the U.S (Lapierre et al. 2017)

All observations came from LAGOS-NELIMNO v. 1.054.1 and LAGOS-NEGEO v. 1.03 (LAke multi-scaled GeOSpatial and temporal database) were generated by government agencies and universities. Datasets compiled water quality data from the summer stratified season (June 15 – September 15) in the recent 10 years. The yearly median Chla and other water quality values were reported.

Repository 15 – National Water Quality Monitoring Council (https://www.waterqualitydata.us/portal/#countrycode=CA&siteType=Lake%2C%20Reservoir%2C%20Impoundment&sampleMedia=Biological&sampleMedia=Water&sampleMedia=water&mimeType=csv)

Chla data for Canadian lakes between 1982-2017 was retrieved from the National Water Quality Monitoring Council. Other sampling parameters, including the physical and chemical composition of the water at the monitoring site, was also obtained. Samples were collected and processed using the National Water-Quality Assessment and the U.S. Environmental Protection Agency National Rivers and Streams Assessment procedures and protocols.

Repository 17 – Lake Kasumigaura Database (http://db.cger.nies.go.jp/gem/inter/GEMS/database/kasumi/contents/datalist.html)

This database is a compilation of surveyed Chla, water quality and other chemical and biological parameters of Lake Kasumigaura in Japan in between 1977-2016. 12 stations were sampled monthly.

Unique identification

All data required spatial coordinates (i.e. latitude and longitude). However, there were instances where multiple samples were taken at the same location, separated by year, month, or study. We could not treat every spatial coordinate as an independent lake because some coordinates were surveyed within the same lake either within or among studies. Therefore, we assigned a unique identifier (hereafter survey instance, labeled “uniqueID” in the dataset to every chlorophyll data point separated by coordinate, year, month, and study. To determine unique lake identifiers that correspond with each survey instance, we used the HydroLAKES database of lake location (Messager et al. 2016; http://wp.geog.mcgill.ca/hydrolab/hydrolakes/). We matched the spatial polygons of lakes present within the HydroLAKES database with the spatial coordinates extracted from the studies. In instances where the survey instance did not match a lake within HydroLAKES database, we conducted a Google search to determine if the lake was unique from others. Using these methods, we generated a unique lake identifier that associate with each of our survey instances.   The country was determined from the geographic coordinates of the lake.

Geomorphometric characteristics

We collected lake volume, surface area, mean depth, maximum depth, secchi depth, and pH from the original data provider when available within the study. For lake samples where metadata were not available we conducted searches in other relevant primary literature, online web sources including Google Earth, Wikipedia, LakeNet (http://www.worldlakes.org/), ILEC (http://www.ilec.or.jp/en/), GLR (http://www.worldlake-db.com), HydroLAKES (http://wp.geog.mcgill.ca/hydrolab/hydrolakes), or contacted authors to obtain information.

In situ Chlorophyll data

Our team acquired Chla data for 8557 lakes distributed across 44 countries and on every continent including Antarctica (Figure 2). Globally, 8260 lakes were monitored *in situ*, whereas 297 were collected by satellite. Each Chla measurement corresponded with a lakes latitude and longitude, and the year in which the measurement was taken, converted to standardized units (mg/L) (Table 2). In some cases, the same lake was sampled in multiple locations and/or sampled multiple times within the year (e.g. monthly). Chla values were mostly collected at the surface level or by integrated water samples. Sampling method techniques varied, however, with analysis by spectrophotometry (37%), fluorometry (21%), or 3) other (17%) (Table 1). If the method of sample collection and analysis was not described in a manuscript or was part of another dataset it was labelled as “undescribed” (25%) (Table 1).

A comprehensive discussion of details of each of the standard methods of Chla extraction can be typically found in individual manuscripts. Generally, Chla water samples were filtered, and then extracted using an organic solvent (e.g. acetone or ethanol). The Chla concentrations were then determined by a spectrophotometer (to record light absorbance of Chla at a specific wavelength) or by a fluorometer (to record light fluorescence of Chla at a specific wavelength). Other methods of data collection included high performance liquid chromatography and sonication/freeze-thaw method.

