8-2019

An assessment of periphyton communities in five Upper Peninsula streams, MI

Aaron Jeffrey Christiansen
Grand Valley State University

ScholarWorks Citation

Christiansen, Aaron Jeffrey, "An assessment of periphyton communities in five Upper Peninsula streams, MI" (2019). *Masters Theses*. 944.
https://scholarworks.gvsu.edu/theses/944

An assessment of periphyton communities in five Upper Peninsula streams, MI

Aaron Jeffrey Christiansen

A Thesis Submitted to the Graduate Faculty of

GRAND VALLEY STATE UNIVERSITY

In

Partial Fulfillment of the Requirements

For the Degree of

Master of Science in Biology

Biology Department

August 2019

Abstract

This project quantified lotic periphyton community change from May 2018-October 2018 in five, first and second-order Lake Superior tributary streams. Using periphyton communities, land use, geology, and abiotic factors pertinent to stream ecosystems we evaluated periphyton community succession. Using periphytometers, periphyton communities were collected and identified monthly to quantify community succession. Total phosphorus and total Kjeldahl nitrogen were measured monthly during the study. Depth, velocity, specific conductivity, and canopy cover were measured to quantify some of the physical factors within the streams. Non-metric multidimensional scaling analysis indicated that the periphyton communities were similar between streams (ADONIS p-value =0.73) but was changing seasonally (ADONIS p-value <0.001). Dominant diatom taxa found were *Synedra*, *Nitzschia*, *Melosira*, *Navicula*, and *Diatoma*. Principal component analysis found that most streams had similar characteristics throughout the sampling period but depth. Chemical analysis from the streams indicated that these systems contained low nutrients but were classified as oligotrophic based on the trophic state index. Nutrients in the streams were very low; total phosphorus ranged from 50-70 µg/L meaning the streams meet the oligotrophic threshold. Nitrogen concentrations within these streams peaked at 1.00 mg/L following leaf abscission from the riparian vegetation in the fall but was found to be <0.5 mg/L throughout the rest of the sampling period. It has been hypothesized that Lake Superior is beginning to undergo the process of ultra-oligotrophication or when total phosphorus levels are <1 µg/L within the water column. The Lake Superior basin could be greatly impacted by climate change, introduction of invasive species, and potential warming air temperatures, which could accelerate ultra-oligotrophication within the basin and cause a reduction in biodiversity of Lake Superior and its tributaries.

Table of Contents

Chapter

List of Tables

List of Figures

List of Abbreviations

Dissolved Oxygen = DO

Total Kjeldahl nitrogen = TKN

Total phosphorus = TP

Canopy cover = CC

Temperature = T

Stream depth = z

Chapter I

Introduction

Periphyton can be used as model organisms when researching changing conditions within streams to observe the impacts of anthropogenic pollution and climate effects on aquatic systems (Singh et al. 2017). Periphyton communities are the collection of green algae, diatoms, blue-green algae, heterotrophic bacteria, and fungi that create attached assemblages within streams (McCall et al. 2017; Rashid et al. 2013). Rapid community changes within periphyton communities occur due to the fast generation time and adaptability of these organisms within aquatic systems (Snyder et al. 2002). Factors impacting periphyton species composition include increasing temperature, fluctuating nutrient levels, predation, and shifting substrate (Francoeur, Biggs et al. 1999; R. J. Stevenson et al. 2006). Periphyton communities can also give insight to changing conditions within the water system due to the rapid ability of the communities to change to shifting seasonal conditions and anthropogenic alterations (Biggs & Smith, 2002; Godwin & Carrick, 2008). Periphyton research can be used to make predictions on how rising water temperature and higher concentrations of nutrients can impact communities within stream ecosystems, both areas relevant to potential impacts of climate change. Using periphyton as bioindicators can be a relatively inexpensive way of monitoring streams because they show increased biomass of diatoms at lower total phosphorus concentrations, while at high total phosphorus concentrations communities resemble a higher biomass of green and blue-green algae (Stelzer & Lamberti, 2001).

In-stream nutrients vital to periphyton communities are nitrogen (N) and phosphorus (P) in both their organic and inorganic forms (Biggs, 2000; Francoeur et al., 1999; Matheson et al. 2012). These nutrients are common within aquatic systems and are naturally occurring from a variety of sources within nature. Most of the nutrients within the Lake Superior Basin flow in from the surrounding tributaries (Hershey, Anne E & Wold, 1999). The presence of N and P are important drivers of periphyton community presence and succession. N and P concentrations can vary seasonally with factors including leaf abscission, detrital breakdown, presence of shredding invertebrates, and nutrient spiraling (Allen & Hershey, 1996; Biggs et al. 1998; Mulholland, et al. 1985). Lower concentrations of phosphorus within these streams can lead to the periphyton being composed highly of pennate diatoms while high concentrations of phosphorus would lead to periphyton being composed of green algae, blue-green algae, and stalked diatoms (Biggs et al., 1998; Quinn & Hickey, 1990; Rugenskiet al. 2008). The presence or absence of nutrients within an aquatic system can often be directly correlated to the species that are present at a given time (Biggs, 1990; Cantonati & Lowe, 2014). Nutrient presence and absence can be used as a direct correlation of periphyton community assemblage (Santos, et al. 2018). Knowing the concentration of nutrients within aquatic systems allows for the study of periphyton communities and can be used in a variety of studies and to use them as bioindication.

Successional changes are common to occur within periphyton over time and as water temperatures rise. It has been described that diatoms would inhabit streams in early spring (Honeyfield & Maloney, 2015; Robarts & Zohary, 1987) and the community would progress to stalked diatoms and green algae into mid-summer (Carpenter & Waite, 2000; Guasch et al., 1998; Kilroy & Bothwell, 2011). Periphyton successional stage is used as a bioindicator of stream health (Jyrkänkallio-Mikkola et al. 2018; Piggott et al. 2015; Pillsbury et al. 2019; Welsh & Ollivier, 1998). Streams with a high disturbance frequency would be found to contain communities dominated by pennate diatoms while streams with a less frequent disturbance frequency would be hypothesized to contain mucilaginous green algae communities. This seasonal shift of periphyton can give insight to the health of the ecosystem, grazer presence, riparian vegetation, and anthropogenic influences within a stream. Future climate change predictions could lead to a shift in this understanding as air temperatures continue to warm and nutrients become available to stream communities. The successional stage of periphyton communities is directly controlled by the frequency of disturbance that occurs within the system. It has been reported that biofilm thickness and biomass are directly related to the age and diversity within the biofilm itself (Reisinger, Tank, & Dee, 2016; Sekar et al. 2002). As the biofilms get larger and thicker in late successional stages, they become more susceptible to being damaged through high flooding, erosion, and substrate disturbance. These late successional mats are composed of green algae, blue-green algae, and stalked diatoms and can shade out lower stage organisms of diatoms like *Synedra, Navicula,* and *Nitzschia* (Biggs et al., 1998; Jones, 1977; Sekar et al., 2002).

The introduction of fine sediments can have direct impacts on physical and chemical characteristics of stream ecosystems. These sediments can reduce light availability to communities (Waters 1995; Wood and Armitage 1997), limited hard surfaces for periphyton to colonize (Biggs 1995; Kondolf et al. 2014), a reduction in periphyton abundance and biomass has been observed with varying levels of sedimentation and wash-out (Foy 1976). These fine sediments are considered to be the greatest source of water quality degredation within an aquatic ecosystem (Biggs, 2000) but the loss of abundance of periphyton communities might not mean a loss of primary production within streams (Dodds & Smith, 2016). Periphyton communities can quickly adapt to reduced abundance through increasing chlorophyll concentrations within cells being able to maintain primary production within streams (Dodds & Smith, 2016; Gottlieb et al. 2006; Wood & Armitage, 1997). This adaptability makes these organisms key factors in monitoring a changing climate and allows for stream health to be monitored.

As the overall climate of Earth continues to raise water temperature within streams, periphyton communities would be directly impacted. Climate change has been found to cause earlier snow melts and more severe precipitation events around the world (Trenberth, 2011; Walther et al., 2002). These earlier snow melts are hypothesized to lead to earlier blooming of riparian vegetation and nutrient uptake by organisms (Feminella M.E.;Resh,V.H., 1989; Shigeru Nakano, Hitoshi Miyasaka, 1999). With global air temperatures rising we could see an increase in green algal and cyanobacterial blooms worldwide (Snyder et al., 2002). The seasonal change of periphyton communities has been used as bioindicators of increasing water temperatures through observing the present communities compared to their life histories (Wu et al. 2017). Stevenson and Pan (1999) used diatoms as an indicator to assess environmental conditions within streams due to their ease of use and utility in showing changes in water temperature, light availability, nutrient concentration alterations, and disturbance impacts on aquatic systems. Another example of periphyton as bioindication is the use of these communities in surveying the presence of heavy metals within aquatic environments (Huang et al., 2017; Kaonga & Monjerezi, 2012; Li, Zheng, & Liu, 2010). Increasing water temperatures would be predicted to cause an increase in the abundance of *Melosira, Cladophora, Oedogonium,* and *Microcystis* over time (Brown, Low-Décarie, Pillsbury, Fox, & Scott, 2017; Guasch et al., 1998; Piggott et al., 2015), and have the potential to reduce assemblage diversity (Cantonati and Lowe 2014). This loss of diversity may impact higher trophic levels through the reduction in macroinvertebrate grazing potential (Moerke et al. 2005) or the death of fish populations through harmful algal blooms and die-offs (Francoeur et al. 2017; Michalak et al., 2013).

In addition, the Lake Superior water basin may be undergoing the process of ultra-oligotrophication, where decreasing available phosphorus (< 1 µg/L) can limit periphyton growth and diversity (Sterner, 2014). Stream ecosystems within the basin would experience the greatest impact from ultra-oligotrophication due to a loss of nutrients becoming available from riparian zones (Michelutti et. al 2003). The flow of streams and nutrient spiraling can lead to a coupling effect of total nutrient concentrations found within these systems (Ward et al., 2017). Low total nitrogen and phosphorus concentrations can lead to decreased successional changes and has been found to house lower a lower diversity of organisms (Michelutti et al. 2003; Pan et al. 2000; Rosemond, 1994). Lake Superior; long being considered an oligotrophic system; largely receives its water inputs from tributaries, groundwater discharge, and rainfall (Hershey and Wold 1999). The potential ultra-oligotrophication of these tributaries could impact nursery habitat for migrating suckers (*Catostomus spp.)* (Beauchamp et al. 1994), invertebrate populations within streams (Álvarez & Peckarsky, 2005; Feminella M.E.;Resh,V.H., 1989; Greenwood & Rosemond, 2005), and could promote the growth of the low nutrient bloom forming diatom *Didymosphenia* (Bothwell et al. 2011). An understanding of the ecology and diversity of primary producers within these systems and knowing how abiotic variables could be correlating to periphyton growth seasonally could assist in the management and health of the Lake Superior basin long term. The downstream transfer of organic matter and nutrients into Lake Superior from its tributaries could be impacted by changing environmental factors from climate change. As air temperatures continue to climb, terrestrial plants are beginning to bloom earlier in the spring as snow melt begins sooner. This is hypothesized to lead to lower concentrations of phosphorus and nitrogen within these streams and could eventually lead to some of the issues that have been previously discussed.

Purpose

This project investigated the seasonal shift of periphyton communities spatially and temporally across five streams in the Upper Peninsula of Michigan from May 2018-October 2018. I quantified if community change does occur and if so, attempted to correlate these changes to environmental changes occurring seasonally. The streams in question are understudied systems and, using streams in a relatively remote area of the Upper Peninsula would allow for qualitative analysis of community structure and abiotic factors and help understand how climate change and anthropogenic influences may be impacting these systems. This study also intends to investigate nutrient concentrations within each tributary to gain additional information to answer if ultra-oligotrophication is occurring within the tributaries of Lake Superior.

Scope

Within headwater streams diatoms such as *Diatoma, Nitzchia, and Synedra* are the most abundant genera found and would arrive quickly after first snowmelt (Bernhardt & Likens, 2004; Lynch & Magoulick, 2016; Michelutti et al., 2003; Nebgen & Herrman, 2019). These genera are understood to have greater presence in colder temperatures with low nutrients. Understanding periphyton community structure, seasonal shifts, and physiochemical characteristics allows for a heightened understanding of these stream ecosystems. This study made use of previous techniques within the field of algal ecology through the use of periphytometers and physiochemical variables within streams (Stevenson & Bahls, 1999) and permits an increased knowledge of an understudied region of the world that has a relatively low anthropogenic impact.

Significance

Periphyton are an important group of organisms and are found in all aquatic ecosystems while displaying great diversity and abundance within aquatic ecosystems (Santos et al. 2018). These communities have also been found to be excellent model organisms for quantifying changing environmental conditions, including seasonal shifts, because they quickly respond to changing environmental conditions (Stelzer and Lamberti 2001). Understanding seasonal shifts in periphyton communities over time in five creeks would permit predictions of how future changes in temperature and nutrient concentrations may influence periphyton assemblages.

Objectives

The goal of this study was to compare the periphyton communities of five Lake Superior tributaries from May 2018-October 2018. I considered differences in geology/land use, nutrient concentrations of total Kjeldahl nitrogen (TKN), total phosphorus (TP), and physical stream conditions in these streams (Biggs, 1990; Stevenson et al. 2006). I hypothesized that periphyton communities would change temporally but remain similar spatially during this experiment due to the proximity of these streams to each other and their similar physical characteristics. Taking these conditions into consideration allows an understanding of the periphyton community, seasonal shifts that are occurring within the community, and what it could mean when correlated to physiochemical parameters within each stream. Specifically, I used periphytometers to collect monthly community samples; and performed statistical analysis to compare species and environmental trends to determine how periphyton communities were seasonally shifting within streams.

An assessment of periphyton communities in five Upper Peninsula streams, MI

Aaron J. Christiansen[2] and Dr. M. Megan Woller-Skar [3]

Department of Biology, Grand Valley State University, 1 Campus Drive, Allendale, MI, 49401, USA

E-mail addresses: christia@mail.gvsu.edu[2]; wollerm@gvsu.edu[3]

Chapter II

Abstract

This project investigated the seasonal shift of periphyton communities spatially and temporally across five streams in the Upper Peninsula of Michigan from May 2018-October 2018. I quantified if community change does occur and if so, attempted to correlate these changes to environmental changes occurring seasonally. The first and second order streams in question are understudied systems and, using streams in a relatively remote area of the Upper Peninsula would allow for qualitative analysis of community structure and abiotic factors and help understand how climate change and anthropogenic influences may be impacting these systems. This study also intends to investigate nutrient concentrations within each tributary to gain additional information to determine the trophic status within the tributaries of Lake Superior. Periphyton, being aquatic organisms found in all systems, provide an excellent organism for the study of stream function and diversity. Using periphytometers, periphyton communities were collected and identified once monthly to understand if a community shift was occurring and how the communities related within the streams. Total phosphorus and total Kjeldahl nitrogen were measured to understand the specific chemical concentrations over the sampling period. Depth, flow velocity, conductivity, and canopy cover were measured to understand some of the physical factors found within the streams. Non-metric multidimensional scaling analysis found that the periphyton community was similar within streams (ADONIS p-value =0.73) but was changing seasonally (ADONIS p-value <0.001). Principal component analysis found that most streams had similar characteristics throughout the sampling period but depth. Chemical analysis from the streams discovered that these systems contained low nutrients but were classified as oligotrophic based on the trophic state index. Nutrients in the streams were very low; total phosphorus ranged from 50-70 µg/L meaning the streams meet the oligotrophic

threshold. Nitrogen concentrations within these streams peaked at 1.00 mg/L following leaf abscission from the riparian vegetation in the fall but was found to be <0.5 mg/L throughout the rest of the sampling period. The Lake Superior basin could be greater impacted through changes in climactic events, introduction of invasive species, and potential warming air temperatures which could accelerate ultra-oligotrophication within the basin and cause a reduction in biodiversity of Lake Superior and its tributaries.

Introduction

The study of periphyton has been used in conjunction with several projects in recent times (Lohman, Kirk. Jones, John R. Baysinger-daniel, 1991; Nebgen & Herrman, 2019; Riseng, C. M., et al. 2004; Shigeru Nakano, Hitoshi Miyasaka, 1999). Using periphyton successional change for stream monitoring projects and monitoring climate change effects on streams (Brown et al., 2017; Langridge & Daniels, 2017; Molina-Navarro, et al. 2018; Piggott et al., 2015). Periphyton can be used to monitor changing nutrient concentrations in both natural streams (Dodds et al. 2002; Santos et al., 2018; Sekar et al., 2002) and impacted streams (Dinh & Death, 2018; Dodds et al., 2002; Wood & Armitage, 1997). Using periphyton successional change can give insight to the presence of trace metals (Huang et al., 2017; Wu et al., 2017), stream nutrient state classification (Dodds, et al. 1998; Lufafa, et al. 2003; Trebitz et al., 2008), invasive species impacts (Bothwell et al., 2014; Cantonati & Lowe, 2014; Francoeur et al., 2017; Kilroy & Bothwell, 2011; Walsh et al. 2016), and climate change impacts on streams (Brown et al., 2017; Jyrkänkallio-Mikkola et al., 2018; Stasio et al. 1996). These studies can be used to help identify the strong points on using algal ecology as means of indication of how a changing environment could be impacting lakes and streams around the world. Benthic periphyton communities specifically can show how a potential decrease in nutrients of the Lake Superior basin could impact how the ecology of these tributaries could be impacted.

