THE EFFECTS OF LAKE ACIDIFICATION ON SMALL-BODIED FISH POPULATIONS

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April 26th, 2024

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An Undergraduate Thesis Submitted in
Partial Fulfillment of the Requirements for the
Degree of Honours Bachelor of Environmental Management

Faculty of Natural Resources Management
Lakehead University
April 26th, 2024

Major Advisor

Second Reader

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ABSTRACT

MacIsaac, C. 2024. The effects of lake acidification on small-bodied fish populations. Undergraduate Thesis, Faculty of Natural Resources Management, *Lakehead University*, Thunder Bay ON. 30 pp.

Keywords: acidification, acid rain, biological recovery, chemical recovery, extirpation, re-establishment

Industrialization has had adverse effects on the environment. Through mining and burning of fossil fuels, acidic precursors are emitted into the atmosphere creating acid rain. Acid rain is then deposited into freshwater lakes, causing lake acidification which can in turn affect the aquatic ecosystem. The purpose of this study was to investigate the effects lake acidification has on small-bodied fish across three lakes that were each subjected to acidification experiments in the IISD Experimental Lakes Area. The effects of acidic deposition on small-bodied fish have not been widely studied. The prediction is that increased acidification in the lakes would lead to reduced small-bodied fish populations. Abundance was measured against lake pH for each species to determine periods of chemical and biological recovery, as well as threshold limits for each fish. The findings show that most of the observed species did experience decline when acidification increased; However, Slimy Sculpin seemed to be more sensitive than the rest, while Northern Pearl Dace abundance increased in response to acidification. Further studies should be performed to determine absolute threshold values for species, including Slimy Sculpin and Pearl Dace based on the findings of this thesis.

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ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr. Michael Rennie for his guidance through the writing and analysing process and for taking the time to meet with me to ensure I was on the right track. His knowledge on the subject was invaluable, and really helped shape the direction of this thesis. I would also like to thank Lauren Hayhurst, not only for agreeing to be my second reader, but the kindness and generosity of taking time out of her busy schedule to provide me with resources I needed to be successful, especially when it came to presentations. Finally, I would like to extend my thanks to the IISD Experimental Lakes area, for allowing me access to the data needed to conduct this study. Thank you.

INTRODUCTION

Freshwater ecosystems provide services to humans and support a wide range of biodiversity. Among the numerous environmental challenges this ecosystem must face is lake acidification. Lake acidification largely occurs from anthropogenic activities such as mining and burning of fossil fuels (Hellström 2012). Major chemical proprietors contributing to lake acidification are sulfurous oxides like SO_2 (H_2SO_4) and nitrous oxides (HNO_3). These chemicals are often emitted in gaseous form and are able to travel long distances before reaching the ground. It is likely to reach these lakes in the form of acid rain, particle settling, or surface runoff (Neary et al. 1990).

Acidification of lakes occurs when the pH of the water body decreases as a result of elevated concentrations of hydrogen ions, making the water more acidic (Freedman 2018). Impacts of acid rain on terrestrial and aquatic ecosystems have not been widely studied. Thus, the impact of lake acidification on aquatic ecosystems and fish populations remains an important area of research as many lakes are continuing to suffer from historic atmospheric acidification.

Fish play an important role in determining health and stability of aquatic ecosystems (Yan et al. 1995). They are sensitive to environmental changes, often reflected by abundance or growth, and can provide information on the consequences of lake acidification (Mills et al. 2001). They are also a key indicator of lake recovery, post acidification (Yan et al. 1995).

The aim of this undergraduate thesis was to explore the effects of lake acidification on aquatic ecosystems, with a specific focus on its effects on small-bodied fish populations. Acidification experiments have previously taken place with focus primarily on larger fish species; However, changes in the minnow community have not been thoroughly explored. My study describes how changes in the water chemistry impacts fish abundance in relation to the pH of the lake. Additionally, I compared the data across three experimental lakes to seek consistencies in response to acidification among species. I hypothesize that increased levels of lake acidification in the IISD Experimental Lakes Area (IISD-ELA) will contribute to reduced small-bodied fish abundance.

LITERATURE REVIEW

Acid rain has been an issue since the 1950s (Freedman 2018). However, the idea thar acid rain was detrimental to environments became prevalent in the 1970s (Freedman 2018, Yan et al. 1995). Rain is considered acidic at a pH of 5.65 or less. Acid rain is often influenced by anthropogenic sources, especially from smelters and industry (Beamish 1976, Freedman 2018, Schindler et al. 1985, Yan et al. 1995). Sulfur dioxides (SO_2) and nitric oxides (NO_x) are precursors to acid rain (Beamish 1976, Freedman 2018, Yan et al. 1995). Other sources of acidic deposition are dust from areas of low vegetation or unpaved roads that are picked up and carried in the wind (Freedman 2018). When acid rain falls on a water body, it may result in the pH of the lake becoming more acidic (Freedman 2018). Surface waters that are vulnerable to acidification lack acid neutralizing capacity or have low alkalinity (Freedman 2018). It is estimated that there are over 4 million km^2 of lakes in Canada which are highly sensitive to acid deposition, and over 1.8 million km^2 that are moderately sensitive (Freedman 2018). Acidic precursors have reduced emissions within the past 25 years; however, there have been few studies of recovery of surface waters (Freedman 2018, Yan et al. 1995).