In situ water chemistry data

We compiled total phosphorus (TP; mg/L), total nitrogen (TN; mg/L), phosphate (PO_4; mg/L), total nitrate and nitrite (NO_3 and NO_2; mg/L), dissolved organic carbon (DOC; mg/L), dissolved oxygen (DO; mg/L), and ammonia (NH_3; mg/L) from 57% of the sampling observations which also presented, at minimum, lake Chla data, sampling date and geographic coordinates. The methodology used to obtain in situ water chemistry data varied between papers and is described in Table 1. Generally, water chemistry samples were analyzed spectrophotometrically, fluorometrically, or by a multi parameter water quality probe (e.g. Yellow Springs Instrument, which was supplemented with additional calibration methods to ensure measurement accuracy).

DATA RECORDS

We have published the MSdata.csv and RepoData.csv in an open access repository (https://github.com/afilazzola/ChlorophyllDataPaper.git) with data from the published manuscripts and data repositories that were systematically processed to extract chlorophyll data (Table 1). Each of these files contains citation information such as the authors, year that the study was published, location published (e.g. journal, data repository), and whether the dataset was included within our study. Each of these files list studies that were explored as potentially having chlorophyll data but were excluded.

The uniqueID.csv file contains general information about each survey instance that connects across the other files (Table 1). The first column has a unique identifier that corresponds with every survey instance that is separated by year, month, geospatial point, and study. This file is to be used for subsetting the survey points by respective analyses, such as within a certain timeframe or country. This file also contains a column of lake identifiers corresponding to each of the survey instances because within and among studies, some lakes were surveyed multiple times at different locations. The chl.csv file contains all the chlorophyll values reported in mg/L and associated with the unique identifier (Table 2). The waterchem.csv file contains all the reported data for concentration of lake water including total nitrogen, total phosphorus, phosphates, nitrates/nitrites, dissolved organic carbon, dissolved oxygen, and ammonia (Table 2). Finally, the LakeChar.csv contains data about the lake characteristics when reported, such as surface area, mean lake depth, and maximum lake depth (Table 2).

TECHNICAL VALIDATION

We conducted quality control and quality assurance across the datasets to validate the data from each of the independent sources. The sources of data were diverse coming from government programs, independent research groups, Long-Term Ecological Research sites, and non-profit monitoring agencies. In total, there were 16,782 unique survey instances that needed to be checked for synchrony among methods and values. After the data was assembled from each of the manuscripts and online repositories, we first checked the coordinates for each lake. When possible, the name of the lake described in the paper was compared to the described coordinates. Any errors or erroneous observations in location (e.g. negative longitudes for studies in the eastern hemisphere) were determined by comparing study descriptions with points and using a map of lakes (Figure 2).

We compared the distribution of chlorophyll values to identify potential outliers that could indicate an incorrect measurement. The units across all datasets were standardized to all be mg/L from multiple other options including µg/L, mg/m^3, & g/m^3. All lakes that had units mg/m^2 were removed because they were based on downscaling of surface water only and did not convert properly to mg/L. We rounded all values of chlorophyll to 0.0001 mg/L (0.1 µg/L) because analytical equipment used within studies rarely had better precision. We used a histogram of log-transformed chlorophyll from all available data to identify outliers. The frequency of chlorophyll values when log-transformed approximated a normal distribution and all values were within an expected range (Figure 3). Lakes with chlorophyll values of zero were observed in some arctic and alpine lakes. Many of the extremely high values (>1 mg/L) including the maximum value observed (1.86 mg/L) were from a study by Marselina & Burhanudin (2017) that measured the water quality of extremely polluted lakes in Indonesia. More than half of the lakes were considered oligotrophic with chlorophyll values less than 1 µg/L.

USAGE NOTES

We provide code in R within our guide to join all these files by their unique identifier for further analysis. We recommend to compensate for some missing lake characteristics that were not reported in the searched manuscripts, such as lake volume, depth, or surface area, that authors utilize the HydroLAKES database (Messager et al. 2016; https://www.hydrosheds.org/).

CODE AVAILABILITY

All code for analyses included within this manuscript as well as meta-data files (including unique identifiers, repository and manuscript data, lake characteristics, water Chla and chemistry data, and water sample collection method) are provided on an open access repository at https://afilazzola.github.io/ChlorophyllDataPaper/. Within the repository, we also provide code for unit conversion (e.g. µg/L to mg/L), extracting climate data from Climatic Research Unit in East Anglia (http://www.cru.uea.ac.uk/), and joining the separate data files into one master data file.