Tributary streams play a vital role in the distribution and delivery of nutrients into lakes through seasonal runoff of N and P into Lake Superior (Rugenski et al. 2008). Within the Lake Superior basin, nutrients are becoming less available for biological uptake overtime (Kireta & Saros, 2019) through events like climate change (Kireta & Saros, 2019), early snow melt (Langridge & Daniels, 2017), and more severe rain events (Trenberth, 2011). As temperatures continue to warm and detrital breakdown reduces (Boyero et al., 2011) nutrient spiraling within streams would lengthen and reduce growth within streams (Cantonati & Lowe, 2014; Mulholland et al., 1985). As these events occur, ultra-oligotrophication within Lake Superior would only be enhanced over time and could lead to the bloom of *Didymosphenia* and the reduction of lake phytoplankton over time.

An important component of the benthos, benthic periphyton are a commonly used community for the monitoring and assessment of stream climate change studies (Boyero et al., 2011; Jyrkänkallio-Mikkola et al., 2018; Piggott et al., 2015; Walther et al., 2002). Periphyton communities are the collection of green algae, diatoms, blue-green algae, heterotrophic bacteria, and fungi that create attached assemblages within streams (Rashid et al., 2013). Periphyton, being microscopic primary producer, can exhibit extremely diverse communities within small surface areas within the benthos. Because these organisms are photosynthetic, they are directly controlled by factors including: water temperature, light penetration, nutrient concentration, and disturbance regime of the stream (Álvarez & Peckarsky, 2005; Bernhardt & Likens, 2004; Lynch & Magoulick, 2016; McCall et al., 2017; Santos et al., 2018). Periphyton are good indicators of seasonal stream changes due to the ability of these organisms to quickly adapt to changing conditions (e.g., increasing temperature, fluctuating nutrient levels, predation, and shifting substrate) throughout the different seasons. This adaptability makes periphyton key components in stream ecosystems around the world (Chetelat et. al. 1999, Piggot 2015). Abiotic changes around these communities can have a direct impact on what division can dominate the community. The removal of riparian zone vegetation can lead to an increase in water temperature and nutrient concentrations within the stream eventually leading to the presence of stalked green algae and late successional organisms (Dodds, 2007; Foy, Gibson, & Smith, 1976; Guasch et al., 1998). Periphyton can show a reduction in nutrient concentrations by the community being dominated by diatoms and on the extreme end the presence of *Didymosphenia,* an invasive stalked diatom found to bloom in low nutrient systems (Bothwell et al., 2014; Gottlieb et al., 2006; Kilroy & Bothwell, 2011; Mori, et al. 2018; Pillsbury et al., 2019). With periphyton being excellent indicators of change within aquatic environments, they are commonly used in research to monitor stream ecosystem health.

Changing climactic factors are becoming a stronger presence within the natural environment. Current climate predictions show that air temperature will continue to rise, and precipitation events could get more severe. Climate change is assumed to lead to larger disturbances including flooding (Trenberth, 2011), introduction of invasive species (Cantonati & Lowe, 2014), and the loss of native species (Walsh et al., 2016). These events would lead to a disruption of the natural setting within stream ecosystems and would have a direct impact on the communities they could support (Collins, et al. 2011; Dinh & Death, 2018; Lynch & Magoulick, 2016). In northern temperate streams, climate change is predicted to cause a reduction in nutrient concentrations of nitrogen and phosphorus leeching in the spring. The mechanism involves the riparian zone, which is predicted to be heavily influenced by a changing climate. As temperatures warm and snow melt is happening earlier in the spring, riparian zone vegetation would begin to bloom earlier which would lead to increased shading and greater uptake of nutrients in the soil (Hancock, 2002; Nebgen & Herrman, 2019). This increased riparian shading on streams can help with keeping water temperature cool in headwater streams (Nebgen & Herrman, 2019) but current oligotrophic streams could be faced with nutrient limitations which could impact diversity of the benthic community (Brown et al., 2017; Carpenter & Waite, 2000; Matthaei, Guggelberger, & Hubre, 2003). To monitor climactic impacts in aquatic ecosystems, the use of bioindicators have been used to efficiently watch environmental conditions and track changing abiotic variables through time. Commonly used in lotic systems, the benthic community is thought to be the best resource for this type of research as this community can be greatly impacted by sudden changes in streams (Brown et al., 2017; Dinh & Death, 2018; R. J. Stevenson et al., 2006).

The goal of this study was to compare the periphyton communities of five Lake Superior tributaries during much of the ice-free season. I considered differences in geology, land use, nutrient concentrations of total Kjeldahl nitrogen (TKN), total phosphorus (TP), and physical conditions in these streams. I hypothesized that periphyton communities would change temporally but remain similar spatially during this experiment due to the proximity of these streams and their similar physical characteristics. Taking these conditions into consideration allows an understanding of the periphyton community, seasonal shifts that are occurring within the community, and what it could mean when correlated to physiochemical parameter within each stream. Specifically, I used periphytometers to collect monthly community samples; and performed statistical analysis to compare species and environmental trends to determine how periphyton communities seasonally shifted within streams to present conditions.

Methods

Study Sites

I collected samples from Halfaday Creek, Mill Creek, Naomikong Creek, Ankodosh Creek, and Roxbury Creek (Figure 1); all of which are 3rd-order tributaries of the Upper Peninsula of Michigan that drain into Lake Superior. These streams were selected because of their similar characteristics (flow, depth, and substrate), proximity to one another (no more than 3 miles between neighboring streams), and due to the lack of knowledge on these systems. Sample locations were 40 to 70 meters upstream (South) of the Lake Superior lakeshore with two sampling sites at each location. These streams and their sub-watersheds contain soils composed of sand, clay, and fine silts. Stream velocities ranging from 20 m/s in Roxbury creek to 45 m/s in Mill creek (Table 1) and dense riparian vegetation. Halfaday, Mill, Naomikong, and Ankodosh were highly similar while Roxbury was approximately 50 cm deeper than all other streams over the duration of the experiment (Table 1). Abiotic sampling occurred in the beginning of May 2018-October 2018 when periphytometers were deployed whereas periphyton sampling occurred from the end of May 2018-October 2018.

Periphyton collection/Identification

Periphyton surveys were completed at each sample site in Figure 1. I placed two periphytometers in the water column in the thalweg at each study stream (R. J. Stevenson & Bahls, 1999; R. J. Stevenson et al., 2006). These periphytometers were equipped with 8 standard glass microscope slides suspended in the water column just below the water surface (Paller, 1996). Once monthly, I removed the slides and I scraped the surface of the slide into a 75 ml Nalgene cup using a flat edged scalpel. I preserved samples in a solution of 20 ml Lugol’s Iodine and 55 ml deionized water until the color of the solution was a dull orange. Samples were then transported to the lab for identification. A minimum of 500 individuals were identified to genus using 400X magnification using a Leica DME compound microscope (Biggs & Smith, 2002; Jyrkänkallio-Mikkola et al., 2018; Pan et al., 2000) using the identification key Freshwater Algae: Identification, Enumeration, and use as Bioindicators (Bellinger and Sigee, 2015).

Environmental Survey

At each site during periphyton collection, I measured stream flow, stream depth, temperature, conductivity, total phosphorus (TP), total Kjeldahl nitrogen (TKN), and substrate/sediment particle size. I used a YSI 85 to quantify temperature, conductivity, and dissolved oxygen within the streams. Stream velocity was measured using the float method as described by the U.S. Environmental Protection Agency (EPA, 2012, Damanik-Ambarita et al., 2016). Stream depth was measured using a meter stick at the thalweg. I collected one 250 ml whole water sample from the surface adjacent to periphytometers using acid washed bottles from each stream during periphyton collection and delivered to the Lake Superior State University Environmental Analysis Laboratory for TP and TKN analysis. Substrate analysis was completed using a Wolman Pebble Count (Kondolf & Li, 1992; Wolman, 1954) with a Gravelometer but was suspended after June due to substrate homogeneity within streams.

GIS Mapping

ArcGIS version 10.4.1 was used to complete watershed delineation mapping. Using soil data, hydrology maps, and CCAP land raster obtained from the State of Michigan GIS database I was able to construct two maps showing *sub-watershed*s of my streams and the land cover within each *sub-watershed* (Figure II). Using the methods outlined by Dr. David Tarboton of Utah State

University, I was able to complete these maps using the spatial analyst “hydrology” tools. Using the Raster calculator, streams were defined based on flow accumulation using the equation (“fac” > 1500). Soil analysis was completed during this time by creating a shapefile for each sub-watershed and clipping the soil_data shapefile with the watershed file.

Data Analysis

All statistical analyses were conducted in R (version 3.5.1, R-Core team 2017) using the “vegan” package (Oksanen et al., 2018). Non-Metric-Multidimensional-Scaling (NMDS) using the Bray-Curtis distance metric was used to compare periphyton communities in all five creeks from May-October (Clarke, 1993). Post hoc analysis was performed on the NMDS ordination using an analysis of dissimilarity (ADONIS) test which indicated where monthly significance was occurring within the ordination and similarity of percentages (SIMPER) indicated which genera drove separation of clusters between months. Principal Component Analysis (PCA) was used to examine relationships among abiotic data in streams.

Results

Periphyton Community Structure

Strong seasonal patterns in periphyton community structure existed among the five streams. Pennate diatoms were the most abundant algal division; green algae and blue-green algae were found in lower abundances during the summer as water temperatures increased. Towards the end of the experiment, Roxbury creek was showing signs of being more productive based on visual observation as it was showing progression to late stage filamentous algal growth. These communities changed temporally but not spatially during the sampling period, meaning that each stream showed similar communities when sampled but the communities were changing seasonally. Periphyton communities were similar spatially but once compared temporally a shift occurred within the community (Figure 3). This finding indicates that seasonal changes could be driving community interactions. ADONIS (Table 2) post-hoc tests reveal that community dissimilarity by stream was non-significant (p-value = 0.73) and community dissimilarity by month was significant (p-value = 0.001). These results confirm that seasonal shifts are occurring within the periphyton communities in these systems.

SIMPER analysis of the NMDS ordination indicated that *Melosira, Synedra, Diatoma, Cocconeis,* and *Fragellaria* were among the most common genera found during this project (Table 4). Diatoms dominated the periphytic community structure in these systems throughout the study with green algae and blue-green algae being present in lower abundances (Table 4, Figure 5).

Environmental Results

We found that abiotic trends in dissolved oxygen, TKN, velocity, canopy cover were higher in colder months (May and September) while temperature, TP, and conductivity were higher in warmer months (June, July, and August) (Figure 4). Abiotic variables tested were found to be similar within all streams except for Roxbury Creek which differed more by depth (Figure 4). Average depth between streams ranged from 28-40 cm for Ankodosh, Naomikong, Mill, and Halfaday while average depth for Roxbury was found to be 95cm (Table 1). Average temperature, conductivity, dissolved oxygen, TP, and TKN were all similar during the experimental time frame between all creeks (Table 1). Roxbury creek showed reduced canopy cover and flow velocity during this time (Table 1, Figure 4). Soil analysis found that each of the watersheds was composed highly of sand, clay, silt, and fine sediments. Land cover was found to be dominated by deciduous and forested wetlands within each of the sub watersheds sampled (Table 3).

Discussion

Periphyton assemblages

Diatoms dominated periphyton communities within these streams (Table 4, Figure 5). This division is known to inhabit areas of low nutrient concentrations through high nutrient uptake efficiency at colder temperatures and the use of silica to create their cells walls and require minimal nutrients to develop a community (Honeyfield and Maloney 2015, Matthaei et al. 2003, Michelutti et al. 2003, Snyder et al. 2002). The high presence of diatoms and overall community structure was found to be similar in each stream during the sampling period (Figure 3). The dominance of diatoms was maintained throughout the sampling period (Figure 5) but as seasonal successional change occurred green algae including *Ulothrix,* and *Oedogonium* became present during the late summer months (Table 4). More diverse algal communities are correlated with higher total phosphorus concentration in streams (Bernhardt 2004, Chetelat et al. 1999, Dodds 2007, Dodds and Smith 2016, Elwood et al. 1981, Hart et al. 1990). Periphyton communities showed minimal spatial differences over the study period but showed stronger trends in temporal changes correlated with temperature within the creeks. These changes show that seasonal changes in nutrient availability and water temperature were leading to changes in the community. Diatoms are able to quickly inhabit areas directly following winter months before other genera can begin to produce (Ledger et al., 2008; Matthaei et al., 2003; Michelutti et al., 2003; Mori et al., 2018). The ability of these organisms to inhabit areas quickly supports the findings of this experiment that they would be the dominant genera groups found within headwater streams in this region (Battin, Kaplan, Newbold, & Hansen, 2003; Bernhardt & Likens, 2004; Greenwood & Rosemond, 2005). Similar successional patterns have been reported in similar streams, showing dominance of diatoms and little other growth during the growing season (McCall et al., 2017; Pillsbury et al., 2019; Sekar et al., 2002). Stream periphyton succession can show rapid changes in nutrients, disturbance regime, anthropogenic introductions, and other environmental changes that can occur (Li et al., 2010), and the results of this experiment show that these streams are to the most part healthy ecosystems showing expected successional changes for a headwater system from spring to fall.

Silica concentrations within these streams were not measured during the experimental time frame. Similar studies have found silica concentrations between 10-25 mg/L in similar sized streams (Dove & Chapra, 2015; Kireta & Saros, 2019; Trebitz et al., 2008). Lake Superior has been long discussed to have the highest silica levels of all the Great Lakes and has been relatively stable since the 1990s (Dove & Chapra, 2015). These higher concentrations of silica found within the streams is an important driver of diatom abundance and dominance within streams (Kireta & Saros, 2019). Due to the bedrock geology and highly calcareous limestone geology of the Lake Superior region, these silica levels likely would not alter much with seasonal progression, leading to these diatom communities to maintain through successional changes. This impact of silica levels correlated with lower nutrient concentrations found in these oligotrophic streams (Table 1) could be what is leading to the dominance of diatoms including *Synedra, Diatoma, Nitzschia,* and *Navicula.* These organisms showed a higher affinity within this region due to their individual life histories. The four diatom genera mentioned above have been found to prosper in colder temperatures, flowing waters, shaded streams, and areas with high disturbance (Bækkelie, Schneider, Hagman, & Petrin, 2017; Gottlieb et al., 2006; Honeyfield & Maloney, 2015).

Environmental conditions

With environmental conditions within these streams being mostly stable throughout the growing season, successional change was observed to occur. Nutrient concentrations were found to be low within these tributaries (Table 1) but were similar to levels found within similar streams in the Lake Superior basin (Allen & Hershey, 1996; Sterner, 2014; Trebitz et al., 2008). It is predicted that with a changing climate, nutrients would continue to decline within Lake Superior proper and each of its tributaries as air temperatures climb (Kireta & Saros, 2019; Stasio et al., 1996). With more severe rain and snow events predicted to occur in this region, higher flooding events and stream bed disturbance can be anticipated (Langridge & Daniels, 2017; Trenberth, 2011). As snow melt continues to begin earlier into the spring, it is hypothesized that nutrient uptake would become higher in terrestrial plants and nutrient concentrations within streams would decline. This process has been greatly impacting the Lake Superior basin and could be causing the process of ultra-oligotrophication to take place, causing detrimental impacts on primary producers. Lower nutrients within streams can cause the bloom of the invasive algal species *Didymosphenia* (Didymo) which has already been observed within the nearby St. Mary's River. This genera is known to create thick mats of algal growth on top of the water column and can shade out macrophytes and benthic organisms below it (Bothwell et al., 2014; Kilroy & Bothwell, 2011). At the current time, didymo is only found within the Lake Superior watershed but was once found throughout all the Great Lakes (Kilroy & Bothwell, 2011). Monitoring and managing for this invasive would be vital for the long-term health of these waterbodies if didymo becomes prolific within Lake Superior itself.

