Decreasing mortality rates in Northern Pike (*Esox lucius*) influences average length and abundances of populations in Northern Wisconsin fisheries.

BIOS 35502-01: Practicum in Field Biology

Matthew Warren

Advisor: Colin Dassow

2019

ABSTRACT:

Fisheries are inherently difficult to manage to meet the diverse needs of anglers they serve. Northern pike (*Esox lucius*) are a popular sport fish in the Northern United States and are ecologically and economically important to the freshwater ecosystem as an apex predator. With the increasing popularity of catch and release fishing, there is concern for the health of the freshwater fisheries of northern Wisconsin with stunting of growth because of increased density in populations of fish. Northern pike were sampled from Morris Lake on the Wisconsin Michigan border and their total length was measured as well as scale samples used to age each organism with the use of scale annuli. This data set was used to form a Von Bertalanffy growth curve. Growth parameters were used to inform a northern pike population model that simulates individual fish growth over the course of the fish's life. This model was tested against varying growth rate responses to changes in fish density and mortality to find the ideal mortality rate for maximum northern pike length and abundance. It was found that there is a significant difference in fish length in relation to increased mortality rates in simulated populations with varying levels of sensitivity in the population. Average fish size at a given age was inversely related to fish density. This property of fish populations can be used to the benefit of managers who either seek to balance fish size and density in a single population or provide a buffet of management options where different populations are managed differently to meet diverse angler desires

KEYWORDS: northern pike, *Esox lucius*, catch and release, Wisconsin fisheries, Michigan fisheries, Von Bertalanffy, fish mortality, fish populations, sustainability

INTRODUCTION:

Fisheries are inherently difficult to manage and require consideration of both the ecological and social systems when working for conservation of these aquatic biomes (Cox and Walters 2002). In order to balance the diverse needs of anglers, managers of recreational fisheries have used regulations to promote harvest or catch-and-release (CR) ethics on a species and system-specific basis to prevent overfishing. Reaching release rates upwards of 95% for some northern Wisconsin species, CR fishing has grown substantially in the United States, (Hanson et al. 2015; Shaw et al. 2019). With new CR behaviors, some have found the mortality rate of fish has lowered and the density-dependent effects on fish growth have risen causing stunting of fish growth (Gilbert and Sass 2016). However, others have found that the growth rate does not slow as shown in Lorenzen and Enberg (2002). While well intentioned, CR can cause long term harm to fisheries as density of the fish populations increase. This counter-intuitive response by fish populations can alter food web dynamics and angler use of these systems.

Northern pike (*Esox lucius*) are a large, slow growing fish highly susceptible to over-harvest which has promoted the transition to CR fishing by conservation minded anglers. As a popular sport fish, northern pike are highly sought after for their aggressive behaviors and large size. As a piscivore and an apex predator, the density of the species affects the food web through a top-down control consuming young lake whitefish and other coregonids as well as their own species (Paragamian and Bennett 2008). Although some populations are aggressive and reach high densities, some populations have low densities with slow growth rate but increased lifespan and size of organisms. Thus, in these populations removal of a few organisms can be more than the biomass produced in one year in the specific ecosystem (Winter et al. 2001). Given their prevalence across the northern hemisphere and natural occurrence in Morris Lake, northern pike make an ideal model organism for exploring the density dependent effects of CR behavior of an apex predator.

Many factors can influence the growth and life history of aquatic apex predators, but for northern pike the quality and quantity of food are the most influential factors (Charnov et al. 2010). Northern pike exhibit indeterminate growth with a rapid growth period within the first year to survive the cold winter environment. After the first year, growth slows to allow for energy allocation to gonadal development, therefore requiring a surplus of energy over the cost of reproduction is required to grow past maturation (Kennedy et al. 2018). With natural selection favoring a high level of fitness, more energy dense and larger prey are desired as the foraging cost increase (Daniel et al. 2016). This increase is because of the ratio of predator size to prey size increasing, aquatic predators like northern pike need larger prey to avoid energetic bottlenecks and stunting (Kaufman et al. 2006). With an increase in predator density with CR fishing, this could lead to stunting of northern pike in the waters of Wisconsin where these fish are valued for their large size.