ACKNOWLEDGEMENTS

We thank all authors of the data that were used in generating this database either by making their data available in an online repository or providing it through email. Without their extensive fieldwork, this database would not have been possible. This research was funded by an NSERC Discovery grant, Ontario Ministry of Innovation Early Researcher Award, and the Ontario Ministry of Environment Best in Science, York University Research Chair grants awarded to S.S. York University Faculty of Graduate Studies salary also supported O.M.

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TABLES

Table 1. Table attributes and descriptions for meta-data files on studies (MSdata.csv), data repositories (RepoData.csv), unique survey instances (uniqueID.csv), and methods of data collection (Methods.csv).

Data label	Description
MSdata.csv	
ID	Identifier for the published study
Title	Title of published study
Authors	Authors of published study
Source Title	Journal that the study was published in
Publication Year	Year that the study was published
Volume	Volume form journal
Issue	Issue from journal
Beginning Page	First page in the journal that the study was published
Ending Page	Last page in the journal that the study was published
DOI	Digital Object Identifier associated with study
Total Citations	Total number of citations associated with the study as of October 2018
exclude	Whether the study was excluded from the database
reason.simplified	A simplified reason why the study was not used
contacted	Whether the authors were contacted to provide their data
data	Whether the data from the study was included in the database
RepoData.csv	
StudyID	Study identifier to be connected to the data
StudyName	Name of study
Link	Link where data was obtained from
Author	Authors that were listed in study
Title	Title of study
DataSource	Source data was acquired from including databases, repositories, or online searches
Year	Year the dataset was published
Processed	Whether the dataset was processed to be added to the remaining
uniqueID.csv	
uniqueID	Unique identifier for each respective survey instance that exists across all datasets within this database
studyID	The study identifier based on which manuscript or database the data was acquired from. Numbers can be compared against the MSdata spreadsheet for specific manuscript used
Year	Years the surveys were conducted. In some instances, surveys may have been averaged over multiple years (e.g. 1994-1996)
Month	The month that the sample was surveyed (if available)
Lat	Latitude where the survey was conducted
Lon	Longitude where the survey was conducted
StudyLakeName	The name of lake as described within the study
LakeCountry	Country lake was surveyed in
Hydrolakes	Hydrolakes ID obtained from http://wp.geog.mcgill.ca/hydrolab/hydrolakes/. If "NA" no match was obtained
GoogleName	Name of lake obtained from a Google search
UniqueLakeName	Unique lake identifier used within our study to connect multiple surveys of the same lake but with different coordinates.
DataType	Type of data that was acquired
Methods.csv	
StudyID	Study identifier to be connected to the data
PI	Principal investigator of method of data collection

Chl layer	The depth at which the chlorophyll sample was taken
Chl method	The method of which the chlorophyll sample was measured
Chl notes	Notes/comments about extraction chlorophyll methods
Filtered	Whether the chlorophyll sample was filtered or not
TP; TN; PO4; NO3NO2; DOC; DO; NH3 method	The method of which water chemistry samples were measured
TP; TN; PO4; NO3NO2; DOC; DO; NH3 notes	Notes/comments about extraction of water chemistry methods

Table 2. Table attributes and descriptions from three files of chlorophyll concentration (chl.csv), water chemistry(waterchem.csv), and lake morphology (LakeChar.csv).