Ultra-oligotrophication and Climate Change

As previously mentioned, a system is deemed ultra-oligotrophic when nutrient concentrations are consistently below 1 µg/L (Michelutti et al., 2003). This information leads us to conclude that during the time frame of my study these streams would be classified as oligotrophic (Dodds, 2007; Dodds et al. 1998). With nutrients being reduced, this would have an impact on the periphyton community and would help our understanding of why the community was dominated by diatoms like *Diatoma, Synedra, Acnanthes*, and *Melosira*, and early stage green-algae. The impact of ultra-oligotrophication could be felt throughout these ecosystems and could become a greater impact with a changing climate in future years. As conditions continue to warm, we can predict that this would increase periphyton and algal growth within these systems, which could cause an even greater demand on nutrients within the system and limit growth and diversity of successional changes (Allen and Hershey 1996, Biggs 2000, Rosemond et al. 2000). As changes in the community occur, periphyton as a food source change as they move to late successional mats of stalked algae and diatoms. It has been observed that growth of didymo can cause a reduction in the macroinvertebrate community and cause periphyton mats to move to more dense late successional stages (Sanmiguel et al., 2016). If the basin were to move towards the classification of ultra-oligotrophication, these impacts could cause drastic changes to the benthic community of both periphyton and macroinvertebrates causing the ecology of these streams to be impacted through bottom-up trophic cascades.

Figures and Tables

Table 1. Mean measured environmental factors and standard deviations in each creek from May 2018-October 2018. Numbers in parentheses indicate n-size (number of months sampled).

Stream	Depth (cm)	Temperature (˚C)	Dissolved Oxygen (mg/L)	Conductivity (µs)	Velocity (cm/s)	Canopy Cover (%)	Total Phosphorus (µg/L)	Total Kjeldahl Nitrogen (mg/L)
Ankodosh	40.33±16.93 (5)	13.77 ± 5.72 (5)	10.09 ± 1.5 (5)	124.27 ± 46.41 (5)	39.31 ± 19.47 (5)	44.99 ± 18.31 (5)	67.5 ± 33.97 (5)	0.38 ± 0.3 (5)
Halfaday	39.67± 9.93 (5)	10.15 ± 2.16 (5)	11.86 ± 0.89 (5)	85.83 ± 21.58 (5)	32.85 ± 6.0 (5)	44.42 ± 27.86 (5)	66.67 ± 20.38 (5)	0.33 ± 0.38 (5)
Mill	28.33 ± 7.03 (5)	14.3 ± 3.1 (5)	10.12 ± 1	125.42 ± 29.31 (5)	44.65 ± 21.39 (5)	48.61 ± 29.19 (5)	64.5 ± 23.92 (5)	0.46 ± 0.22 (5)
Naomikong	37.17 ± 12.02 (5)	12.83 ± 3.95 (5)	10.59 ± 1.03 (5)	114.3 ± 41.51 (5)	40.06 ± 15.86 (5)	35.6 ± 22.65 (5)	70 ± 58.32 (5)	0.46 ± 0.24 (5)
Roxbury	95.17 ± 12.53 (5)	14.15 ± 3.87 (5)	9.93 ± 1.25 (5)	121.55 ± 48.42 (5)	19.62 ± 33.18 (5)	19.35 ± 34.09 (5)	50.83 ± 29.08 (5)	0.54 ± 0.28 (5)

Table 2. Pairwise Adonis test performed on NMDS analysis in Figure 3. This shows that there was a significant shift in the periphyton community from May-June, June-July, and May/June/July-September. Bolded numbers were numbers found to be significant by a p-value <0.05.

	May	June	July	August	September
May		**0.054**	0.06	0.141	**0.03**
June	-	-	**0.054**	0.076	**0.054**
July	-	-	-	0.141	**0.054**
August	-	-	-	-	0.141
September	-	-	-	-	-

Table 3. Land Cover Distribution within each sub watershed depicted in figure 2.

Stream	Land Cover (%)												
	Developed	Agriculture	Grassland	Deciduous	Evergreen	Mixed	Scrub	Forested Wetland	Shrub Wetland	Emergent Wetland	Open Land	Open Water	Total Area (ha)
Halfaday	0.1	1.6	1.1	77.3	5.1	4.0	5.7	2.6	2.2	0.2	0.1	0.1	1380
Mill	0.0	0.4	0.3	74.7	0.8	1.5	3.0	10.7	6.7	1.9	0.0	0.0	389
Naomikong	0.0	0.0	3.0	59.0	1.8	3.2	11.9	14.5	4.6	1.7	0.0	0.3	984
Ankodosh	0.1	0.1	1.4	56.6	5.8	1.2	10.5	17.4	4.9	1.6	0.0	0.4	1841
Roxbury	0.0	0.0	2.9	42.0	10.8	4.9	7.6	25.5	6.0	0.2	0.0	0.0	612

Table 4. SIMPER analysis of significant findings from Table 1. Cumulative cutoff percentage was set at 50%.

Genera	Change that Occurred		Cumulative %
	May	June	
Synedra (Diatom)	↓	↑	10
Ulothrix (Diatom)	↓	↑	18
Melosira (Filamentous Green)	↓	↑	26
Diatoma (Diatom)	↑	↓	33
Craticula (Diatom)	↑	↓	40
Cocconeis (Diatom)	↑	↓	45.72
	June	July	
Diatoma (Diatom)	↑	↓	8
Cocconeis (Diatom)	↑	↓	14.9
Aphanocapsa (Blue-Green)	↓	↑	21.4
Craticula (Diatom)	↑	↓	26.9
Synedra (Diatom)	↑	↓	32.1
Navicula (Diatom)	↑	↓	37.5
Nitzschia (Diatom)	↑	↓	42.3
Synechochocytis (Diatom)	↓	↑	47.08
Fragilaria (Diatom)	↑	↓	50.4
	July	September	
Aphanocapsa (Blue-Green)	↑	↓	9.7
Diatoma (Diatom)	↑	↓	16.6
Synechochocytes (Diatom)	↑	↓	22.3
Melosira (Filamentous Green)	↑	↓	27.2
Navicula (Diatom)	↑	↓	32
Nitzschia (Diatom)	↑	↓	36.6
Ulothrix (Filamentous Green)	↑	↓	41.02
Synedra (Diatom)	↑	↓	45.12
Fragilaria (Diatom)	↑	↓	49.14

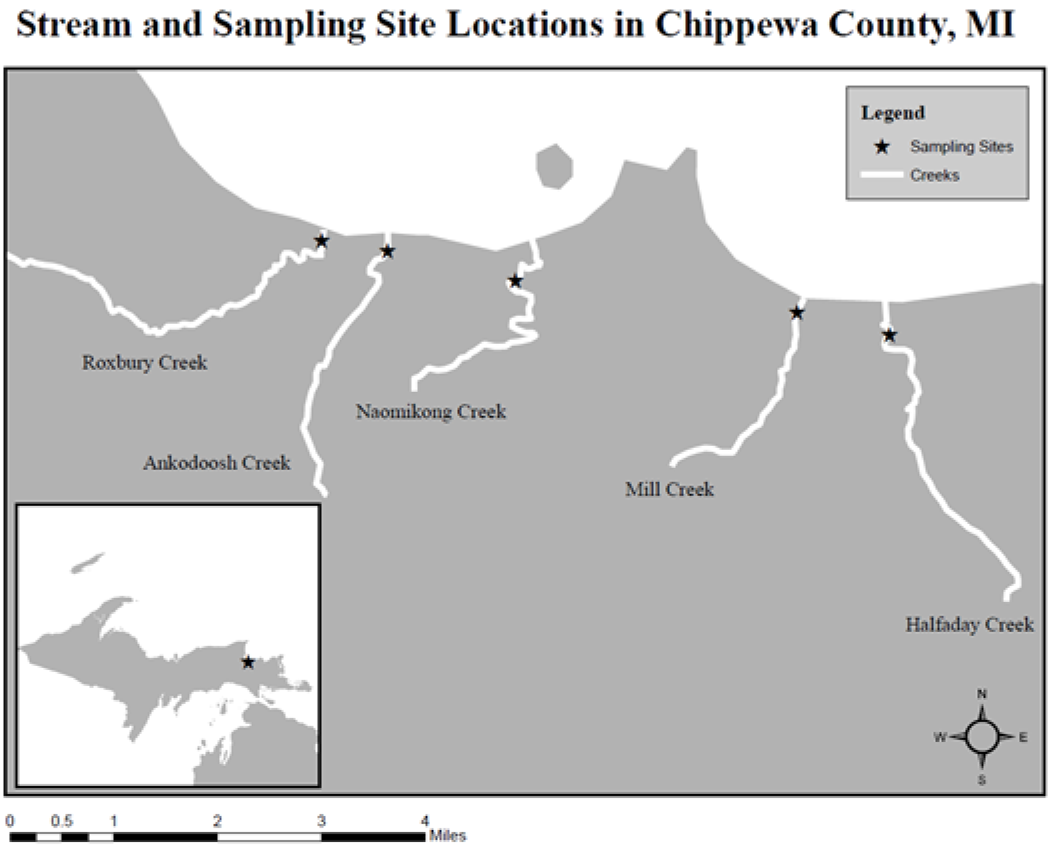


Figure 1. Map of sampling sites within Chippewa County, MI. Sampling sites are designated with a black

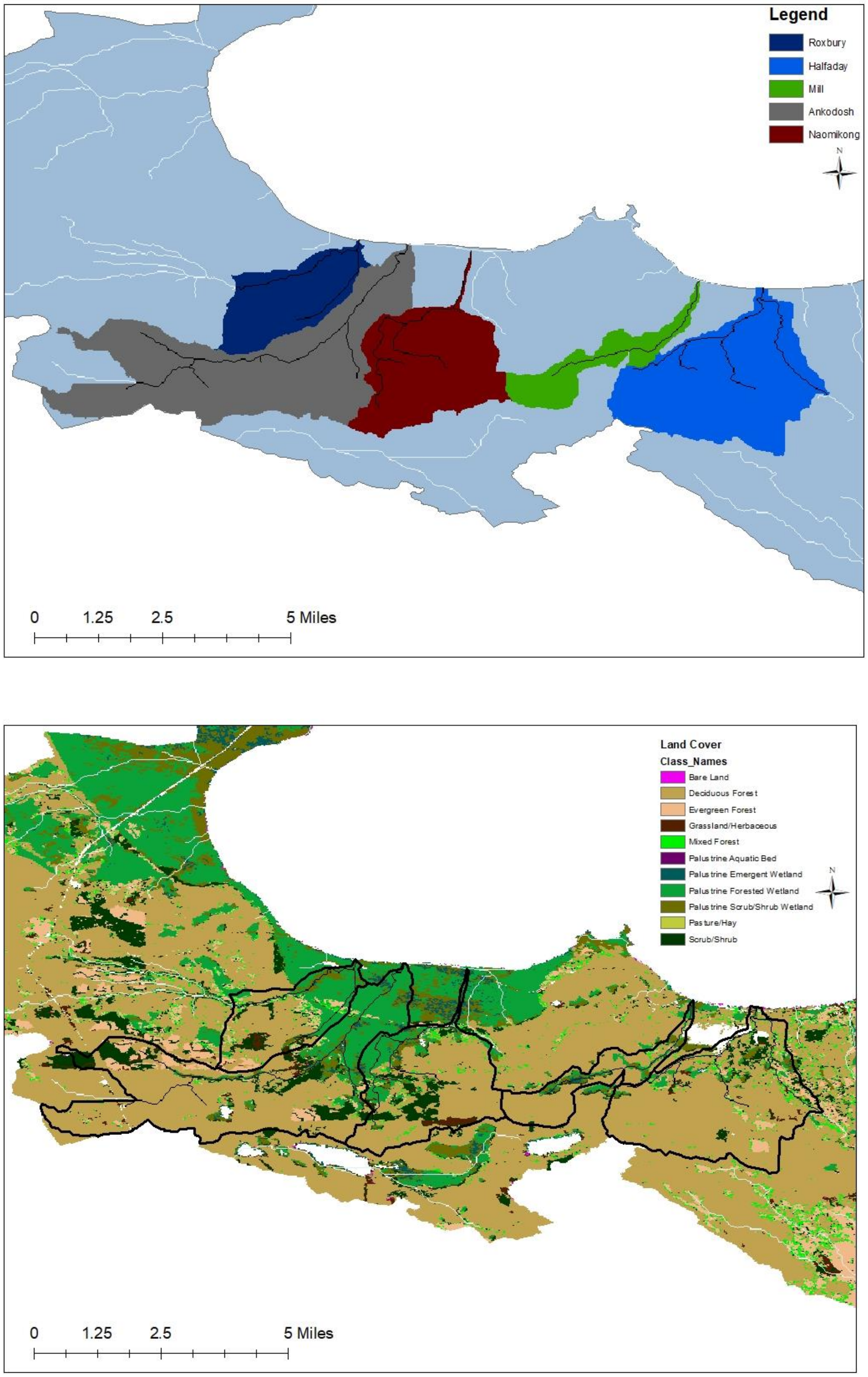


Figure 2. Watershed delineation maps showing watershed boundaries of each stream (Top) and watershed map showing land cover within each subwatershed (Bottom). Soil analysis within the *sub-watershed*s found that each stream had a mixture of sandy, clay, and fine sediments substrates within.

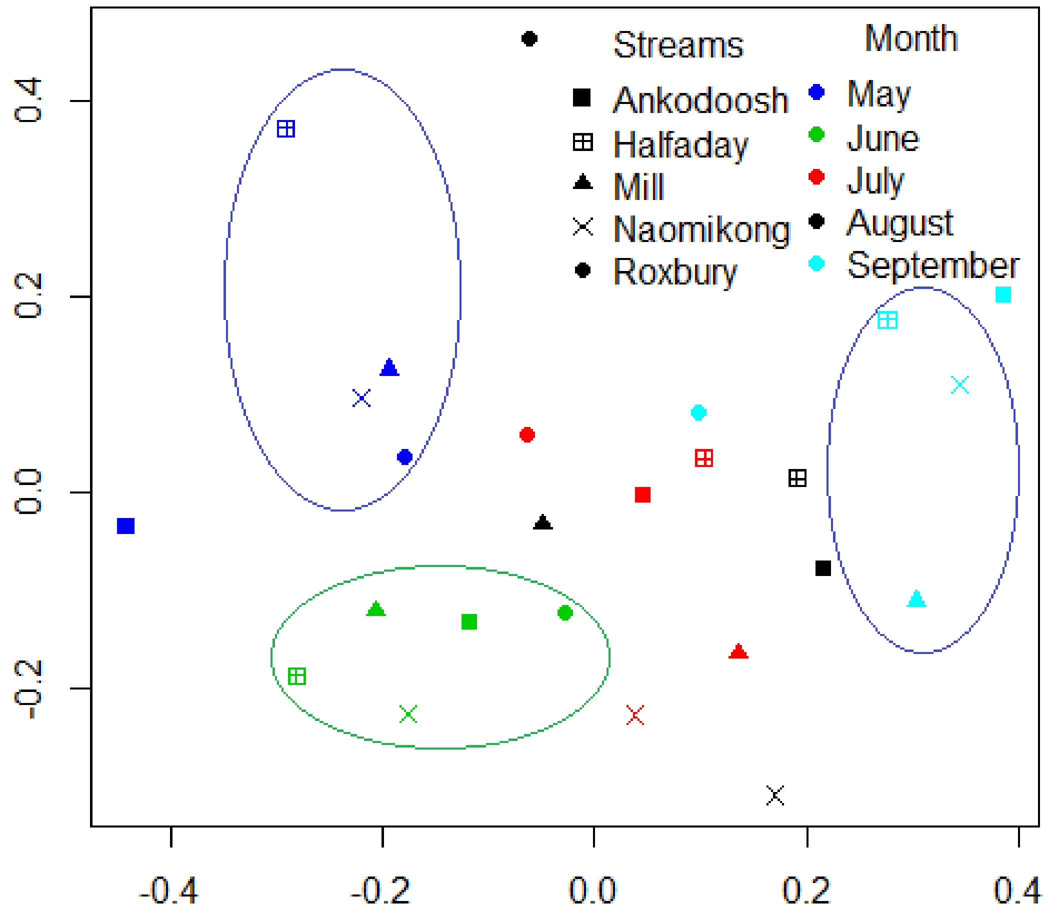


Figure 3. NMDS ordination showing trends in periphyton community shifts during the study period. This plot shows that the communities within the streams are similar during sampling periods but as we moved throughout the summer months the communities shifted. Stress = 14.47%.