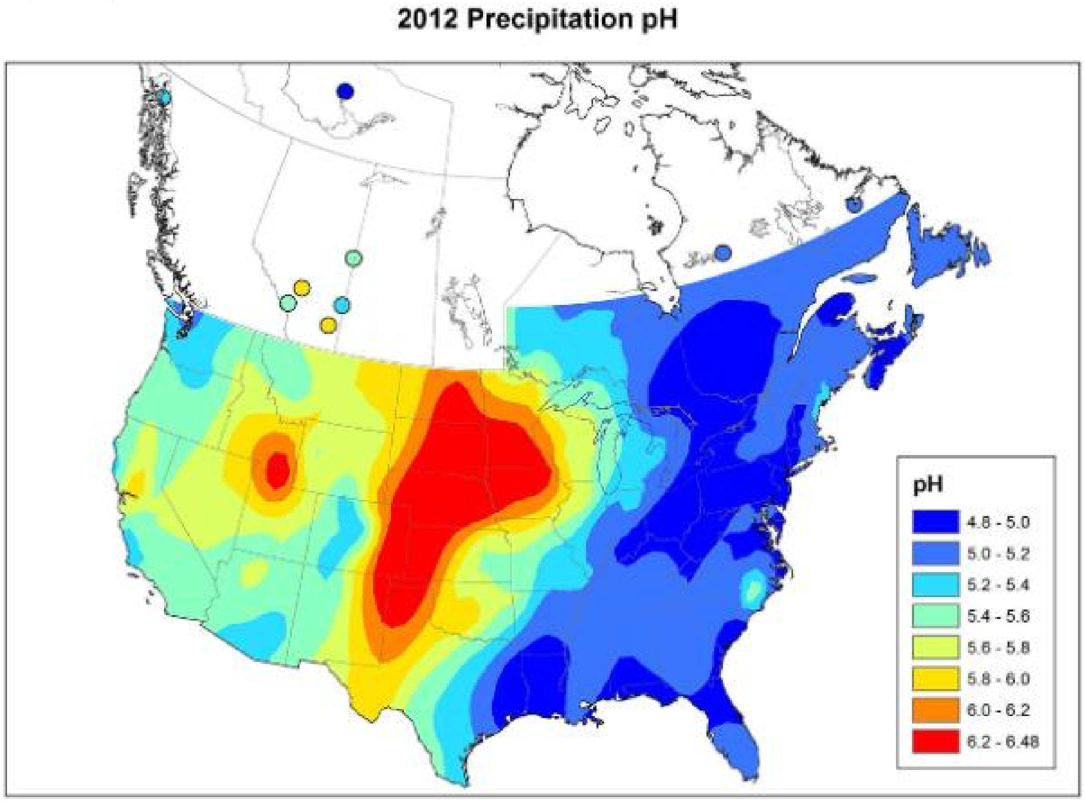

Figure 1. Visual representation of distribution of acidic deposition in form of acid rain from 2012 (Freedman 2018).

The consensus of many acidification studies is that at a pH of 6.0 or less, sensitive fish species begin to decline (Lacoul et al. 2011, Rago & Wiener 1986, Beamish 1976). Fish in younger life stages, such as fry or juveniles are more sensitive to acidification than adults (Gunn & Mills 1998). It has been suggested that there is a pH threshold where aquatic biota is no longer viable, whether as a food source or through reproductive failure (Baker & Christensen 1991, Mills et al. 1987, Schindler et al. 2014). Further expanded upon in the study by Mills et al. (2000), the pH thresholds of several species: Fathead Minnow (*Pimephales promelas*) at pH 5.9, Slimy Sculpin (*Cottus cognatus*) at pH 5.6-5.9, and the Northern Pearl Dace (*Margariscus nachtriebi*) at pH

5.1. Beamish (1976) determined that Lake Chub (*Couesius plumbeus*) disappeared at pH 4.7-4.5, while Rahel & Magnuson (1983) determined the threshold of Northern Redbelly Dace (*Chrosomus eos*) was pH 6.1.

Acid lakes have a negative impact on algal growth (Hellström 2012). While abundance of algae may increase during acidification, the quality of the algae is diminished to the point that it is no longer a viable food source (Hellström 2012); this was evidenced in Schindler et al. (2014) with an increase in phytoplankton that was not a suitable food source for zooplankton. This is relevant to my study to relate potential bottom-up trophic cascade effects of reduced prey for small-bodied fish species in lake food webs. Predation may also increase in acidified water bodies, as there is reduced prey refuge areas (Driscoll et al. 2001, Lacroix et al. 2011). Research into the effects of lake acidification on small-bodied fish species has not been widely studied, since a primary focus has been on large-bodied and sport fish. Possibly, the disappearance of larger fish species in these historical acidification experiments may be attributed to the extirpation of the small-bodied fish prey sources detailed in this report.

Studies in the La Cloche mountains in Ontario, focused on overall fish abundance rather than specific species (Harvey 1975); Mills et al. (1992, 2002, 1998) has performed several studies in the IISD-ELA on the effects of acidification on Lake Whitefish (*Coregonus clupeaformis*), Lake Trout (*Salvelinus namaycush*) and White Sucker (*Catostomus commersonii*). The study by Mills et al. (2002) was located within

302N and primarily focused on the survival of Lake Whitefish. This study determined that low phosphorus could make a lake more susceptible to acidification. Phosphorus is also important as it leads to more algal growth, which means more food for the lower trophic levels, like phytoplankton (Mills et al. 2002, Schindler et al. 2014). However, this study did determine that if fertilization is too extreme during pH recovery, it will lead to Lake Whitefish extirpation, while an appropriate amount will contribute to growth and abundance in the species. Recruitment and abundance were highest during fertilization, and the study determined that for 302N a pH of 5.1 was not acidic enough to affect Lake Whitefish, and it was determined that it was toxicity from algal growth that thrived in the acidic conditions that extirpated Lake Whitefish (Mills et al. 2002). Although small-bodied fish were caught and their data recorded in lake 223 and the separated north and south basins of lake 302 (302N and 302S), these data were not the focus of the results assessment in 223. Further, the data for small-bodied fish were never worked on in 302N and 302S, which enabled me to run my abundance and pH comparisons across the small-bodied fish species in the historically acidified lakes.

In the pH recovery of 223, Fathead Minnow reestablished and were assumed to do so due as a result of population immigration (Mills et al. 2000). Despite the estimated threshold for Fathead Minnow of pH 5.9, the species returned to the lake over a period of nine years when the pH was below this value (Mills et al. 2000). Factoring in their typical lifespan of three to five years, reinforces that other parameters can contribute to overall fish species richness in otherwise generally inhospitable acidified lakes (Beamish 1976, Rago & Weiner 1986, Amarasinghe & Welcomme

2001). Research on small-bodied fish is important. Not only do these species play a pivotal role in aquatic ecosystem biodiversity, but they are also an important part of the food web and vital for survival of many sport fish.

MATERIALS AND METHODS

Study Area

The IISD-ELA is located on Treaty 3 traditional territory and consists of 58 lakes and their watersheds. These lakes are away from human development and industry and are set aside for scientific research purposes. They are a series of experimental and reference lakes that can be used to study large-scale whole-ecosystem effects and to determine solutions to freshwater issues. The lakes used in this study were lakes 223, 302 North (302N), and 302 South (302S). The latter two lakes were originally the same lake; however, they were separated into 2 basins by a vinyl sea curtain in 1982, restricting access and isolating both water chemistry and fish populations between the two. Therefore, they are treated as separate lakes in this study.