Attribute (column header)	Description of attribute	Data with values (%)
chl.csv		
uniqueID	Unique identifier for each respective survey instance that exists across all datasets within this database	
ChlUnits	The units that total phosphorus is reported (all mg/L)	
ChlValues	Average concentration of chlorophyll a in freshwater lakes at each survey instance	100
waterchem.csv		
uniqueID	Unique identifier for each respective survey instance that exists across all datasets within this database	
TP.units	The units that total phosphorus is reported (all mg/L)	
TP.value	Average concentration of total phosphorus in freshwater lakes at each survey instance	77.2
TN.units	The units that total nitrogen is reported (all mg/L)	
TN.value	Average concentration of total nitrogen in freshwater lakes at each survey instance	58.6
PO4.units	The units that phosphates are reported (all mg/L)	
PO4.value	Average concentration of phosphates in freshwater lakes at each survey instance	9.9
NO3NO2.units	The units that nitrates and nitrites are reported (all mg/L)	
NO3NO2.value	Average concentration of nitrates and nitrites are in freshwater lakes at each survey instance	10.9
DOC.units	The units that dissolved organic carbon are reported (all mg/L)	
DOC.value	Average concentration of dissolved organic carbon in freshwater lakes at each survey instance	22.5
DO.units	The units that dissolved oxygen are reported (all mg/L)	
DO.value	Average concentration of dissolved oxygen are in freshwater lakes at each survey instance	8.3
NH3.units	The units that ammonia are reported (all mg/L)	
NH3.value	Average concentration of ammonia are in freshwater lakes at each survey instance	31.7
LakeChar.csv		
LakeVolume	The volume of the lake that was surveyed in m3	< 1
SurfaceArea.units	The units used for measuring the surface area of the lake that was surveyed	
SurfaceArea.value	The measured surface area of the lake that was surveyed	57.6
Depth.mean	The average depth of the lake that was sampled in meters	12.6
Depth.max	The maximum depth of the lake that was sampled in meters	26.5
Secchi	The distance underwater that the secchi depth was no longer visible from the surface (meters)	29.3
pH	The pH of sampled water	9.7

FIGURES

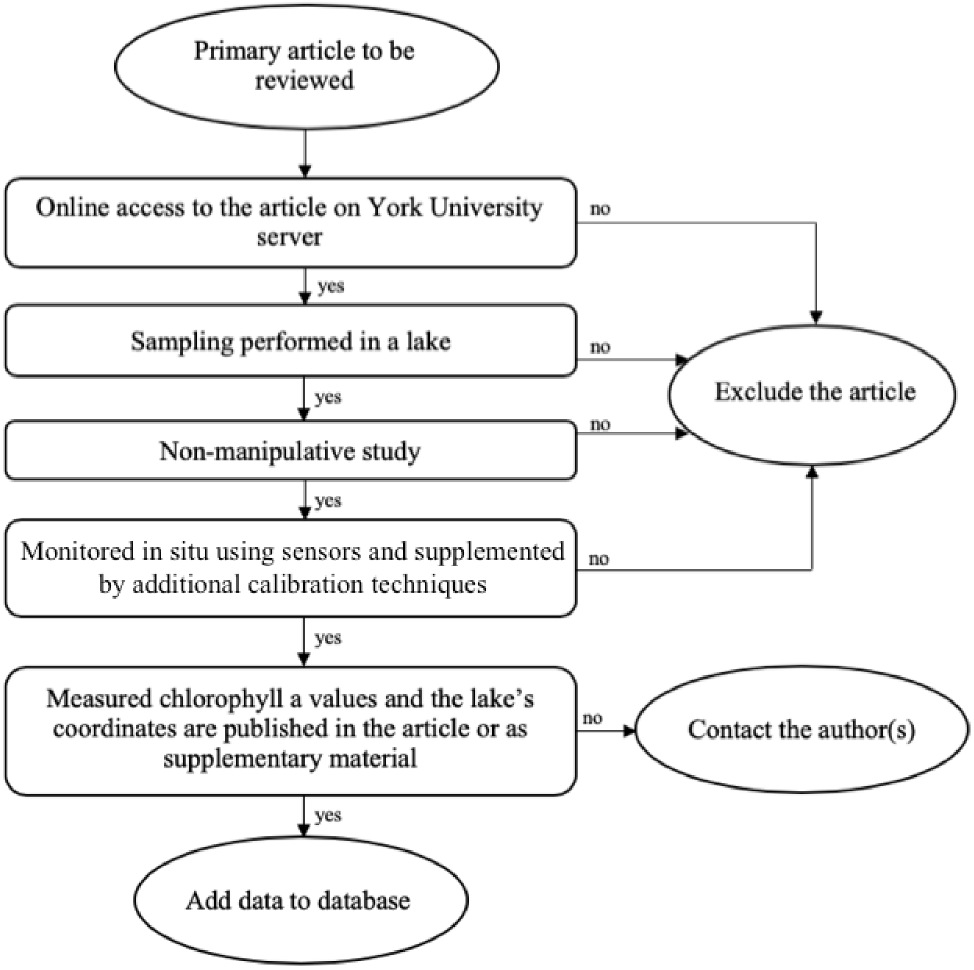

Figure 1. Workflow for all datasets included in the global chlorophyll and water chemistry database.