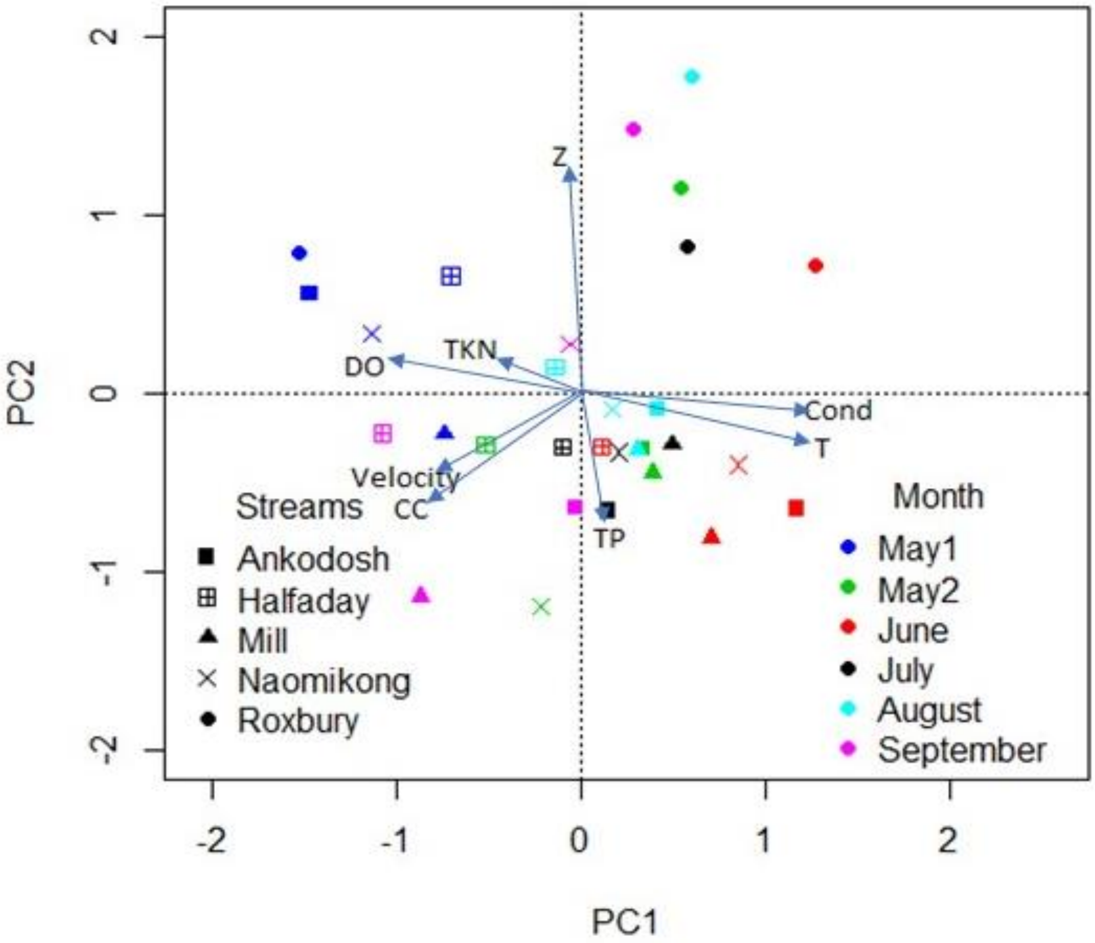
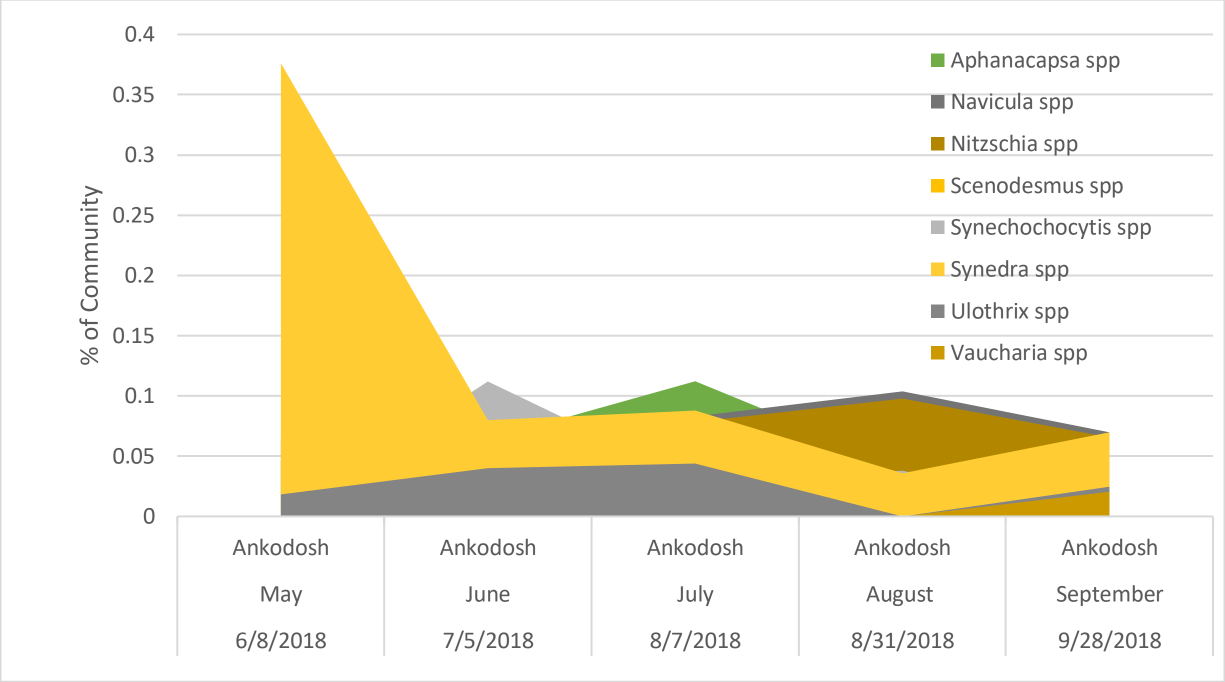
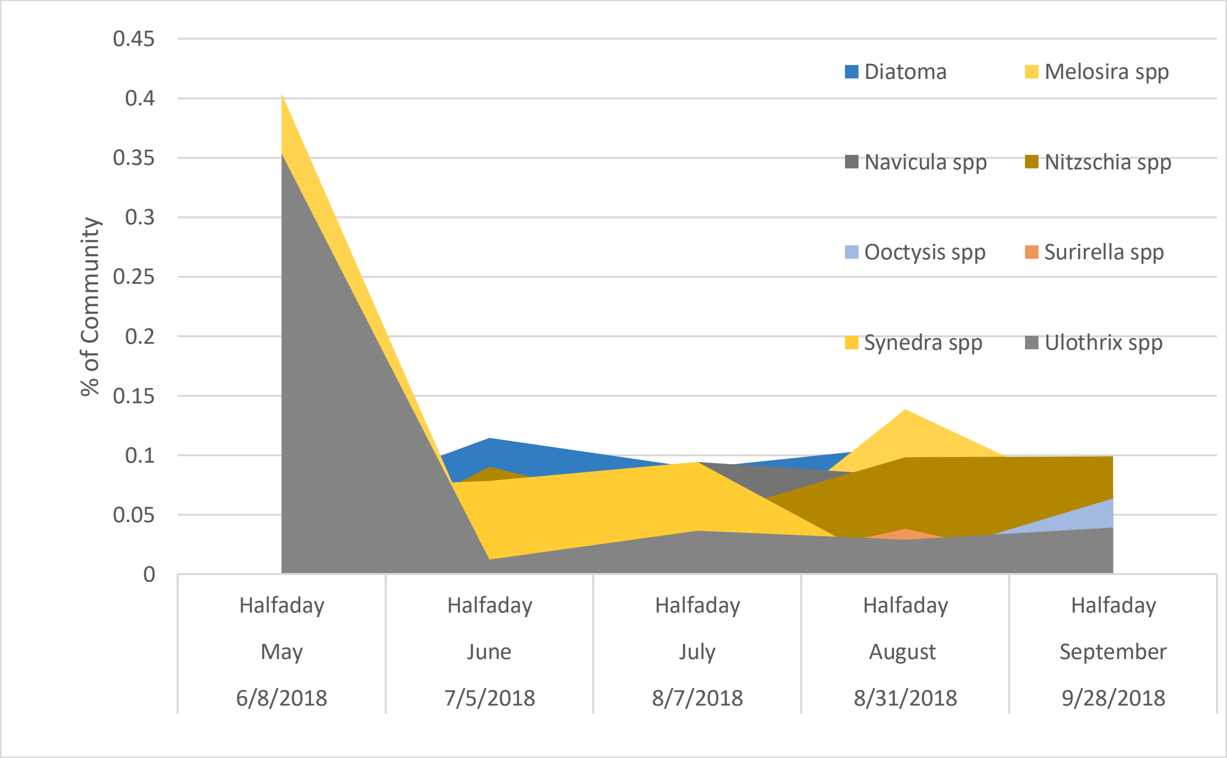
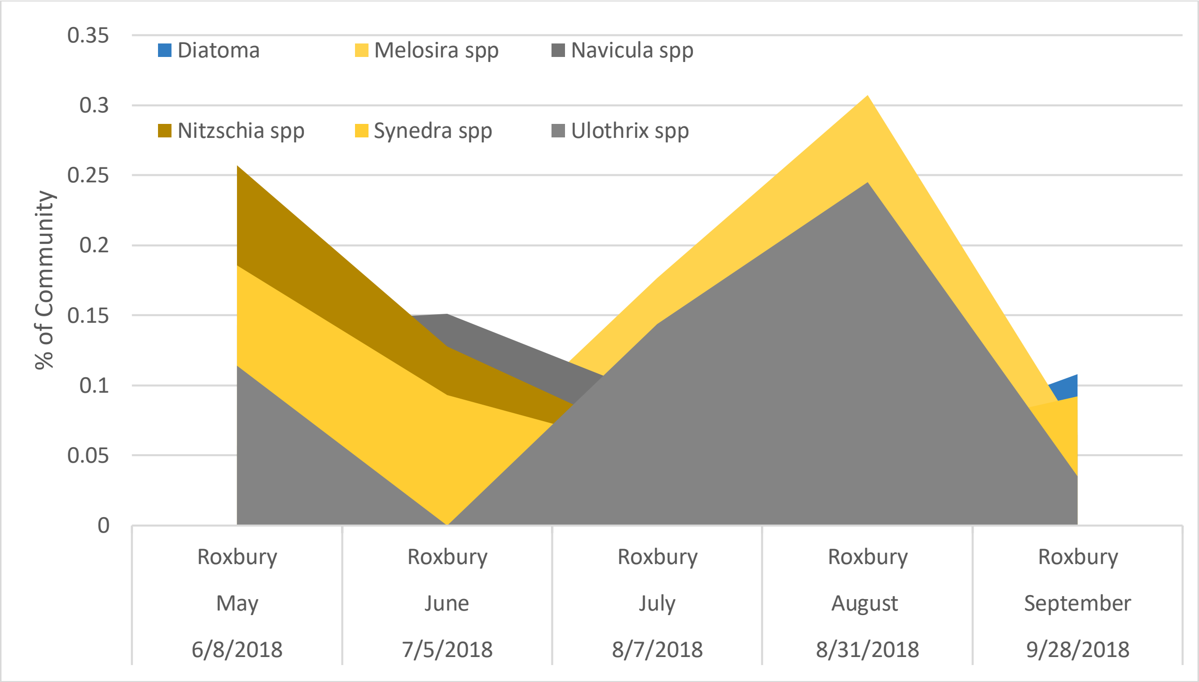
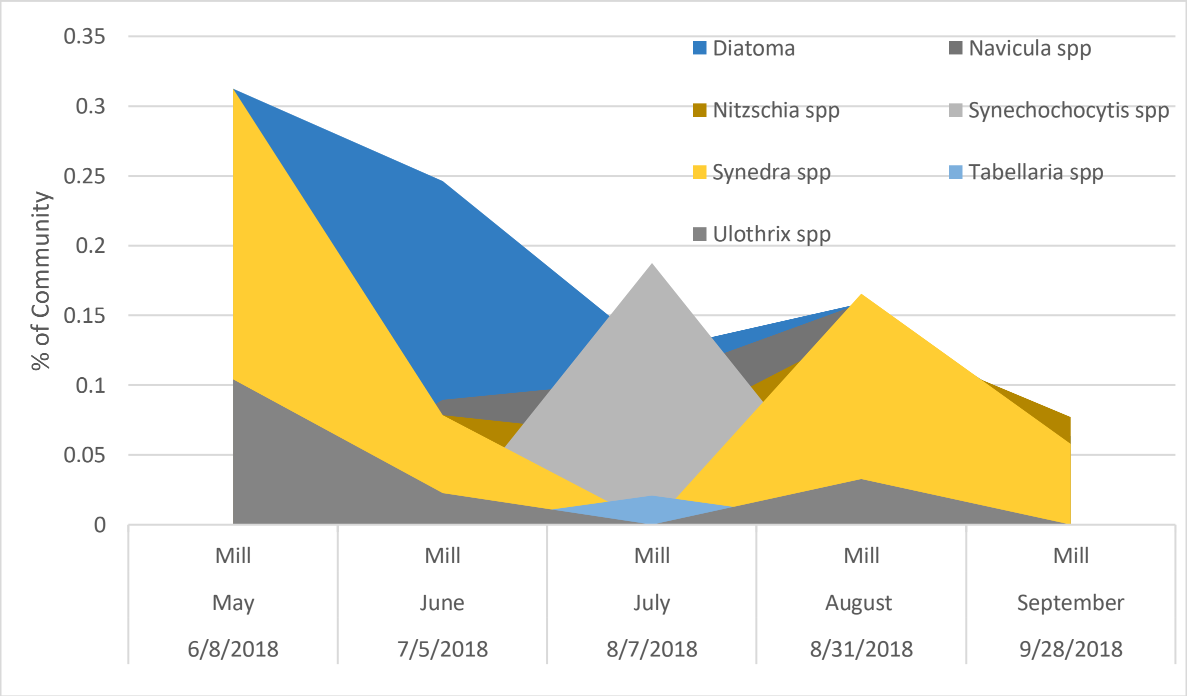


Figure 4. Principal Component Analysis of measured environmental variables within my study sites. PCA1 accounts for 47% of the variation while PCA2 accounts for 18%, totaling 65% variation explained by the first two axes. Abbreviations: DO = dissolved oxygen, TKN = total Kjeldahl nitrogen, TP = total phosphorus, CC = canopy cover, Cond = conductivity, T = temperature, Z = stream depth.


0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
% of Community
Aphanacapsa spp
Navicula spp
Nitzschia spp
Scenodesmus spp
Synechochocytis spp
Synedra spp
Ulothrix spp
Vaucharia spp
Ankodosh May 6/8/2018
Ankodosh June 7/5/2018
Ankodosh July 8/7/2018
Ankodosh August 8/31/2018
Ankodosh September 9/28/2018


0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
% of Community
Diatoma
Melosira spp
Navicula spp
Nitzschia spp
Ooctysis spp
Surirella spp
Synedra spp
Ulothrix spp
Halfaday May 6/8/2018
Halfaday June 7/5/2018
Halfaday July 8/7/2018
Halfaday August 8/31/2018
Halfaday September 9/28/2018


0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
% of Community
Diatoma
Melosira spp
Navicula spp
Nitzschia spp
Synedra spp
Ulothrix spp
Roxbury May 6/8/2018
Roxbury June 7/5/2018
Roxbury July 8/7/2018
Roxbury August 8/31/2018
Roxbury September 9/28/2018


0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
% of Community
Diatoma
Navicula spp
Nitzschia spp
Synechochocytis spp
Synedra spp
Tabellaria spp
Ulothrix spp
Mill May 6/8/2018
Mill June 7/5/2018
Mill July 8/7/2018
Mill August 8/31/2018
Mill September 9/28/2018

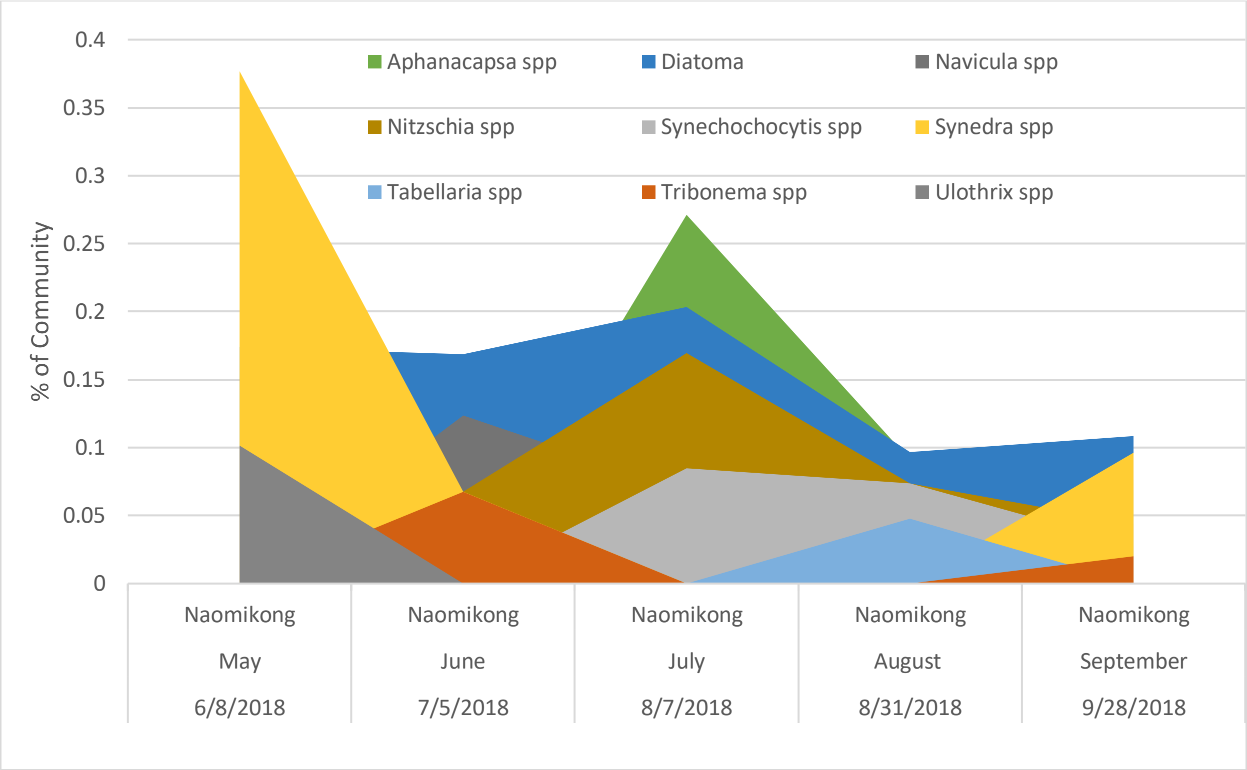


Figure 5. Species composition figures showing monthly changes in community structure in each stream during sampling period.

