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The effects of surface temperature and chlorophyll concentration on fish abundance in the Great Lakes

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Abstract

Human activity in recent years has caused massive changes to the environment, which in turn has had an impact on species diversity as ecological niches change in their size and composition (USGCRP, 2017). In this paper, we investigate whether human activity surrounding the Great Lakes - in particular Lake Ontario and Lake Erie - has impacted the abundance of four commonly found species of fish in these lakes. Two common effects of human activity on water bodies are chemical deposits, which increase algae growth and chlorophyll concentration, and the increase in surface water temperature. We studied the change in chlorophyll concentration and average annual surface water temperature from 1995 - 2011 and looked at how these physicochemical disturbances in the lakes may have impacted 4 different species of fish, namely Lake Whitefish, Walleye, Yellow Perch, and Freshwater Drum. To do this, we utilized public datasets from Canadian and American environmental agencies that study temperature and chemical properties of the Great Lakes, as well as fishery data that track fish catch in these lakes. Using linear mixed-effects models, we discern the effects that chlorophyll and temperature have independently had on abundance of each of the fish species we studied, and performed Tukey tests to find the comparative effects these variables have had on pairs of species. We found that increasing chlorophyll concentrations in the lakes has contributed to the overall increase in fish abundance in the lakes, while increasing temperatures have caused a decline in fish populations in the lakes. There is also a significantly different effect of these variables between species of

fish, although the comparison between Walleye and Lake Whitefish failed to find a significantly different impact of the variables on their total abundance. We come to the conclusion that changes in physicochemical properties in freshwater bodies like Lake Ontario and Lake Erie have a significant impact on fish populations, which can differ between different species of fish.

Introduction

Excessive greenhouse gas emissions and nutrient loading generated from human activities are two major threats to aquatic environments. The greenhouse gases accumulate in the atmosphere and absorb infrared radiation from the Earth's surface (Houghton 2005). This gradually increases the temperature of aquatic environments. At the same time, nutrient pollution can lead to algal blooms in water bodies which is often measured by chlorophyll levels (Foulon et al., 2020; Knefelkamp et al., 2007).

Currently, there are several studies on how the fluctuation of temperature and chlorophyll level influence the abundance of marine species. The result of most of the studies supports that these two environmental changes affect the abundance of many aquatic species. Zainuddin (2011) found chlorophyll-a concentration and sea surface temperature (SST) play an important role in explaining the distribution and abundance of skipjack tuna in Bone Bay. A few years later, Abdellaoui's (2017) study showed sea surface temperature is negatively correlated to sardine catch-per-unit-effort (CPUE) and chlorophyll-a is weakly correlated to the CPUE at short term variations in the AI-Hoceima fishing area.

However, the research on freshwater animals is limited. In this project, we study four freshwater species (Freshwater Drum, Lake Whitefish, Walleye, Yellow Perch) in Lake Ontario and Lake Erie from 1995 to 2011. The abundance data of the four species is from the fish production dataset of the Great Lake Fishery Commission. They collect commercial fish catch data of the Great Lakes from 1867 to 2015 (Great Lakes Fishery Commission - Great Lakes Databases, 2015). This dataset was chosen because it contains many aquatic species so that different responses between species can be investigated. In terms of the physicochemical data, the temperature data produced from near real-time satellite temperature imagery of NOAA CoastWatch Great Lakes Node, and the chlorophyll data is from a global database in freshwater lakes.

Our hypothesis is that the abundance of the four species is influenced by lake surface temperature and chlorophyll concentration. Algae may increase the food source of the four species, and enhanced temperature may decrease the dissolved oxygen level in the water. Therefore, we predicted that the fish abundance is positively correlated with chlorophyll level and negatively correlated with surface temperature.

Methods

Data Description

We used 3 data sources for our analysis, with data from both Lake Erie and Lake Ontario. The original chlorophyll data was taken from a study by Filazzola et. al., who created a database through systematic reviews of chlorophyll concentrations in freshwater bodies around the world. (Filazolla, 2020) From their dataset, we used data from Lake Ontario and Lake Erie for the years 1995 - 2011. We got temperature data for both of these lakes from the National Oceanic and Atmospheric Administration (NOAA), a US government agency that tracked the physical characteristics of the great lakes from 1995-2011 as part of their Great Lakes Surface Environmental Analysis (GLSEA). (CoastWatch, 2019) Commercial fish production data, including fish catch data stratified by species and measurement in thousands of pounds, was found through the Great Lakes Fishery Commision (GLFC) from which we got the data for our 4 species of interest. (GLFC, 2015) We then combined the columns for Year (between 1995-2011), Avg..Chl. (Average Chlorophyll Concentration in mg/L), Avg..Temp. (Average Temperature in ˚C), Lake.Whitefish (Annual Catch of Lake Whitefish in Thousands of Pounds), Yellow.Perch (Annual Catch of Yellow Perch in Thousands of Pounds), Freshwater.Drum (Annual Catch of Freshwater Drum in Thousands of Pounds), and Walleye (Annual Catch of Walleye in Thousands of Pounds). This data was put into 2 separate .csv files, with an additional column for LakeName specifying if the data was referring to Lake Ontario or Lake Erie. The files were named Ontario.csv and Erie.csv, which can be found in our supplementary material.