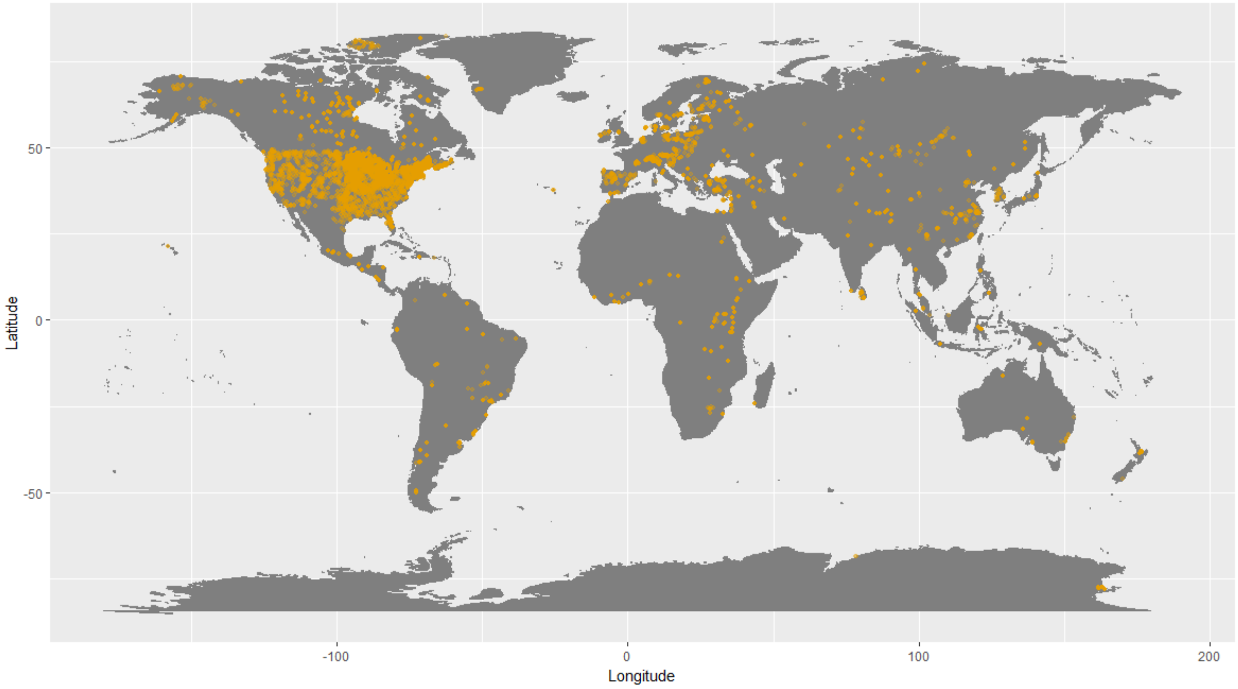

Figure 2. Global distribution of lakes included in database that have measured chlorophyll values.