References

Allen, N. A. N. S., & Hershey, A. E. (1996). Seasonal Changes in Chlorophyll a Response to Nutrient Amendments in a North Shore Tributary of Lake Superior. *Journal of the North American Benthological Society.*, *15*(2), 170–178.

Álvarez, M., & Peckarsky, B. L. (2005). How do grazers affect periphyton heterogeneity in streams? *Oecologia*, *142*(4), 576–587. https://doi.org/10.1007/s00442-004-1759-0

Bækkelie, K. A. E., Schneider, S. C., Hagman, C. H. C., & Petrin, Z. (2017). Effects of flow events and nutrient addition on stream periphyton and macroinvertebrates: an experimental study using flumes. *Knowledge & Management of Aquatic Ecosystems*, (418), 47. https://doi.org/10.1051/kmae/2017041

Battin, T. J., Kaplan, L. A., Newbold, J. D., & Hansen, C. M. E. (2003). Contributions of microbial biofilms to ecosystem processes in stream mesocosms. *Nature*, *426*(6965), 439–442. https://doi.org/10.1038/nature02152

Beauchamp, D. A., Byron, E. R., & Wurtsbaugh, W. A. (1994). Summer Habitat Use by Littoral-Zone Fishes in Lake Tahoe and the Effects of Shoreline Structures. *North American Journal of Fisheries Management*, *14*(2), 385–394. https://doi.org/10.1577/1548-8675(1994)014<0385:shublz>2.3.co;2

Bernhardt, E. S., & Likens, G. E. (2004). Controls on periphyton biomass in heterotrophic streams. *Freshwater Biology*, *49*(1), 14–27. https://doi.org/10.1046/j.1365-2426.2003.01161.x

Biggs, B. J. F. (2000). Eutrophication of Streams and Rivers: Dissolved Nutrient-Chlorophyll Relationships for Benthic Algae. *Journal North American Benthological Society*, *19*(1), 17–31. https://doi.org/10.2307/1468279

BIGGS, B. J. F. (1990). Use of relative specific growth rates of periphytic diatoms to assess enrichment of a stream. *New Zealand Journal of Marine and Freshwater Research*, *24*(1), 9–18. https://doi.org/10.1080/00288330.1990.9516398

Biggs, B. J. F., & Smith, R. A. (2002). Taxonomic richness of stream benthic algae: Effects of flood disturbance and nutrients. *Limnology and Oceanography*, *47*(4), 1175–1186. https://doi.org/10.4319/lo.2002.47.4.1175

Biggs, B. J. F., Stevenson, R. J., & Lowe, R. L. (1998). A habitat matrix conceptual model for stream periphyton. *Archiv Fur Hydrobiologie*, *143*(August), 21–56. https://doi.org/10.1017/CBO9781107415324.004

Bothwell, M. L., Taylor, B. W., & Kilroy, C. (2014). The Didymo story: The role of low dissolved phosphorus in the formation of Didymosphenia geminata blooms. *Diatom Research*, *29*(3), 229–236. https://doi.org/10.1080/0269249X.2014.889041

Boyero, L., Pearson, R. G., Gessner, M. O., Barmuta, L. A., Ferreira, V., Graça, M. A. S., … West, D. C. (2011). A global experiment suggests climate warming will not accelerate litter decomposition in streams but might reduce carbon sequestration. *Ecology Letters*, *14*(3), 289–294. https://doi.org/10.1111/j.1461-0248.2010.01578.x

Brown, T. R. W., Low-Décarie, E., Pillsbury, R. W., Fox, G. A., & Scott, K. M. (2017). The effects of elevated atmospheric CO2 on freshwater periphyton in a temperate stream. *Hydrobiologia*, *794*(1), 333–346. https://doi.org/10.1007/s10750-017-3108-4

Cantonati, M., & Lowe, R. L. (2014). Lake benthic algae: toward an understanding of their ecology. *Freshwater Science*, *33*(2), 475–486. https://doi.org/10.1086/676140

Carpenter, K. D., & Waite, I. R. (2000). Relations of habitat-specific algal assemblages to land use and water chemistry in the Willamette Basin, Oregon. *Environmental Monitoring and Assessment*, *64*(1), 247–257. https://doi.org/10.1023/A:1006460802772

Clarke, K. R. (1993). Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology*.

Collins, S. F., Moerke, A. H., Chaloner, D. T., Janetski, D. J., & Lamberti, G. a. (2011). Response of dissolved nutrients and periphyton to spawning Pacific salmon in three northern Michigan streams. *Journal of the North American Benthological Society*, *30*(3), 831–839. https://doi.org/10.1899/10-164.1

Conti, M. E., & Cecchetti, G. (2003). A biomonitoring study: Trace metals in algae and molluscs from Tyrrhenian coastal areas. *Environmental Research*, *93*(1), 99–112. https://doi.org/10.1016/S0013-9351(03)00012-4

Damanik-Ambarita, M. N., Lock, K., Boets, P., Everaert, G., Nguyen, T. H. T., Forio, M. A. E., … Goethals, P. L. M. (2016). Ecological water quality analysis of the Guayas river basin (Ecuador) based on macroinvertebrates indices. *Limnologica*, *57*, 27–59. https://doi.org/10.1016/j.limno.2016.01.001

Delpla, I., Jung, A. V., Baures, E., Clement, M., & Thomas, O. (2009). Impacts of climate change on surface water quality in relation to drinking water production. *Environment International*, *35*(8), 1225–1233. https://doi.org/10.1016/j.envint.2009.07.001

Dinh, Y. T. H., & Death, R. G. (2018). Do disturbance and periphyton productivity affect stream invertebrate traits? *Freshwater Science*, *37*(2), 367–379. https://doi.org/10.1086/697924

Dodds, Walter K., Jones, John R., and Welch, E. B. (1998). Suggested Classification of Stream Trophic State: Distributions of Temperate Stream Types by Chlorophyll, Total Nitrogen, and Phosphorus. *Journal of Water Research*, *32*(5), 1455–1462.

Dodds, W. K. (2007). Trophic state, eutrophication and nutrient criteria in streams. *Trends in Ecology and Evolution*, *22*(12), 669–676. https://doi.org/10.1016/j.tree.2007.07.010

Dodds, W. K., Jones, J. R., & Welch, E. B. (1998). Suggested classification of stream trophic state: Distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus. *Water Research*, *32*(5), 1455–1462. https://doi.org/10.1016/S0043-1354(97)00370-9

Dodds, W. K., & Smith, V. H. (2016). Nitrogen, phosphorus, and eutrophication in streams. *Inland Waters*, *6*(2), 155–164. https://doi.org/10.5268/IW-6.2.909

Dodds, W. K., Smith, V. H., & Lohman, K. (2002). Nitrogen and phosphorus relationships to benthic algal biomass in temperate streams. *Canadian Journal of Fisheries and Aquatic Sciences*, *59*, 865–874. https://doi.org/10.1139/f06-040

Doretto, A., Piano, E., Bona, F., & Fenoglio, S. (2018). How to assess the impact of fine sediments on the macroinvertebrate communities of alpine streams? A selection of the best metrics. *Ecological Indicators*, *84*(August 2017), 60–69. https://doi.org/10.1016/j.ecolind.2017.08.041

Dove, A., & Chapra, S. C. (2015). Long-term trends of nutrients and trophic response variables for the Great Lakes. *Limnology and Oceanography*, *60*(2), 696–721. https://doi.org/10.1002/lno.10055

Feminella M.E.;Resh,V.H., J. W. ;Powe. (1989). Periphyton reponses to invertebrate grazing and riparian canopy in three nothern California coastal streams. *Freshwater Biology*, *22*, 445–457.

Foy, R. H. (1983). Interaction of temperature and light on the growth rates of two planktonic Oscillatoria species under a short photoperiod regime. *British Phycological Journal*, *18*(3), 267–273. https://doi.org/10.1080/00071618300650281

Foy, R. H., Gibson, C. E., & Smith, R. V. (1976). The influence of daylength, light intensity and temperature on the growth rates of planktonic blue-green algae. *British Phycological Journal*, *11*(2), 151–163. https://doi.org/10.1080/00071617600650181

Francoeur, S. N., Biggs, B. J. F., Smith, R. A., & Lowe, R. L. (1999). Nutrient Limitation of Algal Biomass Accrual in Streams: Seasonal Patterns and a Comparison of Methods. *Source Journal of the North American Benthological Society*, *18*(2), 242–260. Retrieved from http://www.jstor.org/stable/1468463

Francoeur, S. N., Peters Winslow, K. A., Miller, D., & Peacor, S. D. (2017). Mussel-derived stimulation of benthic filamentous algae: The importance of nutrients and spatial scale. *Journal of Great Lakes Research*, *43*(1), 69–79. https://doi.org/10.1016/j.jglr.2016.10.013

Godwin, C. M., & Carrick, H. J. (2008). Spatio-temporal variation of periphyton biomass and accumulation in a temperate spring-fed stream. *Aquatic Ecology*, *42*(4), 583–595. https://doi.org/10.1007/s10452-007-9133-z

Goldman, J. C., & Carpenter, E. J. (1974). A kinetic approach to the effect of temperature on algal growth. *Limnology and Oceanography*, *19*(5), 756–766.

Gottlieb, A. D., Richards, J. H., & Gaiser, E. E. (2006). Comparative study of periphyton community structure in long and short-hydroperiod Everglades marshes. *Hydrobiologia*, *569*(1), 195–207. https://doi.org/10.1007/s10750-006-0132-1

Greenwood, J. L., & Rosemond, A. D. (2005). Periphyton response to long-term nutrient enrichment in a shaded headwater stream. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*(9), 2033–2045. https://doi.org/10.1139/f05-117

Guasch, H., Ivorra, N., Lehmann, V., Paulsson, M., Real, M., & Sabater, S. (1998). Community composition and sensitivity of periphyton to atrazine in flowing waters: The role of environmental factors. *Journal of Applied Phycology*, *10*(2), 203–213. https://doi.org/10.1023/A:1008035212208

Hancock, P. J. (2002). Human impacts on the stream-groundwater exchange zone. *Environmental Management*, *29*(6), 763–781. https://doi.org/10.1007/s00267-001-0064-5

Hershey, Anne E and Wold, A. P. (1999). Spatial and Temporal Variability of Nutrient Limitation in 6 North Shore Tributaries to Lake Superior. *Journal of the North American Benthological Society*, *18*(1), 2–14.

Honeyfield, D. C., & Maloney, K. O. (2015). Seasonal patterns in stream periphyton fatty acids and community benthic algal composition in six high-quality headwater streams. *Hydrobiologia*, *744*(1), 35–47. https://doi.org/10.1007/s10750-014-2054-7

Huang, W., Liu, X., Peng, W., Wu, L., Yano, S., Zhang, J., & Zhao, F. (2017). Periphyton and ecosystem metabolism as indicators of river ecosystem response to environmental flow restoration in a flow-reduced river. *Ecological Indicators*, (November), 0–1. https://doi.org/10.1016/j.ecolind.2017.11.025

Jones, R. I. (1977). Factors Controlling Phytoplankton Production and Succession in a Highly Eutrophic Lake (Kinnego Bay , Lough Neagh): II . Phytoplankton Production and Its Chief Determinants Author (s): Roger I . Jones Published by : British Ecological Society Stable U, *65*(2), 561–577.

Jyrkänkallio-Mikkola, J., Siljander, M., Heikinheimo, V., Pellikka, P., & Soininen, J. (2018). Tropical stream diatom communities – The importance of headwater streams for regional diversity. *Ecological Indicators*, *95*(July), 183–193. https://doi.org/10.1016/j.ecolind.2018.07.030

Kaonga, C. C., & Monjerezi, M. (2012). Periphyton and Earthworms as Biological Indicators of Metal Pollution in Streams of Blantyre City, Malawi. In *Water Pollution* (pp. 2–22). InTech. https://doi.org/10.5772/28781

Kazama, S., & Watanabe, K. (2018). Estimation of periphyton dynamics in a temperate catchment using a distributed nutrient-runoff model. *Ecological Modelling*, *367*, 1–9. https://doi.org/10.1016/j.ecolmodel.2017.11.006

Kilroy, C., & Bothwell, M. (2011). Environmental control of stalk length in the bloom-forming, freshwater benthic diatom didymosphenia geminata (Bacillariophyceae). *Journal of Phycology*, *47*(5), 981–989. https://doi.org/10.1111/j.1529-8817.2011.01029.x

Kireta, A. R., & Saros, J. E. (2019). Contemporary abundance patterns of Cyclotella sensu lato diatom taxa in Lake Superior: Assessing responses to physical and chemical gradients and potential links to climate change. *Journal of Great Lakes Research*, *45*(1), 119–128. https://doi.org/10.1016/j.jglr.2018.11.014

Kondolf, G. M., & Li, S. (1992). The Pebble Count Technique for Quantifying Surface Bed Material Size in Instream Flow Studies. *Rivers*, *3*(2), 80–87. Retrieved from papers2://publication/uuid/83AB2BFE-DF8A-4A2E-ADCE-D2542AC5CB7B

Langridge, R., & Daniels, B. (2017). Accounting for Climate Change and Drought in Implementing Sustainable Groundwater Management. *Water Resources Management*, *31*(11), 3287–3298. https://doi.org/10.1007/s11269-017-1607-8

Ledger, M. E., Harris, R. M. L., Armitage, P. D., & Milner, A. M. (2008). Disturbance frequency influences patch dynamics in stream benthic algal communities. *Oecologia*, *155*(4), 809–819. https://doi.org/10.1007/s00442-007-0950-5

Li, L., Zheng, B., & Liu, L. (2010). Biomonitoring and bioindicators used for river ecosystems: Definitions, approaches and trends. In *Procedia Environmental Sciences* (Vol. 2, pp. 1510–1524). https://doi.org/10.1016/j.proenv.2010.10.164

Lohman, Kirk. Jones, John R. Baysinger-daniel, C. (1991). Experimental Evidence for Nitrogen Limitation in a Northern Ozark Stream. *Journal of the North American Benthological Society*, *10*(1), 14–23.