Data Analysis

The individual datasets were combined in R to create a single dataset containing the year of recorded observations, average annual chlorophyll concentration in mg/L, average annual surface water temperature (by taking an average of daily temperature data over a year for both lakes) in ˚C, and annual fish catch size for 4 species of fish in thousands of pounds. The fish catch data were converted to a population size by dividing annual fish catch by the average weight in pounds of an adult fish from each species. The information for individual masses of each species of fish were found through the Government of Ontario and Government of Indiana websites. (Government of Ontario, 2021; Government of Indiana, 2021). The dataset was transformed in R by mutating the 4 columns and dividing the catch value by the average weight of each fish and multiplying by a thousand to get the absolute population of each species for each year. We then gathered the fish populations into one column and the respective species names into another to create a long format of the dataset, which is more suitable for analysis.

Testing Assumptions

Assumptions were tested for two hypotheses: one to investigate if chlorophyll concentration has a significant effect on populations of fish species, and the other to test if average surface temperature of each lake has a significant effect on populations of fish species. We built 2 linear models to describe these relationships, using the species populations as the response variable and the interaction between species names and either average temperature or chlorophyll concentration as the input variable. We used these models as arguments in the plot() function which was then used to create Q-Q and residual plots to test assumptions for homogeneity and uniformity of our data:

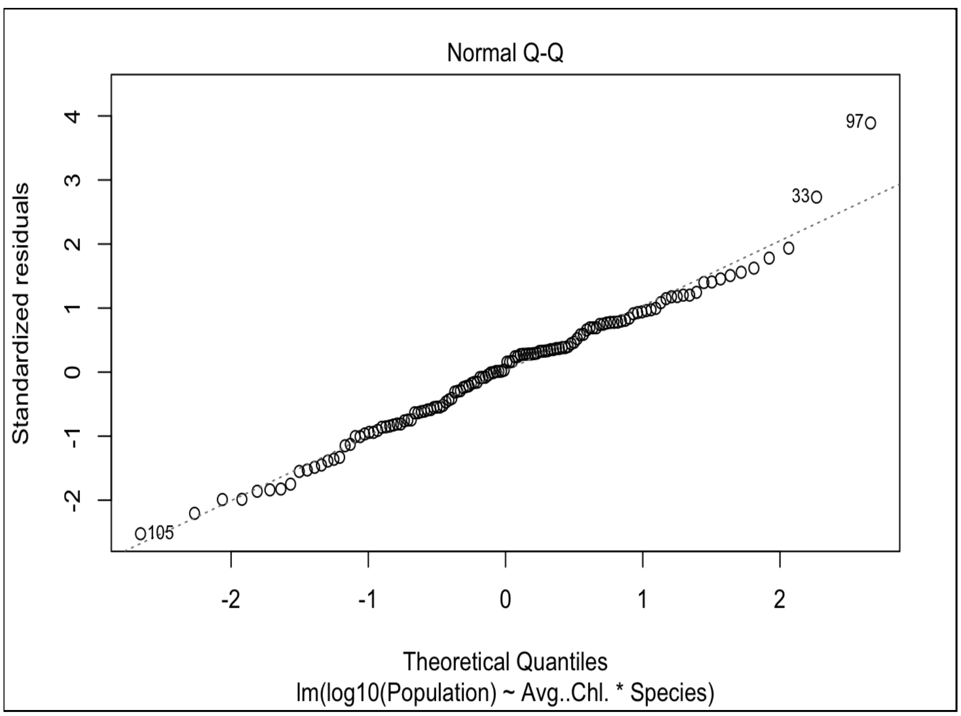

Fig.1: Q-Q plot showing uniformity of data when a linear model is plotted with log10 of species_catch as the response variable, and the interaction between species and average chlorophyll concentration as the input variable. Data is mostly uniform.