Acidification

Lake 223 was acidified starting in 1976. Over a period of eight years, sulfuric acid was added to lower pH, ultimately reaching a low of 5.02 in 1981 (Schindler et al. 1985).

Lake 302N began acidification in 1982 with use of HNO_3, to be later replaced by HCl, as it had stronger acidification effects, so less was needed. In addition to HCl, $NaSO_4$ and $NaNO_3$ were also added in order to mimic what a naturally acidified lake would be composed of. Acid was deposited into the surface layer of the lake by a fibreglass boat preceded by the barrel drip method in years prior. Water samples were collected to be analysed and for pH to be measured (Mills et al. 2002).

Lake 302S was acidified in the same years as 302N. The pre-acidification pH of lake 302S was 6.8 in 1982 and reached its lowest pH of 4.5 in 1989. Sulfuric acid was dispersed into the surface layer by fibreglass boat during the ice-free season (Mills et al. 1992).

Netting

The small-bodied fish observed in this study were captured by using mesh trap nets. Trap nets can be found described in more detail in Beamish (1973) and Skinner (2004); However; they have a range of 3-15ft in depth, are made of 0.8mm square nylon mesh, and allow for passive and non-lethal capture of fish species of all sexes and sizes. The nets are strung with rope made from either nylon or polypropylene. The pots are fastened using Velcro, and short floats are tied to the top of the rope, while a weighted line keeps the net in position on the substrate. The trap nets were set out overnight and checked daily over a period in the spring and fall. Along with measuring fork length, weighing the fish, and fin scarring for mark-recapture efforts, recruitment was measured by calculating catch per unit effort (CPUE). In this study, the CPUE relates to how many fish were counted in a mesh trap net over a period of a few days.

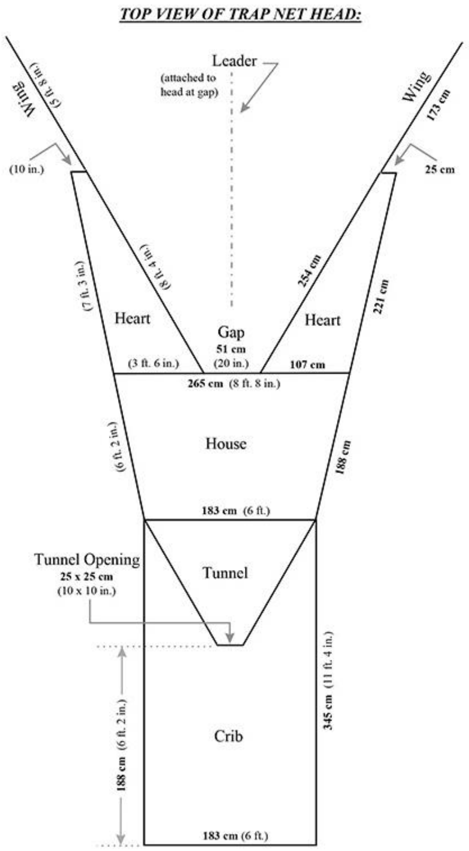

Figure 2. Diagram of an aerial view of a trap net (Skinner & Ball, 2004).

Analysis

In this study, I have defined chemical recovery as when the lake goes from its lowest pH point and returns to a stability of pH 6.0 or higher. This is based of the consensus of pH 6.0 being the threshold where fish begin to disappear (Beamish 1976, Lacoul et al. 2011, Rago & Weiner 1986). Therefore, the fish would theoretically be able to survive when the pH returns to this value or above.

Biological recovery is measured by abundance, or CPUE against pH values for years they are deemed absent or present. Fish absence is when the CPUE is at a value of less than 0.5, while they are considered to be present in years that their CPUE is 0.5 or greater. This was measured against the pH for the years they are absent or present to determine the average pH that caused each species to disappear or recover. Every fish with the exception of Slimy Sculpin was measured solely against epilimnion pH. Slimy Sculpin was measured against epilimnion and hypolimnion pH (when available) as they reside in the hypolimnetic layer of the lake, while the others remain in the epilimnion. Recovery is defined as when a fish species exhibits a CPUE of 0.5 or greater for two or more consecutive years after the lake pH has stabilized, to avoid instances when the species returns for two years and disappears again due to falling pH values.

RESULTS

Chemical recovery in each lake began immediately post acidification. It took 7 years from 1984 to 1991 for lake 223 to chemically recover from the acidification experiment. During these years the lake went from its lowest pH of 5.1 to a pH of 6.1. Lake 302N took 8 years from 1989 to 1997 going from pH 5.04 to 6.37, while lake 302S chemically recovered from 1990 to 1999, a timespan of 9 years. 302S had the lowest recorded pH of all three lakes reaching a pH of 4.5; pH in the other two lakes were similarly reduced to near 5 (Table 1).

Table 1. Time taken for chemical recovery in each lake and their respective pH values during the period.

Lake	Acidification Period	pH Range	Chemical Recovery	pH Range
223	1976-1983	6.6-5.1	1984-1991	5.1-6.1
302N	1982-1989	6.5-5.1	1989-1997	5.0-6.4
302S	1982-1989	6.8-4.5	1990-1999	4.5-6.1

Table 2. Fish absence or presence based on CPUE and their corresponding pH values for the years applicable. Left side represents the timespan in which pH was declining, while the right indicates when pH was increasing towards recovery. N/A represents when the fish was never present in the lake, or when values were not recorded for the species (Lake Chub). Hypolimnion pH included in parentheses for Slimy Sculpin.