Lufafa, A., Tenywa, M. M., Isabirye, M., Majaliwa, M. J. G., & Woomer, P. L. (2003). Prediction of soil erosion in a Lake Victoria basin catchment using a GIS-based Universal Soil Loss model. *Agricultural Systems*, *76*(3), 883–894. https://doi.org/10.1016/S0308-521X(02)00012-4

Lynch, D. T., & Magoulick, D. D. (2016). Effects of pulse and press drying disturbance on benthic stream communities. *Freshwater Science*, *35*(3), 998–1009. https://doi.org/10.1086/687843

Matheson, F. E., Quinn, J. M., & Martin, M. L. (2012). Effects of irradiance on diel and seasonal patterns of nutrient uptake by stream periphyton. *Freshwater Biology*, *57*(8), 1617–1630. https://doi.org/10.1111/j.1365-2427.2012.02822.x

Matthaei, C. D., Guggelberger, C., & Hubre, H. (2003). Local disturbance history affects patchiness of benthic river algae. *Freshwater Biology*, *48*(9), 1514–1526. https://doi.org/10.1046/j.1365-2427.2003.01103.x

McCall, S. J., Hale, M. S., Smith, J. T., Read, D. S., & Bowes, M. J. (2017). Impacts of phosphorus concentration and light intensity on river periphyton biomass and community structure. *Hydrobiologia*, *792*(1), 315–330. https://doi.org/10.1007/s10750-016-3067-1

Michalak, A. M., Anderson, E. J., Beletsky, D., Boland, S., Bosch, N. S., Bridgeman, T. B., … Zagorski, M. A. (2013). Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proceedings of the National Academy of Sciences*, *110*(16), 6448–6452. https://doi.org/10.1073/pnas.1216006110

Michelutti, N., Holtham, A. J., Douglas, M. S. V., & Smol, J. P. (2003). Periphytic diatom assemblages from ultra-oligotrophic and UV transparent lakes and ponds on Victoria Island and comparisons with other diatom surveys in the Canadian Arctic. *Journal of Phycology*, *39*(3), 465–480. https://doi.org/10.1046/j.1529-8817.2003.02153.x

Moerke, A. H., Gerard, K. J., Latimore, J. A., Hellenthal, R. A., & Lamberti, G. A. (2005). Restoration of an Indiana, USA, stream: bridging the gap between basic and applied lotic ecology. *Journal of the North American Benthological Society*, *23*(3), 647–660. https://doi.org/10.1899/0887-3593(2004)023<0647:roaius>2.0.co;2

Molina-Navarro, E., Andersen, H. E., Nielsen, A., Thodsen, H., & Trolle, D. (2018). Quantifying the combined effects of land use and climate changes on stream flow and nutrient loads: A modelling approach in the Odense Fjord catchment (Denmark). *Science of the Total Environment*, *621*, 253–264. https://doi.org/10.1016/j.scitotenv.2017.11.251

Mori, T., Miyagawa, Y., Onoda, Y., & Kayaba, Y. (2018). Flow-velocity-dependent effects of turbid water on periphyton structure and function in flowing water. *Aquatic Sciences*, *80*(1), 1–12. https://doi.org/10.1007/s00027-017-0552-1

Mulholland, P. J., Newbold, J. D., Elwood, J. W., Ferren, L. A., & Webster, J. R. (1985). Phosphorus Spiralling in a Woodland Stream : Seasonal Variations. *Ecological Society of America*, *66*(3), 1012–1023. https://doi.org/10.2307/1940562

Nebgen, E. L., & Herrman, K. S. (2019). Effects of shading on stream ecosystem metabolism and water temperature in an agriculturally influenced stream in central Wisconsin, USA. *Ecological Engineering*, *126*(December 2017), 16–24. https://doi.org/10.1016/j.ecoleng.2018.10.023

Nicholls, K. H., & Hopkins, G. J. (1993). Recent Changes in Lake Erie (North Shore) Phytoplankton: Cumulative Impacts of Phosphorus Loading Reductions and the Zebra Mussel Introduction. *Journal of Great Lakes Research*, *19*(4), 637–647. https://doi.org/10.1016/S0380-1330(93)71251-4

Paller, M. H. (1996). Effectiveness of multiplate invertebrate samplers, periphytometers, and electrofishing for biomonitoring in streams. *Water Research*, *30*(9), 2095–2101. https://doi.org/10.1016/0043-1354(96)00015-2

Pan, Y., Stevenson, R. J., Hill, B. H., & Herlihy, A. T. (2000). Ecoregions and benthic diatom assemblages in Mid-Atlantic Highlands streams, USA. *Journal of the North American Benthological Society*, *19*(3), 518–540. https://doi.org/10.2307/1468112

Piggott, J. J., Townsend, C. R., & Matthaei, C. D. (2015). Climate warming and agricultural stressors interact to determine stream macroinvertebrate community dynamics. *Global Change Biology*, *21*(5), 1887–1906. https://doi.org/10.1111/gcb.12861

Pillsbury, R., Stevenson, R. J., Munn, M. D., & Waite, I. (2019). Relationships between diatom metrics based on species nutrient traits and agricultural land use. *Environmental Monitoring and Assessment*, *191*(4), 228. https://doi.org/10.1007/s10661-019-7357-8

Quinn, J. M., & Hickey, C. W. (1990). Magnitude of effects of substrate particle size, recent flooding, and catchment development on benthic invertebrates in 88 new zealand rivers. *New Zealand Journal of Marine and Freshwater Research*, *24*(3), 411–427. https://doi.org/10.1080/00288330.1990.9516433

Rashid, R., Bhat, R. A., Pandit, A. K., & Bhat, S. (2013). Ecological Study of Periphytic Algal Community of Doodh Ganga and Khansha-Mansha Streams of Yusmarg Forests: A Health Resort of Kashmir Valley, India. *Ecologia Balkanica*, *5*(1), 9–19.

Reisinger, A. J., Tank, J. L., & Dee, M. M. (2016). Regional and seasonal variation in nutrient limitation of river biofilms. *Freshwater Biology*. https://doi.org/10.1086/685829.

Riseng, C. M., Wiley. M.J., Stevenson, R. J. (2004). Hydrologic disturbance and nutrient effects on benthic community structure in midwestern US streams: a covariance structure analysis. *Journal of the North American Benthological Society*, *23*(2), 309–326.

Robarts, R. D., & Zohary, T. (1987). New Zealand Journal of Marine and Freshwater Research Temperature effects on photosynthetic capacity, respiration, and growth rates of bloom-forming cyanobacteria Temperature effects on photosynthetic capacity, respiration, and growth rates of blocm-formi. *New Zealand Journal of Marine and Freshwater Research New Zealand Journal of Marine and Freshwater Research*, *213*(21), 391–399. https://doi.org/10.1080/00288330.1987.9516235

Rosemond, A. D. . (1994). Multiple Factors Limit Seasonal Variation in Periphyton in a Forest Stream. *Journal of the North American Benthological Society*, *13*(3), 333–344.

Rugenski, A. T., Marcarelli, A. M., Bechtold, H. A., & Inouye, R. S. (2008). Effects of temperature and concentration on nutrient release rates from nutrient diffusing substrates. *Journal of the North American Benthological Society*, *27*(1), 52–57. https://doi.org/10.1899/07-046R1.1

Sanmiguel, A., Blanco, S., Álvarez-Blanco, I., Cejudo-Figueiras, C., Escudero, A., Pérez, M. E., … Bécares, E. (2016). Recovery of the algae and macroinvertebrate benthic community after Didymosphenia geminata mass growths in Spanish rivers. *Biological Invasions*, *18*(5), 1467–1484. https://doi.org/10.1007/s10530-016-1095-4

Santos, S. A. M., dos Santos, T. R., Furtado, M. S. R., Henry, R., & Ferragut, C. (2018). Periphyton nutrient content, biomass and algal community on artificial substrate: response to experimental nutrient enrichment and the effect of its interruption in a tropical reservoir.

Limnology, *19*(2), 209–218. https://doi.org/10.1007/s10201-017-0533-z

Sekar, R., Nair, K. V. K., Rao, V. N. R., & Venugopalan, V. P. (2002). Nutrient dynamics and successional changes in a lentic freshwater biofilm. *Freshwater Biology*, *47*(10), 1893–1907. https://doi.org/10.1046/j.1365-2427.2002.00936.x

Shigeru Nakano, Hitoshi Miyasaka, and N. K. (1999). Terrestrial-Aquatic Linkages : Riparian Arthropod Inputs Alter Trophic Cascades in a Stream Food Web. *Ecology*, *80*(7), 2435–2441.

Singh, S., James, A., & Bharose, R. (2017). Biological Assessment of Water Pollution Using Periphyton Productivity : A Review. *Nature Environment and Pollution Technology*, *16*(2), 559–567.

Smith, V. H., Tilman, G. D., & Nekola, J. C. (1998). Eutrophication: Impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution*, *100*(1–3), 179–196. https://doi.org/10.1016/S0269-7491(99)00091-3

Snyder, E. B., Robinson, C. T., Minshall, G. W., & Rushforth, S. R. (2002). Regional patterns in periphyton accrual and diatom assemblage structure in a heterogeneous nutrient landscape. *Canadian Journal of Fisheries and Aquatic Sciences*, *59*(3), 564–577. https://doi.org/10.1139/f02-021

Stasio, B. T. De, Hill, D. K., Kleinhans, J. M., Nibbelink, N. P., & Magnuson, J. J. (1996). Potential Effects of Global Climate Change on Small North-Temperate Lakes : Physics , Fish , and Plankton. *Limnol. Oceanogr.*, *41*(5), 1136–1149.

Stelzer, R. S., & Lamberti, G. A. (2001). Effects of N : P ratio and total nutrient concentration on stream periphyton community structure, biomass, and elemental composition. *Limnology and Oceanography*, *46*(2), 356–367. https://doi.org/10.4319/lo.2001.46.2.0356

Sterner, R. (2014). C:N:P stoichiometry in Lake Superior: freshwater sea as end member. *Inland Waters*, *1*(1), 29–46. https://doi.org/10.5268/iw-1.1.365

Stevenson, B. R. J., & Bahls, L. L. (1999). Periphyton protocols, 1–23.

Stevenson, R. J., Rier, S. T., Riseng, C. M., Schultz, R. E., & Wiley, M. J. (2006). Comparing effects of nutrients on algal biomass in streams in two regions with different disturbance regimes and with applications for developing nutrient criteria. *Hydrobiologia*, *561*(1), 149–165. https://doi.org/10.1007/s10750-005-1611-5

Stirling, H. P., & Dey, T. (1990). Impact of intensive cage fish farming on the phytoplankton and periphyton of a Scottish freshwater loch. *Hydrobiologia*, *190*(3), 193–214. https://doi.org/10.1007/BF00008187

Trebitz, A. S., Brazner, J. C., Cotter, A. M., Knuth, M. L., Morrice, J. A., Peterson, G. S., … Kelly, J. R. (2008). Water Quality in Great Lakes Coastal Wetlands: Basin-wide Patterns and Responses to an Anthropogenic Disturbance Gradient. *Journal of Great Lakes Research*, *33*(sp3), 67–85. https://doi.org/10.3394/0380-1330(2007)33[67:wqiglc]2.0.co;2

Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climate Research*, *47*(1–2), 123–138. https://doi.org/10.3354/cr00953

Walsh, J. R., Carpenter, S. R., & Vander Zanden, M. J. (2016). Invasive species triggers a massive loss of ecosystem services through a trophic cascade. *Proceedings of the National Academy of Sciences*, *113*(15), 4081–4085. https://doi.org/10.1073/pnas.1600366113

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., … Bairlein, F. (2002). Ecological responses to recent climate change. *Nature*, *416*(6879), 389–395. https://doi.org/10.1038/416389a

Ward, P. R. B., Anders, P. J., Minshall, G. W., C., H., Hoyle, G. M., & Yassien, H. (2017). Nutrient uptake during low-level fertilization of a large 7th order oligotrophic river. *Canadian Journal of Fisheries and Aquatic Science*, (May), 1–42.

Welsh, H. H., & Ollivier, L. M. (1998). Stream Amphibians as Indicators of Ecosystem Stress : A Case Study from California ' s Redwoods. *Ecological Applications*, *8*(4), 1118–1132.

Wolman, G. M. (1954). A Method of Sampling Coarse River-Bed Material. *Transactions, American Geophysical Union*, *35*(6), 951–956.

Wood, P. J., & Armitage, P. D. (1997). Biological effects of fine sediment in the lotic environment. *Environmental Management*, *21*(2), 203–217. https://doi.org/10.1007/s002679900019

Wu, N., Dong, X., Liu, Y., Wang, C., Baattrup-Pedersen, A., & Riis, T. (2017). Using river microalgae as indicators for freshwater biomonitoring: Review of published research and future directions. *Ecological Indicators*, *81*(May), 124–131. https://doi.org/10.1016/j.ecolind.2017.05.066

Chapter III

Extended Review of Literature

Introduction

Phycology is classified as the study of periphyton. Within the field of phycology, researchers can study Benthic Periphyton “Periphyton”: which are photosynthetic organisms attached to a surface (Rashid et al. 2013). This field of research is important because it can allow for early detection of water quality problems, human health problems, finding trace metals in water sources, and predicting nutrient input locations (Conti & Cecchetti, 2003). The main area of research within phycology is using periphyton to monitor nutrient presence within streams and lakes and how this could be influencing growth of these organisms over a set period (Hasson 1990). Studying periphyton can have extensive applications in a variety of studies, ranging from macroinvertebrates to fish and phytoplankton (Álvarez & Peckarsky, 2005; Francoeur et al. 2017). In this review, we will be observing how the field of Phycology has been used in the past and how it is being used in current times to broaden our understanding of natural ecosystems and climactic changes.

Periphyton growth

Much like any ecosystem, different species can grow in different habitats. This holds true for periphyton communities, which can vary greatly between freshwater lakes and rivers (Biggs et al., 1998; Cantonati & Lowe, 2014; Snyder et al., 2002). Periphyton community differences can be found with changes in sunlight availability, nutrients, daylength, and overall temperature of the water system (Foy, 1983; Foy et al., 1976). The influences of temperature have been heavily studied in aquatic ecosystems and have found that as temperature increases, growth can greatly increase, and periphyton communities can change as well (Guasch et al., 1998; Kazama

& Watanabe, 2018; Reisinger et al., 2016; Rosemond, 1994). Smith (1986) found that if temperature and nutrients are freely available, changes in periphyton populations will easily be observed in aquatic ecosystems. Temperature can often be considered one of the most important factors when addressing periphyton and periphyton growth in an ecosystem. A correlation found between temperature and periphyton growth showed that as temperature increased, the affinity for periphyton cells to uptake nutrients increased (Goldman & Carpenter, 1974; Reisinger et al., 2016). This is a key factor to consider in research because with current climate conditions warming every year, we could continue to see a positive trend in periphyton growth and nutrient uptake by periphyton.

Stream Nutrients

Nutrients play a key role in the growth of periphyton communities and in changing habitats that individuals can inhabit within an aquatic setting. Different nutrients are available within aquatic ecosystems, the common nutrients that are available for uptake by organisms are Nitrogen and Phosphorus in varying forms, and these nutrients influence periphyton community structure and growth (Dodds, 2007; Dodds & Smith, 2016; Dodds et al., 2002). These nutrients will become more abundant and then become limiting, or not as abundant, which can lead to different organisms dominating. Limiting nutrients can have a strong influence on periphyton because if these nutrients happen to come out of limiting, through natural or anthropogenic additions. This can lead to blooms, or mass growths, in periphyton communities (Lohman et al., 1991; Stevenson et al., 2006). Limiting nutrients are important to keep in mind due to aquaculture and fish hatcheries. These anthropogenic means can be sources of nitrogen, phosphorus, and organic matter that can drastically throw off a natural ecosystem out of balance and can cause a change in the community. An example of periphyton blooms is the Harmful

Periphyton Blooms (HABs) that occur annually in Lake Erie in the Great Lakes. These HABs are found to be caused by eutrophication through the unnatural addition of phosphorus to the water basin (Michalak et al., 2013). These cyanobacteria could inhabit Lake Erie because of the increasing temperature of the lake, the shallow depth of the lake compared to the other Great Lakes, and the immense phosphorus loading from surrounding farm communities. Research in this area could prove to be important for the management and protection of watersheds around the world, the research into prevention of cyanobacteria is relatively understudied and is normally looked at after blooms occur. Areas like this are where monitoring stream nutrients can prevent these issues and is a key area of where my research will consider and be using a variety of methods to further investigate if they would be viable in this field of work.

If a system is Nitrogen or Phosphorus limiting this can influence what periphyton community will grow. It was determined that nutrient competition within habitats often proves to be the leading factor for community structure within ecosystems and that this in combination with temperature and sunlight availability could potentially identify how communities are formed (Tilman 1982). Stream ecosystems can go through a process called Eutrophication, which is defined as the excessive enrichment of nutrients in a water body (Biggs 2000). Eutrophication is often linked to manmade, or anthropogenic, changes to surrounding areas of the ecosystem that cause excess nutrients to enter the water body. With the global nitrogen input into aquatic systems nearly doubling, it has been observed that aquatic plant communities are changing and becoming more abundant and periphyton communities are becoming denser and with greater diversity than seen before (Smith et al. 1998). Some scientists are looking at local hatcheries and fish farms with the idea that since they are adding nitrogen, phosphorus, and organic matter through fish feces and uneaten food, that this could be influencing periphyton and periphyton growth in streams and lakes (Stirling & Dey, 1990). This input of organic matter, nitrogen, and phosphorus can have a strong influence on how species grow and what communities grow in an ecosystem, often these types of changing levels can lead to immigration and emigration of species from areas and can alter home ranges and because of this, the study of periphyton can be phenomenal for early detection of these problems, especially in nutrient stimulation and pollution.