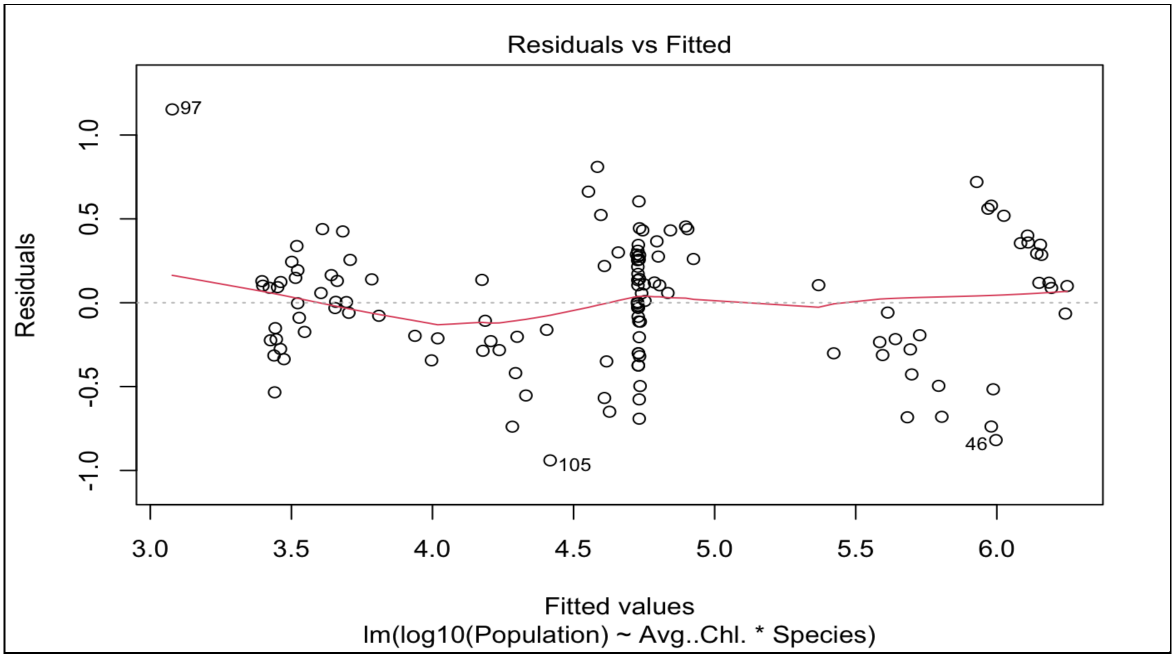

Fig.2: Residual plot showing homogeneity of data when a linear model is plotted with log10 of species_catch as the response variable, and the interaction between species and average chlorophyll concentration as the input variable. Data is mostly homogenous apart from several outliers like residual 97.