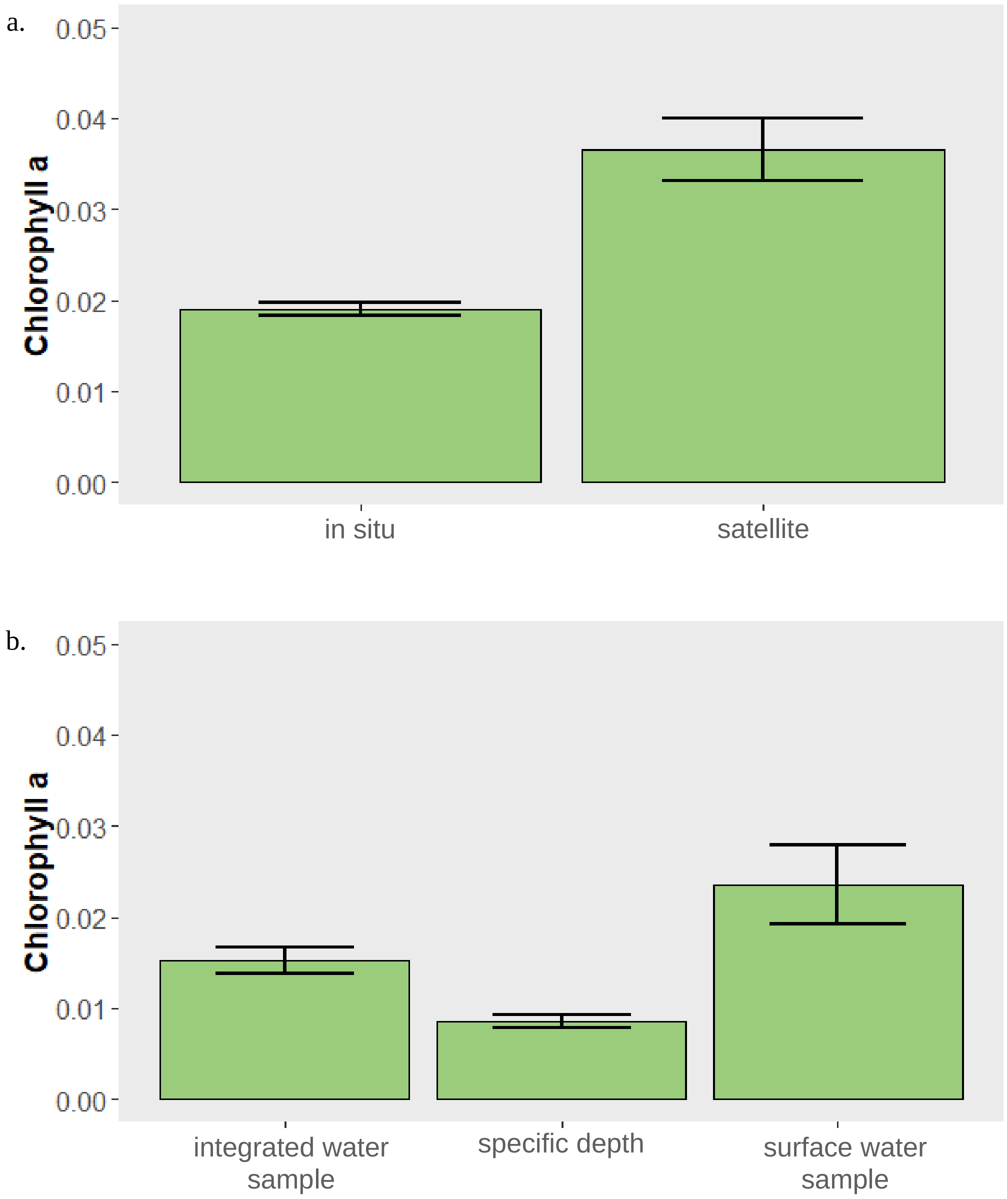

Figure 3. a) Bar plots of mean Chla concentrations +/- SE for *in situ* and modelled data, and b) at different depth profiles.