Seasonality and Periphyton

There are a variety of nutrients that are available to organisms at any given moment. The common nutrients are: phosphorus, nitrogen, phosphate, and nitrate (R. J. Stevenson et al., 2006). It has been documented that nutrient input into streams can vary from high to all nutrients limiting depending on the climate of the season (Rugenski et al., 2008). During the fall we can see massive inputs from leaf litter but then see all input stop when the waterways freeze during the winter in a northern climate with another big increase coming with annual snow melt. It has been hypothesized that seasonal nutrient changes can cause changes nutrient availability and further influence which populations of periphyton can grow during certain seasons (Allen & Hershey, 1996). Seasonality can be the strongest form of population control for periphyton, due to changing nutrients and local weather conditions creating major disturbances within the watershed. The biggest form of disturbances was found to be flooding and nutrient resource supply, which was found to potentially inhibit periphyton growth in streams (Francoeur et al., 1999; Matthaei et al. 2003). Considering this information, it helps us process what is going on in streams and creeks in northern climates during the four seasons. Successional changes are common to occur within periphyton over time and as water temperatures rise. It has been described that diatoms will inhabit streams in early spring (Honeyfield & Maloney, 2015;

Robarts & Zohary, 1987) and will progress to stalked diatoms and green algae into mid-summer (Carpenter & Waite, 2000; Guasch et al., 1998; Kilroy & Bothwell, 2011). Periphyton successional stage is used as a bioindicator of stream health (Jyrkänkallio-Mikkola et al., 2018; Piggott et al., 2015; Pillsbury et al., 2019; Welsh & Ollivier, 1998). Streams with a high disturbance frequency would be found to contain communities dominated by pennate diatoms while streams with a less frequent disturbance frequency would be hypothesized to contain mucilaginous green algae communities. This seasonal shift of periphyton can give insight to the health of the ecosystem, grazer presence, riparian vegetation, and anthropogenic influences within a stream. Future climate change predictions could lead to a shift in this understanding as air temperatures continue to warm and nutrients become available to stream communities. The successional stage of periphyton communities is directly controlled by the frequency of disturbance that occurs within the system. It has been reported that biofilm thickness and biomass are directly related to the age and diversity within the biofilm itself (Reisinger et al., 2016; Sekar et al., 2002). As the biofilms get larger and thicker in late successional stages, they become more susceptible to being damaged through high flooding, erosion, and substrate disturbance. These late successional mats are composed of green algae, blue-green algae, and stalked diatoms and can shade out lower stage organisms of diatoms like *Synedra, Navicula,* and *Nitzschia.*

Successional change in these communities is mostly driven by nutrient concentration, temperature, light availability, and disturbance regime (Biggs et al., 1998; Matthaei et al., 2003; Sekar et al., 2002). More frequent disturbances within lotic environments would cause the periphyton community to resemble an early successional assemblage composed of pennate diatoms and some early stage green algae (Biggs et al., 1998; Matthaei et al., 2003). If disturbances are less frequent within the ecosystem, benthic mats will become more composed of filamentous green algae, blue-green algae, and stalked diatoms (Francoeur et al., 2017; Mori et al., 2018). With climate change predictions calling for more frequent and more severe precipitation events (Trenberth, 2011), it can be predicted that within headwater streams the periphyton community will be highly composed of pennate diatoms (Carpenter & Waite, 2000; Honeyfield & Maloney, 2015; Michelutti et al., 2003). In highly eutrophic systems, periphyton succession is highly accelerated which can lead to large blooms on algae within aquatic systems (Bernhardt & Likens, 2004; Michalak et al., 2013). These blooms can have negative impacts on the ecology of these systems and can sometimes found to be toxic to organisms (Robarts & Zohary, 1987). Monitoring of periphyton successional state can be a useful tool in observing impacts of climate change on aquatic systems (Jyrkänkallio-Mikkola et al., 2018), stream health (Allen & Hershey, 1996), heavy metals within streams (Conti & Cecchetti, 2003; Huang et al., 2017; Wu et al., 2017), and anthropogenic impacts (Dodds et al., 2002; Smith et al., 1998; Wood & Armitage, 1997).

Climate Change

Increasing global air temperatures has become a common topic of discussion in the past decade (Delpla et al. 2009; Jyrkänkallio-Mikkola et al., 2018; Langridge & Daniels, 2017). Global air temperatures are predicted to have increased 1˚C since the industrial revolution began in the late 18th century. The process of climate change is brought on by the release of gaseous carbon dioxide being absorbed into the atmosphere. As temperatures continue to rise, greater precipitation is expected to occur globally. Aquatic communities are directly impacted by this phenomenon through increasing water temperatures. The increase of water temperatures could lead to the increase of invasive species and potentially a shift in the local communities found

(Langridge & Daniels, 2017; Piggott et al., 2015). Changes in environmental factors will have drastic impacts on water chemistry and potentially could lead to changes in nutrient spiraling within the water column.

Periphyton communities can be used to help address the impacts of climate change within lentic and lotic systems (Brown et al., 2017; Jyrkänkallio-Mikkola et al., 2018; Stasio et al., 1996). These assemblages are dependent on sunlight, water temperature, nutrients, and minerals within the stream to form and grow over time (Doretto et al. 2018; Guasch et al., 1998; Rosemond, 1994). As temperatures continue to rise long term, it is predicted that periphyton communities will become composed of green algae, stalked diatoms, and more bloom forming organisms we be able to grow (Francoeur et al., 2017; Michalak et al., 2013; Walsh et al., 2016).

The Laurentian Great Lakes have been heavily impacted by anthropogenic changes and climate change (Francoeur et al., 2017; Nicholls & Hopkins, 1993; Walsh et al., 2016). It has been predicted that within these lakes, climate change will greatly impact the ecology and diversity that is present. Focusing on Lake Superior specifically, it has been hypothesized that climate change will increase precipitation and cause earlier snow melts into the spring with more severe rain events. Lake Superior has been classified as an oligotrophic system that receives its nutrients from groundwater and allochthonous inputs. This earlier snow melt will cause a reduction in nutrients flowing into the tributaries and Lake Superior long term. This earlier melt will cause riparian vegetation to bloom sooner and uptake nutrients before those nutrients can leech into streams and become bioavailable for periphyton communities. This loss of nutrients into the system could move the Lake Superior basin into a state of ultra-oligotrophication (total phosphorus [<1 µg/L]) and would have negative impacts to the overall diversity of periphyton within the system. The reduction of nutrients within these systems could lead to the introduction of invasive bloom forming diatoms like *Didymosphenia*. Didymo is stalk forming diatom that becomes present in colder lakes and streams when low nutrients are present (Bothwell et al., 2014) and has been found in the nearby St. Mary's River. The growth of this diatom could cause a thick layer of algae to grow on the surface of the water body and could shade out benthic periphyton communities. These explained factors could cause extreme changes to the Lake Superior ecosystem long term if trends continue in the way they are.

References

Allen, N. A. N. S., & Hershey, A. E. (1996). Seasonal Changes in Chlorophyll a Response to Nutrient Amendments in a North Shore Tributary of Lake Superior. *Journal of the North American Benthological Society.*, *15*(2), 170–178.

Álvarez, M., & Peckarsky, B. L. (2005). How do grazers affect periphyton heterogeneity in streams? *Oecologia*, *142*(4), 576–587. https://doi.org/10.1007/s00442-004-1759-0

Bækkelie, K. A. E., Schneider, S. C., Hagman, C. H. C., & Petrin, Z. (2017). Effects of flow events and nutrient addition on stream periphyton and macroinvertebrates: an experimental study using flumes. *Knowledge & Management of Aquatic Ecosystems*, (418), 47. https://doi.org/10.1051/kmae/2017041

Battin, T. J., Kaplan, L. A., Newbold, J. D., & Hansen, C. M. E. (2003). Contributions of microbial biofilms to ecosystem processes in stream mesocosms. *Nature*, *426*(6965), 439–442. https://doi.org/10.1038/nature02152

Beauchamp, D. A., Byron, E. R., & Wurtsbaugh, W. A. (1994). Summer Habitat Use by Littoral-Zone Fishes in Lake Tahoe and the Effects of Shoreline Structures. *North American Journal of Fisheries Management*, *14*(2), 385–394. https://doi.org/10.1577/1548-8675(1994)014<0385:shublz>2.3.co;2

Bernhardt, E. S., & Likens, G. E. (2004). Controls on periphyton biomass in heterotrophic streams. *Freshwater Biology*, *49*(1), 14–27. https://doi.org/10.1046/j.1365-2426.2003.01161.x

Biggs, B. J. F. (2000). Eutrophication of Streams and Rivers: Dissolved Nutrient-Chlorophyll Relationships for Benthic Algae. *Journal North American Benthological Society*, *19*(1), 17–31. https://doi.org/10.2307/1468279

BIGGS, B. J. F. (1990). Use of relative specific growth rates of periphytic diatoms to assess enrichment of a stream. *New Zealand Journal of Marine and Freshwater Research*, *24*(1), 9–18. https://doi.org/10.1080/00288330.1990.9516398

Biggs, B. J. F., & Smith, R. A. (2002). Taxonomic richness of stream benthic algae: Effects of flood disturbance and nutrients. *Limnology and Oceanography*, *47*(4), 1175–1186. https://doi.org/10.4319/lo.2002.47.4.1175

Biggs, B. J. F., Stevenson, R. J., & Lowe, R. L. (1998). A habitat matrix conceptual model for stream periphyton. *Archiv Fur Hydrobiologie*, *143*(August), 21–56. https://doi.org/10.1017/CBO9781107415324.004

Bothwell, M. L., Taylor, B. W., & Kilroy, C. (2014). The Didymo story: The role of low dissolved phosphorus in the formation of Didymosphenia geminata blooms. *Diatom Research*, *29*(3), 229–236. https://doi.org/10.1080/0269249X.2014.889041

Boyero, L., Pearson, R. G., Gessner, M. O., Barmuta, L. A., Ferreira, V., Graça, M. A. S., … West, D. C. (2011). A global experiment suggests climate warming will not accelerate litter decomposition in streams but might reduce carbon sequestration. *Ecology Letters*, *14*(3), 289–294. https://doi.org/10.1111/j.1461-0248.2010.01578.x

Brown, T. R. W., Low-Décarie, E., Pillsbury, R. W., Fox, G. A., & Scott, K. M. (2017). The effects of elevated atmospheric CO2 on freshwater periphyton in a temperate stream. *Hydrobiologia*, *794*(1), 333–346. https://doi.org/10.1007/s10750-017-3108-4

Cantonati, M., & Lowe, R. L. (2014). Lake benthic algae: toward an understanding of their ecology. *Freshwater Science*, *33*(2), 475–486. https://doi.org/10.1086/676140

Carpenter, K. D., & Waite, I. R. (2000). Relations of habitat-specific algal assemblages to land use and water chemistry in the Willamette Basin, Oregon. *Environmental Monitoring and Assessment*, *64*(1), 247–257. https://doi.org/10.1023/A:1006460802772

Clarke, K. R. (1993). Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology*.

Collins, S. F., Moerke, A. H., Chaloner, D. T., Janetski, D. J., & Lamberti, G. a. (2011). Response of dissolved nutrients and periphyton to spawning Pacific salmon in three northern Michigan streams. *Journal of the North American Benthological Society*, *30*(3), 831–839. https://doi.org/10.1899/10-164.1

Conti, M. E., & Cecchetti, G. (2003). A biomonitoring study: Trace metals in algae and molluscs from Tyrrhenian coastal areas. *Environmental Research*, *93*(1), 99–112. https://doi.org/10.1016/S0013-9351(03)00012-4

Damanik-Ambarita, M. N., Lock, K., Boets, P., Everaert, G., Nguyen, T. H. T., Forio, M. A. E., … Goethals, P. L. M. (2016). Ecological water quality analysis of the Guayas river basin (Ecuador) based on macroinvertebrates indices. *Limnologica*, *57*, 27–59. https://doi.org/10.1016/j.limno.2016.01.001

Delpla, I., Jung, A. V., Baures, E., Clement, M., & Thomas, O. (2009). Impacts of climate change on surface water quality in relation to drinking water production. *Environment International*, *35*(8), 1225–1233. https://doi.org/10.1016/j.envint.2009.07.001

Dinh, Y. T. H., & Death, R. G. (2018). Do disturbance and periphyton productivity affect stream invertebrate traits? *Freshwater Science*, *37*(2), 367–379. https://doi.org/10.1086/697924

Dodds, Walter K., Jones, John R., and Welch, E. B. (1998). Suggested Classification of Stream Trophic State: Distributions of Temperate Stream Types by Chlorophyll, Total Nitrogen, and Phosphorus. *Journal of Water Research*, *32*(5), 1455–1462.

Dodds, W. K. (2007). Trophic state, eutrophication and nutrient criteria in streams. *Trends in Ecology and Evolution*, *22*(12), 669–676. https://doi.org/10.1016/j.tree.2007.07.010

Dodds, W. K., Jones, J. R., & Welch, E. B. (1998). Suggested classification of stream trophic state: Distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus. *Water Research*, *32*(5), 1455–1462. https://doi.org/10.1016/S0043-1354(97)00370-9

Dodds, W. K., & Smith, V. H. (2016). Nitrogen, phosphorus, and eutrophication in streams. *Inland Waters*, *6*(2), 155–164. https://doi.org/10.5268/IW-6.2.909

Dodds, W. K., Smith, V. H., & Lohman, K. (2002). Nitrogen and phosphorus relationships to benthic algal biomass in temperate streams. *Canadian Journal of Fisheries and Aquatic Sciences*, *59*, 865–874. https://doi.org/10.1139/f06-040

Doretto, A., Piano, E., Bona, F., & Fenoglio, S. (2018). How to assess the impact of fine sediments on the macroinvertebrate communities of alpine streams? A selection of the best metrics. *Ecological Indicators*, *84*(August 2017), 60–69. https://doi.org/10.1016/j.ecolind.2017.08.041

Dove, A., & Chapra, S. C. (2015). Long-term trends of nutrients and trophic response variables for the Great Lakes. *Limnology and Oceanography*, *60*(2), 696–721. https://doi.org/10.1002/lno.10055

Feminella M.E.;Resh,V.H., J. W. ;Powe. (1989). Periphyton reponses to invertebrate grazing and riparian canopy in three nothern California coastal streams. *Freshwater Biology*, *22*, 445–457.

Foy, R. H. (1983). Interaction of temperature and light on the growth rates of two planktonic Oscillatoria species under a short photoperiod regime. *British Phycological Journal*, *18*(3), 267–273. https://doi.org/10.1080/00071618300650281

Foy, R. H., Gibson, C. E., & Smith, R. V. (1976). The influence of daylength, light intensity and temperature on the growth rates of planktonic blue-green algae. *British Phycological Journal*, *11*(2), 151–163. https://doi.org/10.1080/00071617600650181

Francoeur, S. N., Biggs, B. J. F., Smith, R. A., & Lowe, R. L. (1999). Nutrient Limitation of Algal Biomass Accrual in Streams: Seasonal Patterns and a Comparison of Methods. *Source Journal of the North American Benthological Society*, *18*(2), 242–260. Retrieved from http://www.jstor.org/stable/1468463

Francoeur, S. N., Peters Winslow, K. A., Miller, D., & Peacor, S. D. (2017). Mussel-derived stimulation of benthic filamentous algae: The importance of nutrients and spatial scale. *Journal of Great Lakes Research*, *43*(1), 69–79. https://doi.org/10.1016/j.jglr.2016.10.013

Godwin, C. M., & Carrick, H. J. (2008). Spatio-temporal variation of periphyton biomass and accumulation in a temperate spring-fed stream. *Aquatic Ecology*, *42*(4), 583–595. https://doi.org/10.1007/s10452-007-9133-z

Goldman, J. C., & Carpenter, E. J. (1974). A kinetic approach to the effect of temperature on algal growth. *Limnology and Oceanography*, *19*(5), 756–766.

Gottlieb, A. D., Richards, J. H., & Gaiser, E. E. (2006). Comparative study of periphyton community structure in long and short-hydroperiod Everglades marshes. *Hydrobiologia*, *569*(1), 195–207. https://doi.org/10.1007/s10750-006-0132-1

Greenwood, J. L., & Rosemond, A. D. (2005). Periphyton response to long-term nutrient enrichment in a shaded headwater stream. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*(9), 2033–2045. https://doi.org/10.1139/f05-117

Guasch, H., Ivorra, N., Lehmann, V., Paulsson, M., Real, M., & Sabater, S. (1998). Community composition and sensitivity of periphyton to atrazine in flowing waters: The role of environmental factors. *Journal of Applied Phycology*, *10*(2), 203–213. https://doi.org/10.1023/A:1008035212208

Hancock, P. J. (2002). Human impacts on the stream-groundwater exchange zone. *Environmental Management*, *29*(6), 763–781. https://doi.org/10.1007/s00267-001-0064-5

Hershey, Anne E and Wold, A. P. (1999). Spatial and Temporal Variability of Nutrient Limitation in 6 North Shore Tributaries to Lake Superior. *Journal of the North American Benthological Society*, *18*(1), 2–14.