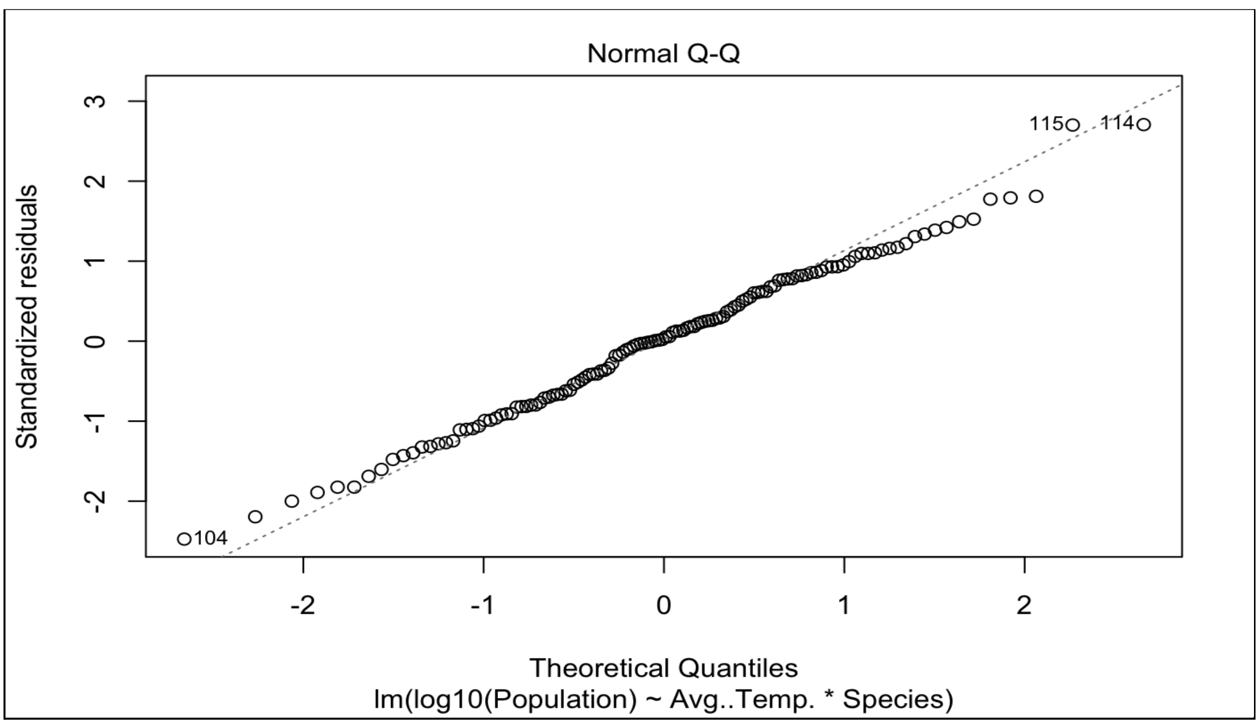

Fig.3: Q-Q plot showing uniformity of data when a linear model is plotted with log10 of species_catch as the response variable, and the interaction between species and average temperature as the input variable. Data is mostly uniform.

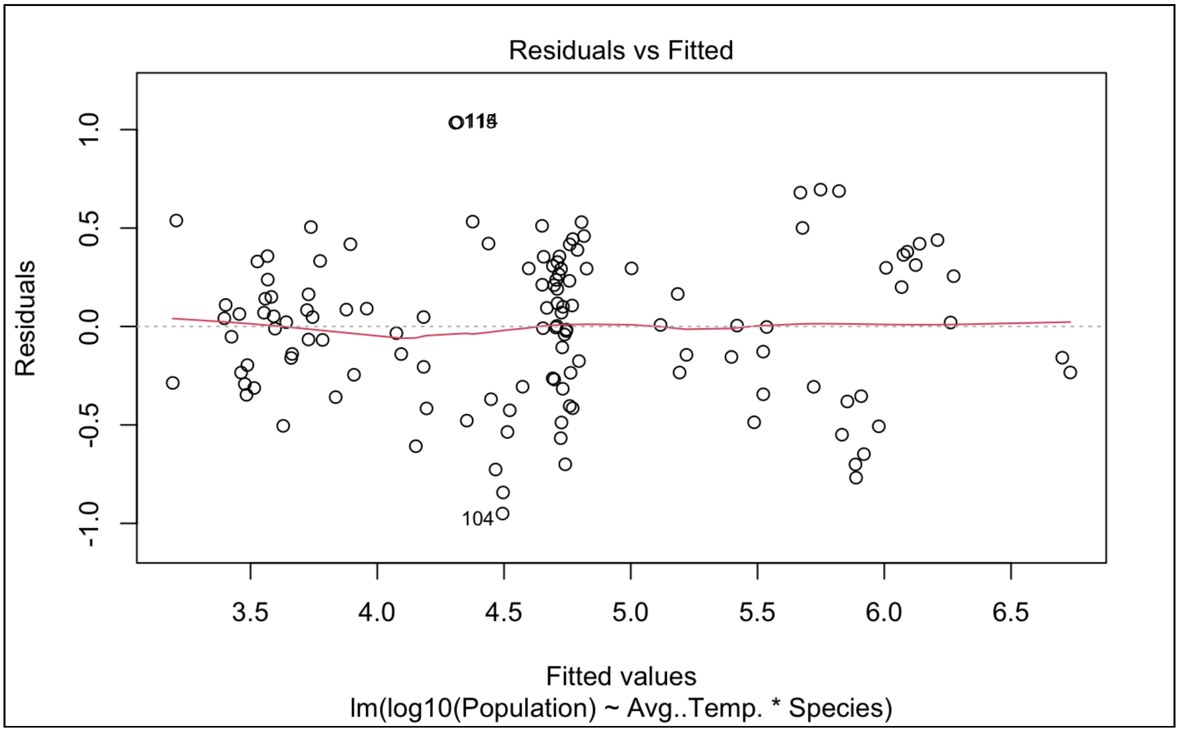

Fig.4: Residual plot showing homogeneity of data when a linear model is plotted with log10 of species_catch as the response variable, and the interaction between species and average temperature as the input variable. Data is mostly homogenous.

The results of our assumption tests suggest that the data was uniform and mostly homogenous, as most of the residuals remained near the line, allowing us to use these models for further analysis.

Constructing Models

We constructed 2 linear mixed-effects models, one for each hypothesis. In each model, the lmer() function was used with log10(species_catch) as the response variable, the interaction between species names and either average temperature or chlorophyll concentration as the input variable, and lake names as a random effect. The models we constructed can be seen below:

1. lmer(log10(species_catch) ~ Avg..Chl.*species + (1|LakeName), data= lakes_long, REML=FALSE)

2. lmer(log10(species_catch) ~ Avg..Temp.*species + (1|LakeName), data= lakes_long, REML=FALSE)

We used the output to discern which species' populations had a significant effect based on chlorophyll concentration and temperature, and used the associated slope and intercept values to build comparative graphs of our own between species as well as analyze overall trends.