		Average pH when CPUE <0.5		Average pH when CPUE >0.5	
Fish	Lake	Spring	Fall	Spring	Fall
Northern Redbelly Dace	223	N/A	N/A	N/A	N/A
	302N	5.4	5.7	6.1	5.2
	302S	5.2	5.7	No values high enough	6.5
Finescale Dace	223	6.1	6.1	7.0	No values high enough
	302N	5.9	5.6	5.3	5.8
	302S	5.0	5.4	5.8	6.0
Lake Chub	223	5.7	N/A	6.6	N/A
	302N	N/A	N/A	N/A	N/A
	302S	N/A	N/A	N/A	N/A
Fathead Minnow	223	5.6	5.5	6.5	6.5
	302N	5.3	5.2	5.8	6.1
	302S	5.1	5.3	5.4	6.2
Northern Pearl Dace	223	6.4	5.5	6.0	6.1
	302N	5.4	No values low enough	5.5	5.5
	302S	No values low enough	No values low enough	5.2	5.7
Brook Stickleback	223	6.1	6.0	6.9	6.1
	302N	N/A	N/A	N/A	N/A
	302S	N/A	N/A	N/A	N/A
Slimy Sculpin	223	6.2 (5.9)	6.2 (5.9)	6.1 (6.2)	6.0 (6.2)
	302N	5.4 (5.8)	5.5 (5.8)	5.6 (5.8)	6.4 (6.0)
	302S	5.2 (5.6	5.7 (5.7)	No values high enough	No values high enough

Table 3. Biological recovery of the subject species in each of the experiment lakes, and their corresponding pH values. Fish that were never present in the lake are indicated with N/A.

Fish	Lake	Disappearance	pH in Year of Extirpation	Re-establishment	pH in Year of recovery
Northern Redbelly Dace	223	N/A	N/A	N/A	N/A
	302N	1987	5.2	None	N/A
	302S	1984	5.5	2001	6.5
Finescale Dace	223	1980	5.6	2012	7.1
	302N	1990	5.2	1999	6.4
	302S	1986	5.1	1997	5.9
Lake Chub	223	1980	5.6	1994	6.6
	302N	N/A	N/A	N/A	N/A
	302S	N/A	N/A	N/A	N/A
Fathead Minnow	223	1980	5.6	1991	6.1
	302N	1988	5.0	1999	6.4
	302S	1988	4.7	1997	5.9
Northern Pearl Dace	223	Always present	N/A	Always present	N/A
	302N	Always present	N/A	Always present	N/A
	302S	Always present	N/A	Always present	N/A
Brook Stickleback	223	1976	6.5	1998	7.0
	302N	N/A	N/A	N/A	N/A
	302S	N/A	N/A	N/A	N/A
Slimy Sculpin	223	1983	5.2	2019	6.8
	302N	1990	5.2	None	N/A
	302S	1984	5.5	None	N/A

Brook Stickleback (*Culaea inconstans*)

Brook Stickleback was only present in lake 223. The average pH when the species was deemed absent in the lake was at a pH of 6.1. When the species was present, the pH averaged 6.5. The period of biological recovery for the Brook Stickleback was from 1976, when they disappeared, to 1998, when they reestablished, with a pH range of 6.5-7.0 during this time. There is a difference of 7 years between the year of chemical recovery and biological recovery, and almost a full pH unit between the two (6.1-7.0).

Fathead Minnow (*Pimephales promelas*)

During the periods when Fathead Minnow was assessed at having a CPUE of less than 0.5, the average pH of lake 223 was 5.6, 302N was 5.3, and 302S was 5.2. The average pH when we observed that the species was present was 6.5 in lake 223, 6.0 in lake 302N, and 5.8 in lake 302S. The overall average across all three lakes when the Fathead Minnow was absent is 5.4, and when they were present it was pH 6.1. The species disappeared from lake 223 in 1980, when the lake was at a pH of 5.6. In lake 302N they were no longer present at a pH of 5.0 in 1988, and in lake 302S they were gone in 1988 at a pH of 4.7. Years of reestablishment for lakes 223, 302N and 302S were 1991, 1999, and 1997 at a pH of 6.1, 6.4, and 5.9 respectively. In lake 223, there was no delay of biological recovery from chemical recovery for this species (Figure 3). It took two years for the Fathead Minnow to reestablish after chemical recovery in 302N, and like the Finescale Dace, this species re-established two years prior to chemical recovery in lake 302S (Figures 4, 5). On average, this species required less of a change in pH from chemical recovery than the other species, besides Brook Stickleback, to be able to recover biologically.

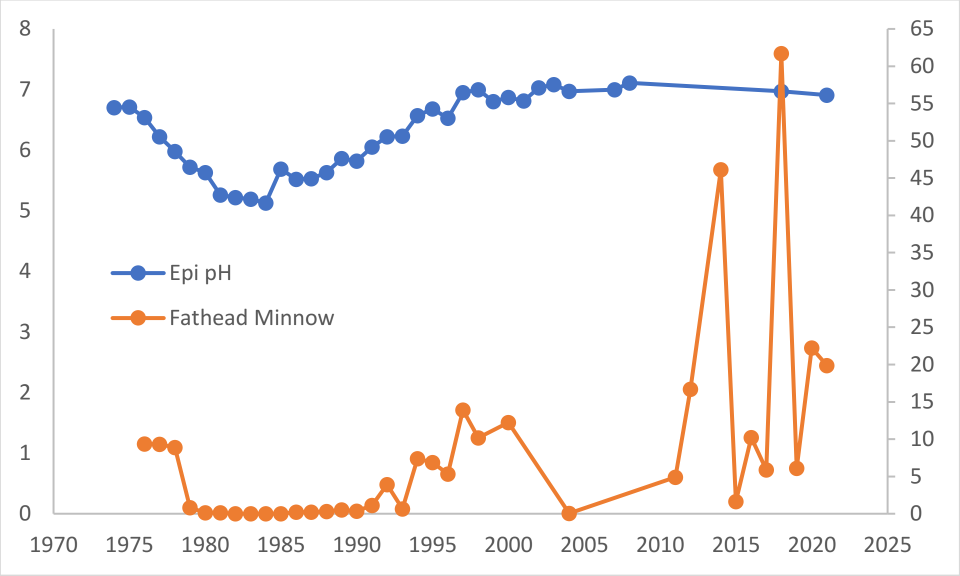

Figure 3. Fathead Minnow abundance in relation to epilimnion pH changes in lake 223.