Honeyfield, D. C., & Maloney, K. O. (2015). Seasonal patterns in stream periphyton fatty acids and community benthic algal composition in six high-quality headwater streams. *Hydrobiologia*, *744*(1), 35–47. https://doi.org/10.1007/s10750-014-2054-7

Huang, W., Liu, X., Peng, W., Wu, L., Yano, S., Zhang, J., & Zhao, F. (2017). Periphyton and ecosystem metabolism as indicators of river ecosystem response to environmental flow restoration in a flow-reduced river. *Ecological Indicators*, (November), 0–1. https://doi.org/10.1016/j.ecolind.2017.11.025

Jones, R. I. (1977). Factors Controlling Phytoplankton Production and Succession in a Highly Eutrophic Lake (Kinnego Bay , Lough Neagh): II . Phytoplankton Production and Its Chief Determinants Author (s): Roger I . Jones Published by : British Ecological Society Stable U, *65*(2), 561–577.

Jyrkänkallio-Mikkola, J., Siljander, M., Heikinheimo, V., Pellikka, P., & Soininen, J. (2018). Tropical stream diatom communities – The importance of headwater streams for regional diversity. *Ecological Indicators*, *95*(July), 183–193. https://doi.org/10.1016/j.ecolind.2018.07.030

Kaonga, C. C., & Monjerezi, M. (2012). Periphyton and Earthworms as Biological Indicators of Metal Pollution in Streams of Blantyre City, Malawi. In *Water Pollution* (pp. 2–22). InTech. https://doi.org/10.5772/28781

Kazama, S., & Watanabe, K. (2018). Estimation of periphyton dynamics in a temperate catchment using a distributed nutrient-runoff model. *Ecological Modelling*, *367*, 1–9. https://doi.org/10.1016/j.ecolmodel.2017.11.006

Kilroy, C., & Bothwell, M. (2011). Environmental control of stalk length in the bloom-forming, freshwater benthic diatom didymosphenia geminata (Bacillariophyceae). *Journal of*

Phycology, *47*(5), 981–989. https://doi.org/10.1111/j.1529-8817.2011.01029.x

Kireta, A. R., & Saros, J. E. (2019). Contemporary abundance patterns of Cyclotella sensu lato diatom taxa in Lake Superior: Assessing responses to physical and chemical gradients and potential links to climate change. *Journal of Great Lakes Research*, *45*(1), 119–128. https://doi.org/10.1016/j.jglr.2018.11.014

Kondolf, G. M., & Li, S. (1992). The Pebble Count Technique for Quantifying Surface Bed Material Size in Instream Flow Studies. *Rivers*, *3*(2), 80–87. Retrieved from papers2://publication/uuid/83AB2BFE-DF8A-4A2E-ADCE-D2542AC5CB7B

Langridge, R., & Daniels, B. (2017). Accounting for Climate Change and Drought in Implementing Sustainable Groundwater Management. *Water Resources Management*, *31*(11), 3287–3298. https://doi.org/10.1007/s11269-017-1607-8

Ledger, M. E., Harris, R. M. L., Armitage, P. D., & Milner, A. M. (2008). Disturbance frequency influences patch dynamics in stream benthic algal communities. *Oecologia*, *155*(4), 809–819. https://doi.org/10.1007/s00442-007-0950-5

Li, L., Zheng, B., & Liu, L. (2010). Biomonitoring and bioindicators used for river ecosystems: Definitions, approaches and trends. In *Procedia Environmental Sciences* (Vol. 2, pp. 1510–1524). https://doi.org/10.1016/j.proenv.2010.10.164

Lohman, Kirk. Jones, John R. Baysinger-daniel, C. (1991). Experimental Evidence for Nitrogen Limitation in a Northern Ozark Stream. *Journal of the North American Benthological Society*, *10*(1), 14–23.

Lufafa, A., Tenywa, M. M., Isabirye, M., Majaliwa, M. J. G., & Woomer, P. L. (2003). Prediction of soil erosion in a Lake Victoria basin catchment using a GIS-based Universal Soil Loss model. *Agricultural Systems*, *76*(3), 883–894. https://doi.org/10.1016/S0308-521X(02)00012-4

Lynch, D. T., & Magoulick, D. D. (2016). Effects of pulse and press drying disturbance on benthic stream communities. *Freshwater Science*, *35*(3), 998–1009. https://doi.org/10.1086/687843

Matheson, F. E., Quinn, J. M., & Martin, M. L. (2012). Effects of irradiance on diel and seasonal patterns of nutrient uptake by stream periphyton. *Freshwater Biology*, *57*(8), 1617–1630. https://doi.org/10.1111/j.1365-2427.2012.02822.x

Matthaei, C. D., Guggelberger, C., & Hubre, H. (2003). Local disturbance history affects patchiness of benthic river algae. *Freshwater Biology*, *48*(9), 1514–1526. https://doi.org/10.1046/j.1365-2427.2003.01103.x

McCall, S. J., Hale, M. S., Smith, J. T., Read, D. S., & Bowes, M. J. (2017). Impacts of phosphorus concentration and light intensity on river periphyton biomass and community structure. *Hydrobiologia*, *792*(1), 315–330. https://doi.org/10.1007/s10750-016-3067-1

Michalak, A. M., Anderson, E. J., Beletsky, D., Boland, S., Bosch, N. S., Bridgeman, T. B., … Zagorski, M. A. (2013). Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proceedings of the National Academy of Sciences*, *110*(16), 6448–6452.

https://doi.org/10.1073/pnas.1216006110

Michelutti, N., Holtham, A. J., Douglas, M. S. V., & Smol, J. P. (2003). Periphytic diatom assemblages from ultra-oligotrophic and UV transparent lakes and ponds on Victoria Island and comparisons with other diatom surveys in the Canadian Arctic. *Journal of Phycology*, *39*(3), 465–480. https://doi.org/10.1046/j.1529-8817.2003.02153.x

Moerke, A. H., Gerard, K. J., Latimore, J. A., Hellenthal, R. A., & Lamberti, G. A. (2005). Restoration of an Indiana, USA, stream: bridging the gap between basic and applied lotic ecology. *Journal of the North American Benthological Society*, *23*(3), 647–660. https://doi.org/10.1899/0887-3593(2004)023<0647:roaius>2.0.co;2

Molina-Navarro, E., Andersen, H. E., Nielsen, A., Thodsen, H., & Trolle, D. (2018). Quantifying the combined effects of land use and climate changes on stream flow and nutrient loads: A modelling approach in the Odense Fjord catchment (Denmark). *Science of the Total Environment*, *621*, 253–264. https://doi.org/10.1016/j.scitotenv.2017.11.251

Mori, T., Miyagawa, Y., Onoda, Y., & Kayaba, Y. (2018). Flow-velocity-dependent effects of turbid water on periphyton structure and function in flowing water. *Aquatic Sciences*, *80*(1), 1–12. https://doi.org/10.1007/s00027-017-0552-1

Mulholland, P. J., Newbold, J. D., Elwood, J. W., Ferren, L. A., & Webster, J. R. (1985). Phosphorus Spiralling in a Woodland Stream : Seasonal Variations. *Ecological Society of America*, *66*(3), 1012–1023. https://doi.org/10.2307/1940562

Nebgen, E. L., & Herrman, K. S. (2019). Effects of shading on stream ecosystem metabolism and water temperature in an agriculturally influenced stream in central Wisconsin, USA. *Ecological Engineering*, *126*(December 2017), 16–24. https://doi.org/10.1016/j.ecoleng.2018.10.023

Nicholls, K. H., & Hopkins, G. J. (1993). Recent Changes in Lake Erie (North Shore) Phytoplankton: Cumulative Impacts of Phosphorus Loading Reductions and the Zebra Mussel Introduction. *Journal of Great Lakes Research*, *19*(4), 637–647. https://doi.org/10.1016/S0380-1330(93)71251-4

Paller, M. H. (1996). Effectiveness of multiplate invertebrate samplers, periphytometers, and electrofishing for biomonitoring in streams. *Water Research*, *30*(9), 2095–2101. https://doi.org/10.1016/0043-1354(96)00015-2

Pan, Y., Stevenson, R. J., Hill, B. H., & Herlihy, A. T. (2000). Ecoregions and benthic diatom assemblages in Mid-Atlantic Highlands streams, USA. *Journal of the North American Benthological Society*, *19*(3), 518–540. https://doi.org/10.2307/1468112

Piggott, J. J., Townsend, C. R., & Matthaei, C. D. (2015). Climate warming and agricultural stressors interact to determine stream macroinvertebrate community dynamics. *Global Change Biology*, *21*(5), 1887–1906. https://doi.org/10.1111/gcb.12861

Pillsbury, R., Stevenson, R. J., Munn, M. D., & Waite, I. (2019). Relationships between diatom metrics based on species nutrient traits and agricultural land use. *Environmental Monitoring and Assessment*, *191*(4), 228. https://doi.org/10.1007/s10661-019-7357-8

Quinn, J. M., & Hickey, C. W. (1990). Magnitude of effects of substrate particle size, recent flooding, and catchment development on benthic invertebrates in 88 new zealand rivers. *New Zealand Journal of Marine and Freshwater Research*, *24*(3), 411–427. https://doi.org/10.1080/00288330.1990.9516433

Rashid, R., Bhat, R. A., Pandit, A. K., & Bhat, S. (2013). Ecological Study of Periphytic Algal Community of Doodh Ganga and Khansha-Mansha Streams of Yusmarg Forests: A Health Resort of Kashmir Valley, India. *Ecologia Balkanica*, *5*(1), 9–19.

Reisinger, A. J., Tank, J. L., & Dee, M. M. (2016). Regional and seasonal variation in nutrient limitation of river biofilms. *Freshwater Biology*. https://doi.org/10.1086/685829.

Riseng, C. M., Wiley. M.J., Stevenson, R. J. (2004). Hydrologic disturbance and nutrient effects on benthic community structure in midwestern US streams: a covariance structure analysis. *Journal of the North American Benthological Society*, *23*(2), 309–326.

Robarts, R. D., & Zohary, T. (1987). New Zealand Journal of Marine and Freshwater Research Temperature effects on photosynthetic capacity, respiration, and growth rates of bloom-forming cyanobacteria Temperature effects on photosynthetic capacity, respiration, and growth rates of blocm-formi. *New Zealand Journal of Marine and Freshwater Research New Zealand Journal of Marine and Freshwater Research*, *213*(21), 391–399. https://doi.org/10.1080/00288330.1987.9516235

Rosemond, A. D. . (1994). Multiple Factors Limit Seasonal Variation in Periphyton in a Forest Stream. *Journal of the North American Benthological Society*, *13*(3), 333–344.

Rugenski, A. T., Marcarelli, A. M., Bechtold, H. A., & Inouye, R. S. (2008). Effects of temperature and concentration on nutrient release rates from nutrient diffusing substrates. *Journal of the North American Benthological Society*, *27*(1), 52–57. https://doi.org/10.1899/07-046R1.1

Sanmiguel, A., Blanco, S., Álvarez-Blanco, I., Cejudo-Figueiras, C., Escudero, A., Pérez, M. E., … Bécares, E. (2016). Recovery of the algae and macroinvertebrate benthic community after Didymosphenia geminata mass growths in Spanish rivers. *Biological Invasions*, *18*(5), 1467–1484. https://doi.org/10.1007/s10530-016-1095-4

Santos, S. A. M., dos Santos, T. R., Furtado, M. S. R., Henry, R., & Ferragut, C. (2018). Periphyton nutrient content, biomass and algal community on artificial substrate: response to experimental nutrient enrichment and the effect of its interruption in a tropical reservoir. *Limnology*, *19*(2), 209–218. https://doi.org/10.1007/s10201-017-0533-z

Sekar, R., Nair, K. V. K., Rao, V. N. R., & Venugopalan, V. P. (2002). Nutrient dynamics and successional changes in a lentic freshwater biofilm. *Freshwater Biology*, *47*(10), 1893–1907. https://doi.org/10.1046/j.1365-2427.2002.00936.x

Shigeru Nakano, Hitoshi Miyasaka, and N. K. (1999). Terrestrial-Aquatic Linkages : Riparian Arthropod Inputs Alter Trophic Cascades in a Stream Food Web. *Ecology*, *80*(7), 2435–2441.

Singh, S., James, A., & Bharose, R. (2017). Biological Assessment of Water Pollution Using Periphyton Productivity : A Review. *Nature Environment and Pollution Technology*, *16*(2), 559–567.

Smith, V. H., Tilman, G. D., & Nekola, J. C. (1998). Eutrophication: Impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution*, *100*(1–3), 179–196. https://doi.org/10.1016/S0269-7491(99)00091-3

Snyder, E. B., Robinson, C. T., Minshall, G. W., & Rushforth, S. R. (2002). Regional patterns in periphyton accrual and diatom assemblage structure in a heterogeneous nutrient landscape. *Canadian Journal of Fisheries and Aquatic Sciences*, *59*(3), 564–577. https://doi.org/10.1139/f02-021

Stasio, B. T. De, Hill, D. K., Kleinhans, J. M., Nibbelink, N. P., & Magnuson, J. J. (1996). Potential Effects of Global Climate Change on Small North-Temperate Lakes : Physics , Fish , and Plankton. *Limnol. Oceanogr.*, *41*(5), 1136–1149.

Stelzer, R. S., & Lamberti, G. A. (2001). Effects of N : P ratio and total nutrient concentration on stream periphyton community structure, biomass, and elemental composition. *Limnology and Oceanography*, *46*(2), 356–367. https://doi.org/10.4319/lo.2001.46.2.0356

Sterner, R. (2014). C:N:P stoichiometry in Lake Superior: freshwater sea as end member. *Inland Waters*, *1*(1), 29–46. https://doi.org/10.5268/iw-1.1.365

Stevenson, B. R. J., & Bahls, L. L. (1999). Periphyton protocols, 1–23.

Stevenson, R. J., Rier, S. T., Riseng, C. M., Schultz, R. E., & Wiley, M. J. (2006). Comparing effects of nutrients on algal biomass in streams in two regions with different disturbance regimes and with applications for developing nutrient criteria. *Hydrobiologia*, *561*(1), 149–165. https://doi.org/10.1007/s10750-005-1611-5

Stirling, H. P., & Dey, T. (1990). Impact of intensive cage fish farming on the phytoplankton and periphyton of a Scottish freshwater loch. *Hydrobiologia*, *190*(3), 193–214. https://doi.org/10.1007/BF00008187

Trebitz, A. S., Brazner, J. C., Cotter, A. M., Knuth, M. L., Morrice, J. A., Peterson, G. S., … Kelly, J. R. (2008). Water Quality in Great Lakes Coastal Wetlands: Basin-wide Patterns and Responses to an Anthropogenic Disturbance Gradient. *Journal of Great Lakes Research*, *33*(sp3), 67–85. https://doi.org/10.3394/0380-1330(2007)33[67:wqiglc]2.0.co;2

Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climate Research*, *47*(1–2), 123–138. https://doi.org/10.3354/cr00953

Walsh, J. R., Carpenter, S. R., & Vander Zanden, M. J. (2016). Invasive species triggers a massive loss of ecosystem services through a trophic cascade. *Proceedings of the National Academy of Sciences*, *113*(15), 4081–4085. https://doi.org/10.1073/pnas.1600366113

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., … Bairlein, F. (2002). Ecological responses to recent climate change. *Nature*, *416*(6879), 389–395. https://doi.org/10.1038/416389a

Ward, P. R. B., Anders, P. J., Minshall, G. W., C., H., Hoyle, G. M., & Yassien, H. (2017). Nutrient uptake during low-level fertilization of a large 7th order oligotrophic river. *Canadian Journal of Fisheries and Aquatic Science*, (May), 1–42.

Welsh, H. H., & Ollivier, L. M. (1998). Stream Amphibians as Indicators of Ecosystem Stress :

A Case Study from California ’ s Redwoods. *Ecological Applications*, *8*(4), 1118–1132.

Wolman, G. M. (1954). A Method of Sampling Coarse River-Bed Material. *Transactions, American Geophysical Union*, *35*(6), 951–956.

Wood, P. J., & Armitage, P. D. (1997). Biological effects of fine sediment in the lotic environment. *Environmental Management*, *21*(2), 203–217. https://doi.org/10.1007/s002679900019

Wu, N., Dong, X., Liu, Y., Wang, C., Baattrup-Pedersen, A., & Riis, T. (2017). Using river microalgae as indicators for freshwater biomonitoring: Review of published research and future directions. *Ecological Indicators*, *81*(May), 124–131. https://doi.org/10.1016/j.ecolind.2017.05.066