Analysis of Variance & Tukey test

A Tukey test was performed to find significant differences between pairs of fish species in terms of the relative impact of chlorophyll concentration and temperature on their respective populations. To do this, we initially used the aov() function with our linear models as the argument to generate sums of squares for the interaction between chlorophyll/temperature and species with their populations as the output. This aov table was used as an argument in the TukeyHSD() function to find if differences between populations between pairs of species were significant given the effect of chlorophyll and temperature.

Results

Chlorophyll analysis

A type 3 ANOVA analysis on our linear model results reveals that chlorophyll has a significant positive effect on overall fish abundance ($p < 0.05$, df= 1), and that the effect differs depending on the species of fish ($p < 0.05$, df= 3). The linear model estimates that for every 1 mg/L increase in chlorophyll concentration, there would be a corresponding 80.66 increase in fish abundance on the log10 scale. Separate graphs with model estimates for each species show that each of the species exhibit a very different relationship between abundance and chlorophyll concentration (Figure 5). A post-hoc Tukey Test comparing the four species shows that there is a significant variation in the magnitude of response between species, with the exception of Lake Whitefish and Walleye, which show identical means ($p > 0.05$)(Figure 6). Yellow Perch and Freshwater Drum were found to have significantly different means from one another as well as from Lake Whitefish and Walleye, driving the significant results ($p < 0.05$)(Figure 6). Although the overall effect of chlorophyll on abundance is positive, a closer look at each of the species shows that a negative relationship between chlorophyll concentration and abundance is found for the species Walleye and Yellow Perch, whereas a positive relationship is found for Freshwater Drum and Lake Whitefish (Figure 5).

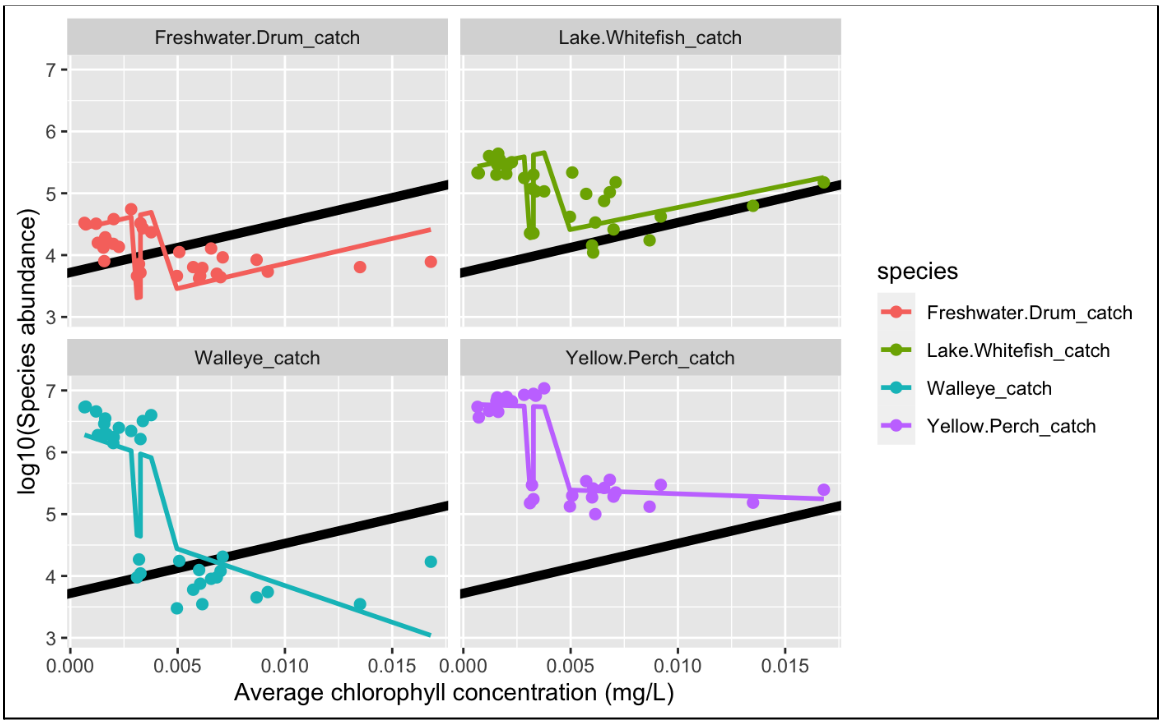

Figure 5: Relationship between chlorophyll concentration and species abundance.