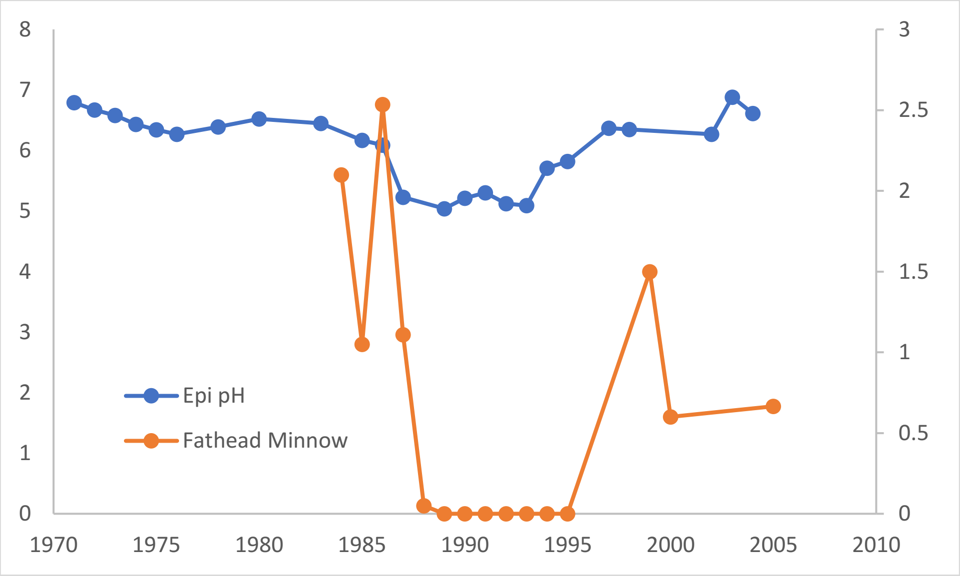

Figure 4. Fathead Minnow abundance in relation to epilimnion pH changes in lake 302N.

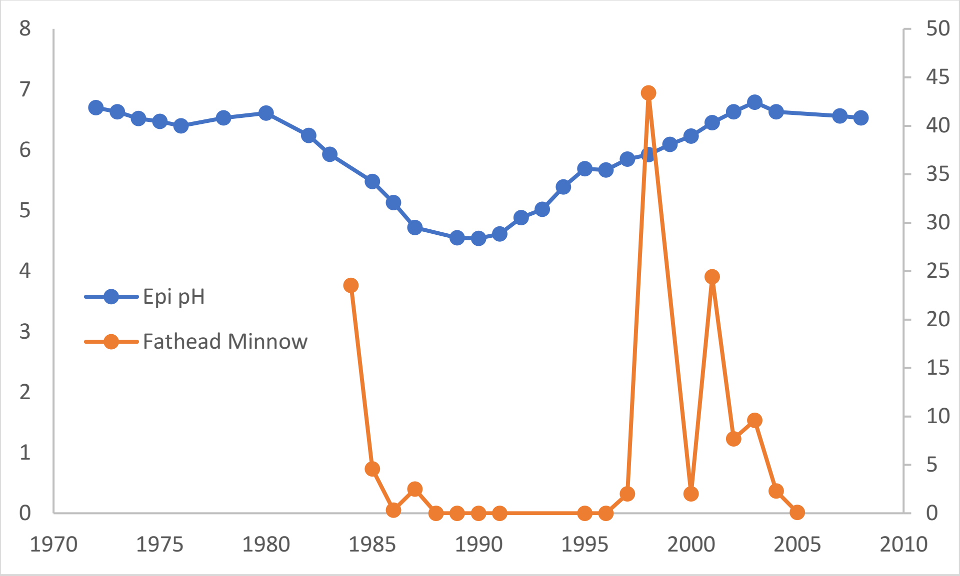

Figure 5. Fathead Minnow abundance in relation to epilimnion pH changes in lake 302S.

Finescale Dace (*Chrosomus neogaeus*)

Finescale Dace disappeared from lake 223 in 1980 when the pH was at 5.6 and biologically recovered in 1994, when the pH was recorded to be 6.6. It took 9 years for the species to biologically recover in lake 302N from 1990 to 1999, with pH ranging from 5.2 to 6.4. It took 11 years in lake 302S from time of disappearance in 1986 to point of biological recovery in 1997. The pH when they were deemed extirpated in 302S was 5.1, and 5.9 when they reestablished. It took 21 years post chemical recovery for the Finescale Dace to reestablish in lake 223, two years post chemical recovery in 302N and the Finescale Dace recovered in lake 302S two years prior to the year of chemical recovery. On average, the Finescale Dace also required more than one pH unit between time of initial impact (5.3) and re-establishment (6.5) to recover averaged across all lakes.

Lake Chub (*Couesius plumbeus*)

The average pH in lake 223 when Lake Chub were present was 6.2, whereas the species was never present in the other two lakes. It disappeared from the lake at a pH of 5.6 in 1980 and did not reestablish until 1994 when the pH hit 6.6. It took 3 years post chemical recovery for the Lake Chub abundance to recover in lake 223, again with a pH unit difference of one.

Northern Pearl Dace (*Margariscus margarita*)

The Northern Pearl Dace was present at all times throughout the acidification experiment. At times when their CPUE dropped below 0.5, the pH averaged 6.0 in lake 223 (Years 1976, 1977, 1981, 1996, 1997, 2004, 2001, 2012), 5.4 in lake 302N (Years 1993, 1994), and their CPUE was never low enough in lake 302S. The average pH for when Northern Pearl Dace were present at an average pH of 6.1 in lake 223, 5.5 in lake 302N and 5.5 in 302S. Since the Northern Pearl Dace was present at all times of the experiment, there was no need for biological recovery of the species. This was the only species observed to have not been affected as negatively as the others by the acidification events in each lake and is reflected by their spike in abundance when the pH reaches some of its lowest points (Figures 6, 7, 8).