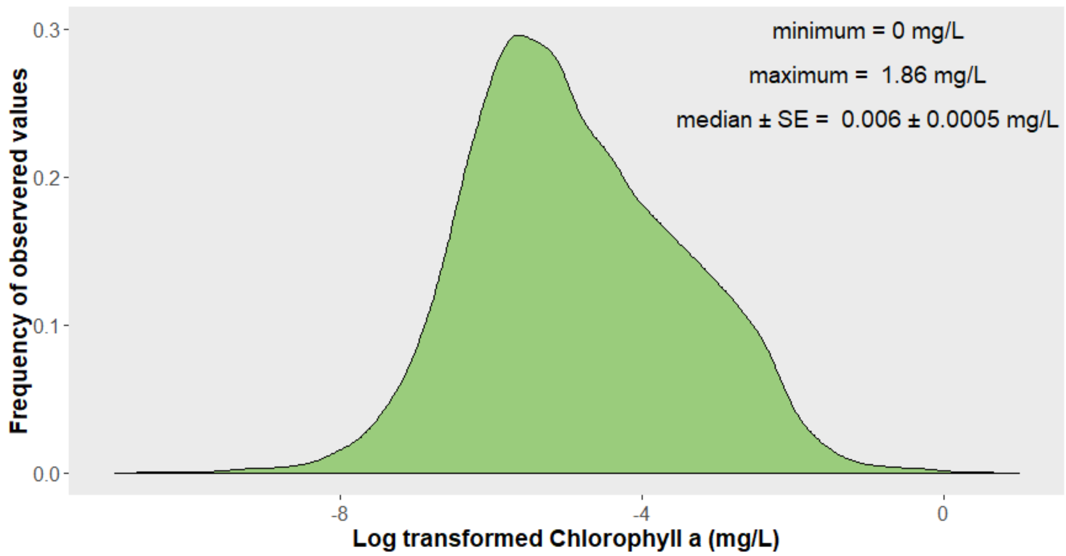

Figure 4. Frequency of observed chlorophyll values found in global lake dataset (n = 16,782).

GENERAL CONCLUSION

There are a wide range of physical, chemical, and biological response variables within a lake that may act as indicators of the effect of climate change and other anthropogenic pressures (Adrian et al. 2009). Chlorophyll concentrations are of particular interest because they represent the trophic state of a lake and are frequently used as a suitable measurement of water quality worldwide (Carlson 1977; Li et al. 2017). Changes in water quality trends and patterns indicated climate warming and disproportionate human disturbance in aquatic ecosystems not only for north temperate regions, but globally as well (Machalak 2016). For this thesis, we focused on water quality changes with respect to climate and other stressors. We empirically quantified temporal trends in lake Chla and other water chemistry variables for the Great Lakes and small inland lakes in Canada and the United States. We then evaluated how climate, morphology, or the introduction of invasive species may be influencing those water quality trends. For the second chapter, we expanded the spatial scale and assembled a freshwater lake Chla global dataset to assess Chla patterns across the entire world. Additionally, we collected other water chemistry values and geomorphometric features for each lake.

Over the past four decades, climate and land use changes in the Laurentian Great Lakes region have been associated with changes in water quality (Magnuson et al. 1997; Williamson et al. 2008). In Chapter 1, we assessed Chla, DOC, TP, and TN concentrations in 36 lakes, all within north temperate regions of Ontario and Wisconsin. We then determined if climate, invasive species or morphology were contributing to observed changes after analyzing ≥20 years-time-series data. Generally over time, we found that lake Chla and TP had significantly declined (with declines occurring at a significantly faster rate in the Great Lakes compared to inland lakes), while DOC had increased (with positive degrees of spatial autocorrelation in small inland lakes). The primary drivers of water quality changes in the Great Lakes and small inland lakes included precipitation, temperature, surface area and the presence of dreissenid mussels, with our models explaining 73.1% and 45.6% of the variation, respectively.

Chlorophyll levels are not only an appropriate measure of water quality within the Great Lakes region, but are also consistently measured at the global scale (Carlson 1977). For Chapter 2, we collected Chla data for 3557 lakes after conducting a systematic literature review of over 3000 manuscripts and compiling data from 15 online repositories. All lakes with Chla values were identified by their spatial coordinates (i.e. latitude and longitude) and followed a set of strict criteria before being included in the global dataset. Further, any geomorphometric characteristics and other water chemistry variable were also collected, if available. This open access dataset will deepen our understanding of the spatial distribution and variability of phytoplankton biomass and associated water chemistry variables in lakes globally.

Changes in water quality are expected to affect lake ecosystems as well as the economies and societies that dependent on clean, fresh water (Vincent 2009). Past climate changes, regarding temperature and precipitation, as well as the incessant addition of anthropogenic pressures has been shown to degrade water quality in terms of changes in Chla concentrations and numerous other water quality properties (Zimmerman et al. 2008). Overall, this thesis indicated that lakes have a strong potential of identifying changing climate conditions in addition to changes in their surrounding landscape with combined temporal and spatial approaches providing a cohesive front of changes in water quality over time and space. The application of these analyses and datasets will hopefully aid researchers to further understand the effects of global environmental change on freshwater ecosystems, processes, and services (Adrian et al. 2009).

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