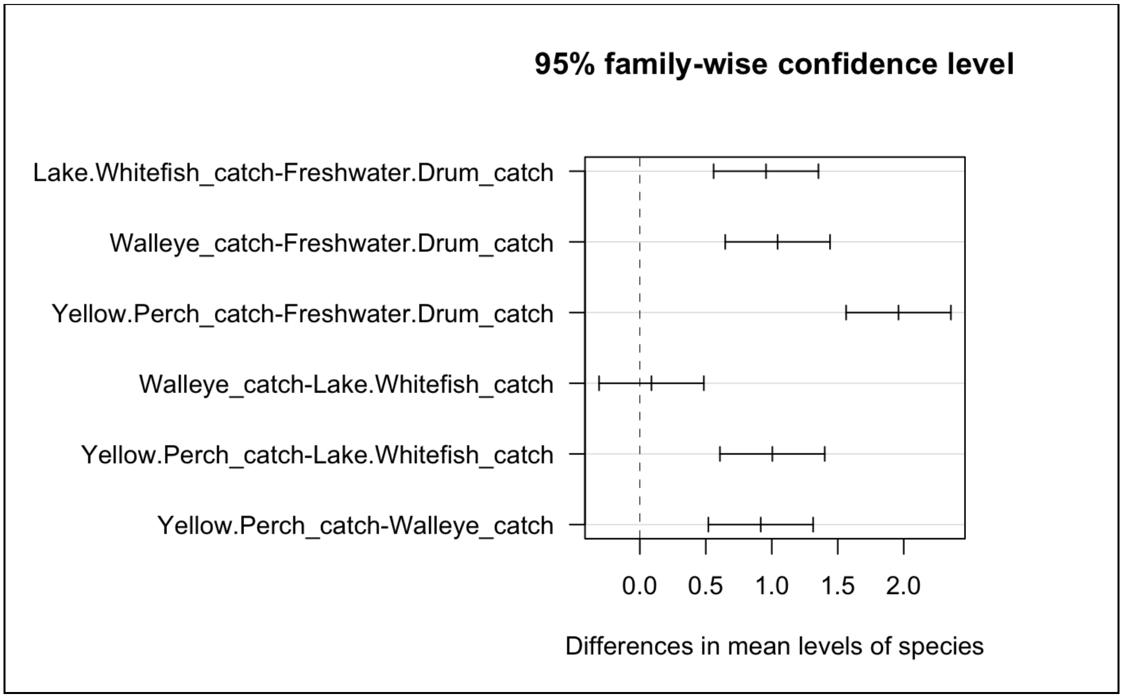

Figure 6: Pairwise comparisons of group means for chlorophyll analysis.

Temperature analysis

A type 3 ANOVA analysis on our linear model results shows that average surface temperature has a significant negative effect on overall fish abundance ($p < 0.05$, df = 1), and that the species of fish has a significant effect on the interaction between temperature and abundance ($p < 0.05$, df = 3). The model estimates that every 1°C increase in temperature is followed by a 0.31 decrease in fish abundance on the log10 scale. Similarly, separate graphs for each species show that surface temperature has a different effect on abundance depending on the species of fish (Figure 7). A post-hoc Tukey Test comparing the four species shows that there is a significant difference in the magnitude of response of each species, with the exception of Lake Whitefish and Walleye, which show identical means ($p > 0.05$)(Figure 8). Similar to our chlorophyll analysis, Yellow Perch and Freshwater Drum were found to have significantly different means from one another as well as from Lake Whitefish and Walleye, driving the significant results ($p < 0.05$)(Figure 8). While temperature has a negative effect on the overall abundance, each species shows a unique response to the variable. A negative relationship between temperature and abundance was found for Freshwater Drum and Lake Whitefish while a positive relationship was found for the species Walleye and Yellow Perch (Figure 7).