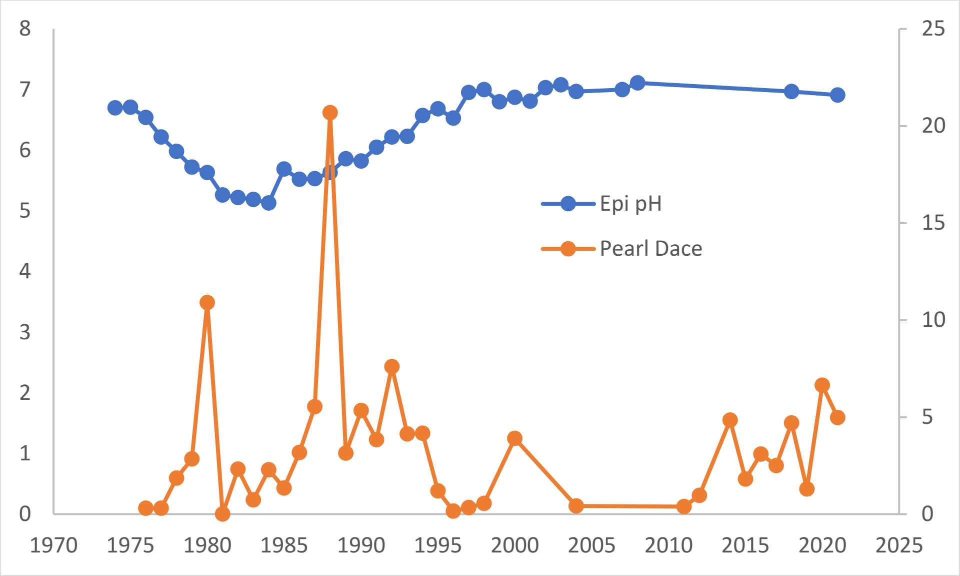

Figure 6. Northern Pearl Dace abundance in relation to changes in epilimnion pH changes in lake 223.

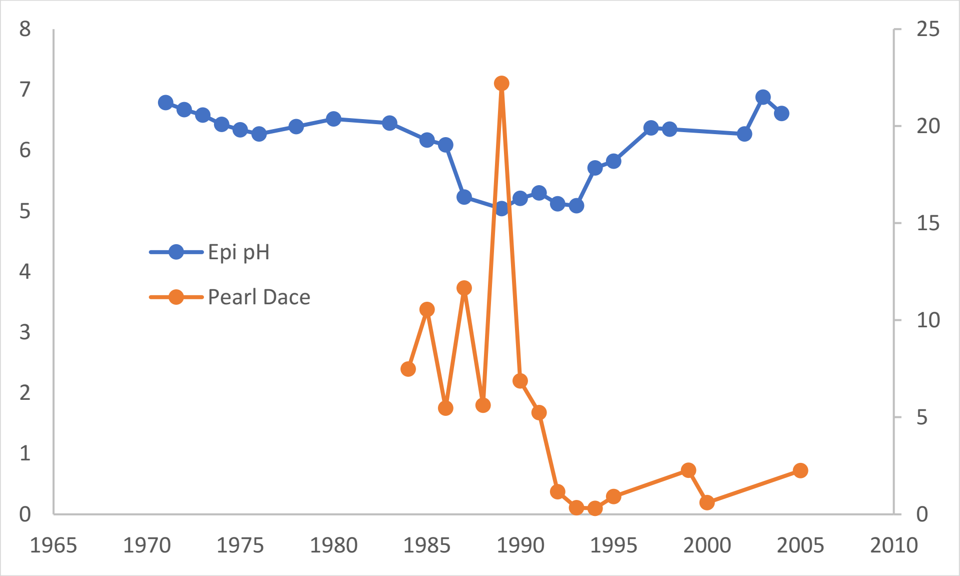

Figure 7. Northern Pearl Dace abundance in relation to changes in epilimnion pH changes in lake 302N.

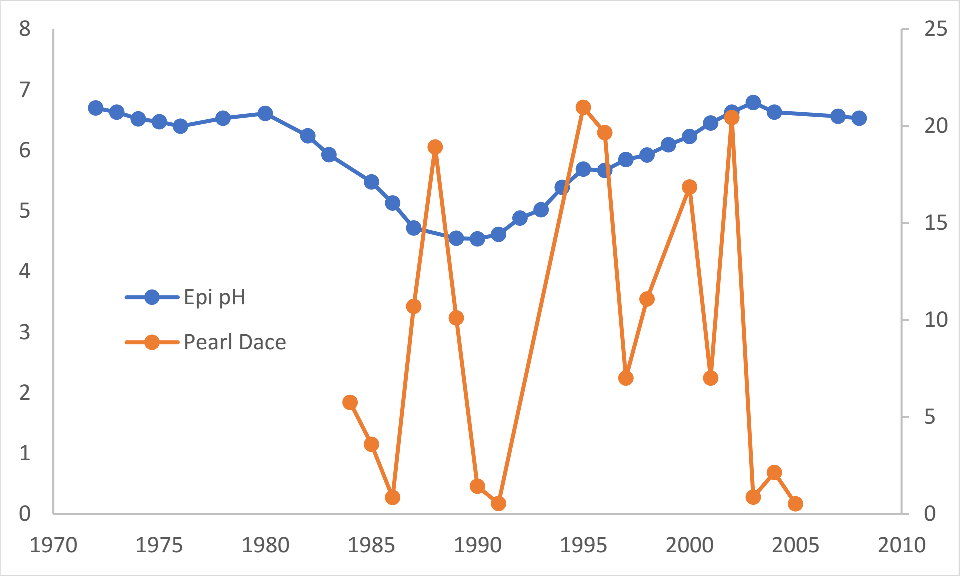

Figure 8. Northern Pearl Dace abundance in relation to changes in epilimnion pH changes in lake 302S.

Northern Redbelly Dace (*Chrosomus eos*)

The Northern Redbelly Dace was not present in lake 223, but it disappeared from lake 302N in 1987 at a pH of 5.2 and from lake 302S in 1984 at a pH of 5.5. Northern Redbelly Dace eventually reestablished in lake 302S in 2001 at a pH of 6.5 and did not recover in 302N over the period monitored (last sampled in 2005). It took two years post chemical recovery for the Northern Redbelly Dace to reestablish in lake 302S. Biological recovery in lake 302S took place two years post chemical recovery with a full pH unit (6.5) above time of extirpation (5.5).

Slimy Sculpin (*Cottus cognatus*)

When Slimy Sculpin were extirpated from lake 223, the average pH of those years was 6.2 (5.9 in the hypolimnion), and 6.1 (6.2 in the hypolimnion) when they were present. In 302N they were absent at an average pH of 5.5 (5.8 in the hypolimnion), and present at a pH of 6.0 (5.9 in the hypolimnion). Their period of biological recovery in lake 223 was from 1983 to 2019, with a pH ranging from 5.2-6.8 during that time, they have not yet reestablished in lakes 302N and 302S since we have stopped monitoring them (Figures 9, 10, 11). The gap between chemical recovery and biological recovery in lake 223 was 28 years. The average pH of extirpation across all three lakes was 5.3. Lake 223 was over 15 times more acidic when Slimy Sculpin was extirpated than when they were able to re-establish.