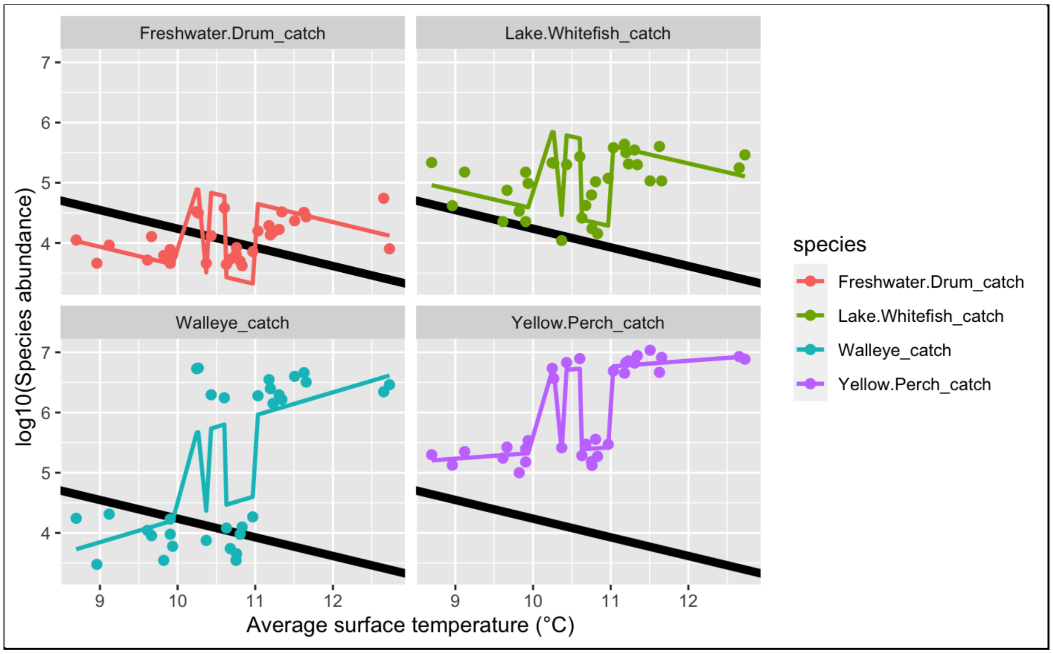

Figure 7: Relationship between surface temperature and species abundance.

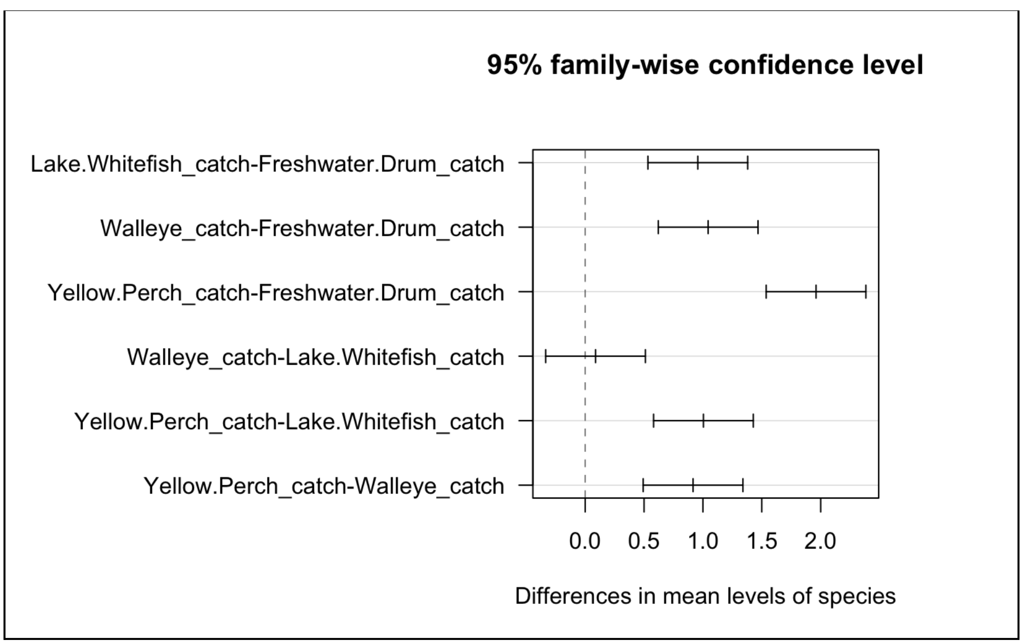

Figure 8: Pairwise comparison of group means for temperature analysis.

Discussion

Our results support our hypothesis and predictions that chlorophyll concentration has a positive effect on fish abundance and surface temperature has a negative effect on fish abundance. They provide almost the same conclusions as previous two studies done on this topic. However, we found that the effect differs greatly between species. Freshwater Drum and Lake Whitefish were found to have an opposite relationship with chlorophyll and temperature to Yellow Perch and Walleye. Therefore, the findings may not be generalizable to all species of fish and depend heavily on the life history traits of individual species.

The different responses to the chlorophyll concentration change between the four species may be due to their different locations in the food web of lakes. The energy from the bottom of a food web needs time to move up through a food chain. In this study, chlorophyll concentration fluctuated but not altered in one direction. Therefore, the environmental change may only affect species at a relatively low position in the food web.

The food sources of Freshwater Drum, Lake Whitefish, and Yellow Perch are similar, including macroinvertebrates and zooplankton, except that Yellow Perch also eat some small fishes (Mason 2003). This means the location of Yellow Perch on the food web is slightly higher than Freshwater Drum and Lake Whitefish. Walleye is a fish eater which is at a higher position in the food web than the other three species. The period of chlorophyll concentration change in one direction may be too short to have an effect on the food sources of Walleye and Yellow Perch so these species are not positively correlated with chlorophyll concentration. At the same time, excessive algae can consume a large amount of oxygen in lakes, which may harm aquatic animals. In summary, Walleye and Yellow Perch might not receive large food benefits from the algal bloom but suffered the low oxygen level, which may be the potential reason for the inverse relationship between the abundance and chlorophyll concentration.

The abundance of Yellow Perch and Walleye is positively correlated with surface temperature, which also is different from Freshwater Drum and Lake Whitefish. The positive relationship may be due to the large prey size of Yellow Perch and Walleye. Legler et al. (2010) found the digestion rates of fish increase with water temperature and decrease with prey size. The prey sizes of Freshwater Drum and Lake Whitefish are small so their digestion rate may be quite fast, which may indicate that the rising space of the digestion rate is limited. While the digestion rate of Yellow Perch and Walleye may be slow due to the large prey size. Therefore, high temperatures may dramatically increase their digestion rate. This increases the amount of energy they get in a given time, and eventually enhances their fitness.

While we found significant results, our study contains multiple limitations that may affect the accuracy and applicability of those results. Firstly, we used fish catch or commercial fish production data as a proxy of fish abundance. The two are not exactly equivalent as fish catch is determined by other factors such as fishing effort, which varies from year to year based on market demands. That is likely one of the reasons Lake Whitefish in Lake Ontario experienced such a steep decline in catch over time. Species catch data was also given in the unit of thousands of pounds, which we had to convert to abundance by dividing it by the average weight of each species. This conversion may not be completely accurate given the variability of fish weight at an individual level, and cause overestimation or underestimation of fish abundance. Furthermore, our data is limited to only four species and does not account for their relative habitats and niches within the lake ecosystem. Additionally, only data from years 1995-2011 were used, which may not be a large enough time window to observe any long term trends.

Research into more fish species and lakes will be needed to draw conclusions on the effects of chlorophyll and temperature on fish more generally, as well as identify ways to predict the response of a given species based on their life history traits.

References

Abdellaoui, B., Berraho, A., Falcini, F., Santoleri, J. R., Sammartino, M., Pisano, A., & Hilm, K. (2017). Assessing the impact of temperature and chlorophyll variations on the fluctuations of sardine abundance in Al-Hoceima (South Alboran Sea). Journal of Marine Science: Research & Development, 7(4), 1-11.

CoastWatch Great Lakes Node. (2019). Great Lakes Statistics. Noaa.gov. https://coastwatch.glerl.noaa.gov/statistic/

Filazzola, A., Mahdiyan, O., Shuvo, A. et al. (2020). A database of chlorophyll and water chemistry in freshwater lakes. Sci Data 7, 310.

Foulon, É., Rousseau, A. N., Benoy, G., & North, R. L. (2020). A global scan of how the issue of nutrient loading and harmful algal blooms is being addressed by governments, non-governmental organizations, and volunteers. Water Quality Research Journal, 55(1), 1-23.

Great Lakes Fishery Commission - Great Lakes Databases. (2015). Glfc.org. http://www.glfc.org/great-lakes-databases.php

Houghton J. 2005. Global warming. Reports on Progress in Physics. 68(6):1343.

Indiana Division of Fish and Wildlife's Animal Information Series Freshwater Drum (Aplodinotus grunniens). (n.d.). Retrieved December 7, 2021, from https://www.in.gov/dnr/fish-and-wildlife/files/fw-freshwater_drum.pdf

Knefelkamp, B., Carstens, K., & Wiltshire, K. H. (2007). Comparison of different filter types on chlorophyll-a retention and nutrient measurements. Journal of Experimental Marine Biology and Ecology, 345(1), 61-70.

Lake Whitefish. (2021). Ontario.ca. https://www.ontario.ca/page/lake-whitefish

Legler, N. D., Johnson, T. B., Heath, D. D., & Ludsin, S. A. (2010). Water temperature and prey size effects on the rate of digestion of larval and early juvenile fish. Transactions of the American Fisheries Society, 139(3), 868-875.

Mason, D. (2003). Quantifying the impact of exotic invertebrate invaders on food web structure and function in the great lakes: A network analysis approach. Interim Prog. Rep. to Gt. Lakes Fish. Comm. yr, 1.

USGCRP. (2017). *Highlights of the Findings of the U.S. Global Change Research Program Climate Science Special Report*. Climate Science Special Report. Retrieved December 13, 2021, from https://science2017.globalchange.gov/chapter/executive-summary/.

Walleye. (2021). Ontario.ca. https://www.ontario.ca/page/walleye

Yellow Perch. (2021). Ontario.ca. https://www.ontario.ca/page/yellow-perch

Zainuddin, M. (2011). Skipjack tuna in relation to sea surface temperature and chlorophyll-a concentration of Bone Bay using remotely sensed satellite data. Jurnal Ilmu dan Teknologi Kelautan Tropis, 3(1).