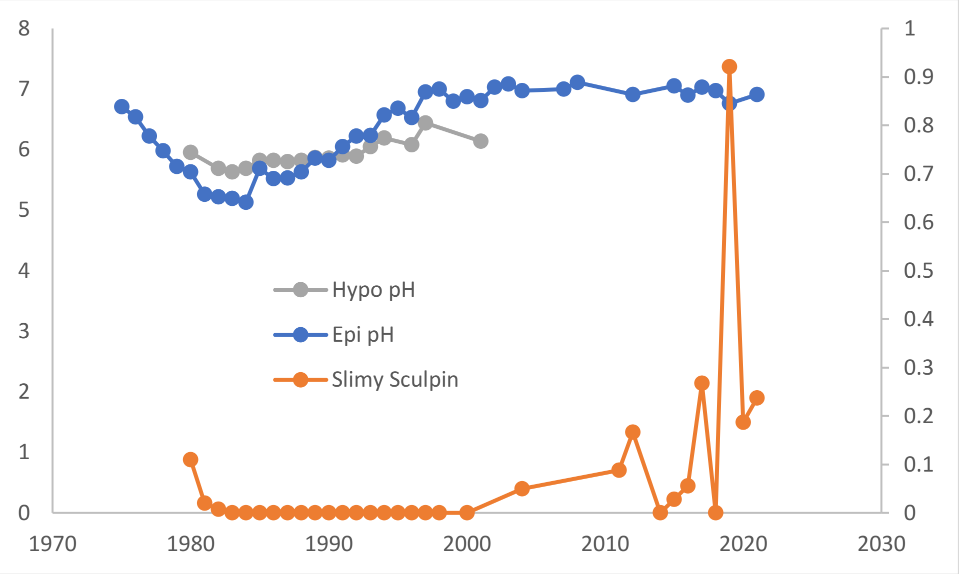

Figure 9. Slimy Sculpin abundance in relation to changes in epilimnion and hypolimnion pH changes in lake 223.

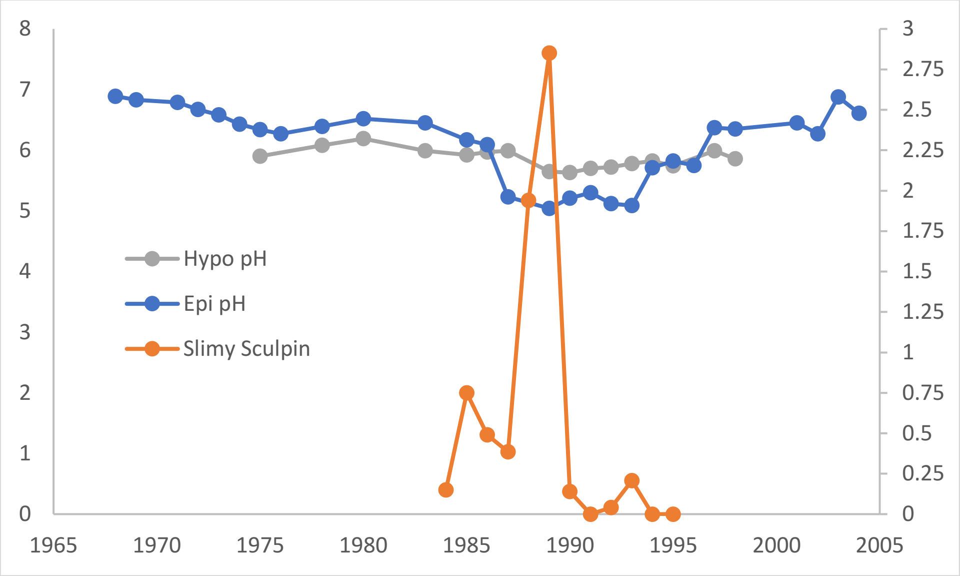

Figure 10. Slimy Sculpin abundance in relation to changes in epilimnion and hypolimnion pH changes in lake 302N.

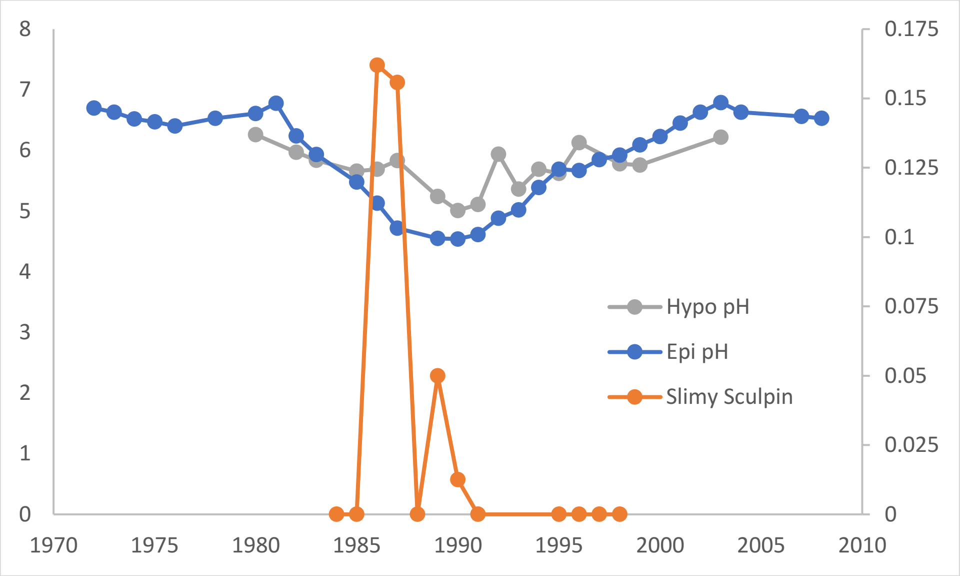

Figure 11. Slimy Sculpin abundance in relation to changes in epilimnion and hypolimnion pH changes in lake 302S.

The average pH when the observed fish species were absent across all lakes was 5.6, while the average pH of when the species were present was 6.0. The average pH of all species in lake 223 when absent was 5.9. In lake 302N, the average pH when the observed species was absent was 5.5, and in 302S it was 5.4. The average pH of lakes 223, 302N, and 302S when the fish were present were 6.4, 5.7, and 5.8 respectively. There was also a trend that the pH was higher in the fall when the observed species was sampled and deemed absent or present, meaning the species seemed to be more tolerant in the spring (Table 2). Species present in lake 302N and lake 302S tolerate lower pH levels before disappearing, likely due to other ecosystem aspects not explored in this study.

DISCUSSION

The goal of this study was to confirm whether acidic deposition in a lake would correlate to a decline in small-bodied fish populations. Based on my findings, I can conclude that this is generally true for many small-bodied fish populations. Some of the studied species seemed to be more sensitive to changes in water chemistry than others, while one particular species seemed to be less impacted by the acidification experiment.

Much of the literature simply makes mention that when lake pH levels increase post-acidification, that fish recovered (Clair et al. 2001, Gunn & Mills 1998, Yan et al. 1995). However, in my analysis I noticed that there was a gap between when the lake would chemically recover and biologically recover. Chemical recovery is the point post-acidification where the pH reaches and tends to stabilize at 6.0 or greater when pH begins to rise during recovery (Driscoll et al. 2001). Biological recovery I defined as when fish began to reappear and stabilize in a lake with a CPUE of 0.5 or higher for 2 or more years. In lake 223, we see that every fish aside from the Fathead Minnow reestablished far later than the point of chemical recovery. Lake 302N saw chemical recovery in 1997, and we have yet to see recovery of Northern Redbelly Dace and Slimy Sculpin. The species that did recover in lake 302N also recovered later than 1997. Finally in lake 302S, the Finescale Dace and Fathead Minnow recovered prior to chemical recovery, while the Slimy Sculpin has not recovered at all. Since it took nearly 30 years between chemical recovery and the recovery of the Slimy Sculpin in lake 223, it is possible that we may see recovery of this species in the coming years, as we are too soon for that 30-year mark in 2024. Biological recovery is not widely understood and may take place over many years (Driscoll et al. 2001, Lacoul et al. 2011).

Five of the seven species observed in this study had graphs that followed the same trend as the Fathead Minnow (Figures 3, 4, 5). The abundance of the species falls off to extirpation, zero, when pH values drop, and the lake becomes more acidic. We then see pH levels begin to rise and eventually stabilize during chemical recovery. Often, the recovery and re-establishment of fish species follows later than the initial point of pH stabilization (Driscoll et al. 2001, Lacoul et al. 2011). This reinforces the fact that acidic conditions are detrimental to fish species.

The Slimy Sculpin typically resides in the hypolimnetic layer of the lake, below the epilimnion where the other species we looked at reside (Mohr 1985). When these acidification experiments took place, the hypolimnetic pH was measured alongside the epilimnion. These recordings show that when the pH of the epilimnion changed, the pH of the hypolimnion was not as affected, and actually remained fairly stable throughout the acidification period. Regardless of this fact, the Slimy Sculpin still faced extirpation when the epilimnion pH dropped. This, paired with their long recovery period leads me to believe that the Slimy Sculpin is much more sensitive than originally thought. A potential explanation for this could be that the Slimy Sculpin will traverse into the epilimnion layer during breeding seasons, to feed, or when the lake is frozen in winter temperatures, exposing them to these lower pH values (Mohr, 1985). This could also explain why we were able to capture many of them in the set trap nets. There is not a lot of literature regarding pH changes in the epilimnion vs. hypolimnetic lake layers; However, based on the literature that states that lakes become more transparent with acidity (Freedman 2018, Keller et al. 2006, Mohr 1985), the hypolimnion warms to greater temperatures which could be attributed to the decline of the Slimy Sculpin.

The other anomaly in my results was the abundance of the Northern Pearl Dace. Much of the literature, and Mills' experiment (2000) determined that the threshold value when Northern Pearl Dace are no longer viable is around the pH of 5.1. In my analysis, this was not the case. In fact, Northern Pearl Dace seemed to do well in the acidic conditions in every lake, their abundance rising as pH dropped. This could be attributed to other factors such as reduced prey competition and competition for other resources in the lake, as well as less risk of predation (Driscoll et al. 2001, Lacroix et al. 2011). Observed in my study, the survivability of Northern Pearl Dace in acidic conditions did not conform to the published literature (Mills 2000), and thus, would be interesting to study in more detail. Furthermore, it is possible that, like the studies on algae (Hellström 2012) and zooplankton (Lacoul et al. 2011, Schindler et al. 1985), larger fish that prey on the Northern Pearl Dace could still have faced extirpation because although Northern Pearl Dace abundance went up, their quality as a food source was no longer suitable for predators, having effects on multiple trophic levels in the aquatic ecosystem.

I would also like to acknowledge that due to the length of time required for data collection from this experiment, some information may have been incomplete, which is unlikely to have cause major changes; however, could have impacted some of my results. In future research I would suggest ensuring pH measurements for all years be completed and recorded for both the epilimnion and hypolimnion lake layers. This would give us a clearer image on the chemical composition of each lake and allow complete pH averages to determine potential concrete threshold limits of certain fish species.

CONCLUSION

The recovery of an aquatic ecosystem has two phases of recovery: chemical recovery and biological recovery. These two phases don’t necessarily complete at the same time, as proven by the gap between pH recovering to a value of 6.0 or greater, and when the small-bodied fish I observed reestablished.

We were able to determine through this study that the consensus in the literature of fish surviving at a pH of 6.0 or greater to be true, as the average pH across all three lakes when the observed small-bodied fish were present aligned with this threshold exactly. The approximate difference between pH that fish can tolerate is 0.4, meaning that fish abundance is likely to decline if the water becomes four times as acidic as their pre-acidification water chemistry. I can also conclude that fish species do generally begin to decline once a lake becomes acidic at a pH of 6.0 or less. Although many species become extirpated during periods of acidification, there is the possibility of recovery once conditions improve.

Some suggested future research stemming from the findings of this study are to investigate why Slimy Sculpin are so sensitive to epilimnion pH changes when the hypolimnetic pH is not as affected, and whether light penetration and hypolimnion temperatures may contribute to this. It would be interesting to observe the survivability of Northern Pearl Dace in acidic conditions further. Finally, I would recommend evaluating and observing the proposed threshold values from various studies further, as they were not supported by my results, therefore they can not be absolute.

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