In this study, I examine the life history of northern pike to create a growth model to estimate fish size and abundance at any age on north temperate lakes. By estimating the age of northern pike through non-lethal methods, this investigation describes the growth of northern pike through their lives in a population that experiences solely CR fishing policies. This data creates a Von Bertalanffy growth curve with growth rates and limits used to inform a population model. This population model tests various levels of fishing mortality and its effect on fish population abundance and length of individual fish. The levels tested are a percentage of mortality with various effects of response to the mortality. The specific hypothesis being tested is that the increased northern pike density at low levels of fishing mortality (CR fishing) results in smaller sized individuals at a given age when compared to populations with higher levels of fishing mortality (partial harvest).

METHODS:

This study was carried out at the University of Notre Dame Environmental Research Center on the border of Michigan and Wisconsin, and consists of 7500 acres of land, containing 30 lakes and bogs. All fish samples were obtained from Morris Lake on the northern edge of the property. Morris Lake is a small (14.64 acres of surface area), eutrophic lake on the northern side of the UNDERC property. The lake varies in depths 0 to 6.7m and is surrounded by alder and evergreen trees. This lake is used recreationally utilizing a CR policy and is rarely fished throughout the year. The lake also has beaver lodges and is known to contain northern pike and an abundance of yellow perch.

Northern pike were captured using fike nets (20-mm stretch mesh, 12.5-m main lead and 7.5-m side leads, 1.3-m x 1.3-m frame, 0.95-m diameter hoops) for four weeks. When captured, the total length (mm) or the length of a fish measured from the tip of the snout to the tip of the longer lobe of the caudal fin with the lobes compressed along the midline was measured. The anal fin was clipped with scissors to prevent double counting as it is the fin that least affects movement within a fish (Kornis et al. 2016). Scales were removed using forceps from each live fish in order to age the organism outlined in Schneider 2001. The scales were removed above the lateral line behind the head on the left side and placed in labeled coin envelopes. The scales were then dried and mounted under a dissection scope where they were aged by measuring and counting the scale annuli. Two individuals aged each scale and its annuli to eliminate potential error.

Once the four-week collection period is over, I ran a statistical analysis through an open source program R studio. Difficulties in catching a wide range of fish sizes necessary to fit a von Bertalanffy growth curve required the addition of supplementary data from the Wisconsin Department of Natural Resources (Benike 2004). Using the combined data sets, a von Bertalanffy growth model was formed to a logistical curve to the discreet age and continuous length of the northern pike (Bertalanffy 1938). A population model was informed using the von Bertalanffy coefficients and run over a range of simulated fishing mortalities. This population model allows us to explore the effects of different levels of fishing mortality on northern pike populations in ways that are not feasible, because of the yearly time scales northern pike populations operate. Key parameters in the model were allowed to vary in order to include stochastic variation in fish growth and mortality observed in the wild. The upper asymptotic fish length, fish growth coefficient, and natural mortality were randomly drawn each year of the simulation from a normal distribution centered on the means calculated from field data. This stochastic function allows for a more natural model to better fit the field population. Because the amount that growth rate K fluctuates is unknown when affected by changes in the fish population density, the growth model was calculated with three varying ranges of sensitivity to fish mortality. 75% of K was the strictest parameters not allowing K to range far with increasing density allowing for the least amount of sensitivity for the northern pike population. 25% of K was the most liberal parameter allowing K to have a large range with the greatest sensitivity to mortality with increasing density.

Fishing mortality is our independent variable which was manipulated to simulate various levels of harvest on the population. The level of mortality was tested over three levels of response variables to determine the most impactful percentage of mortality a lake can obtain. These response variables were calculated from the Von Bertalanffy growth model and our K values, limits, and natural mortality were applied over a 100-year cycle in a 10-hectare sized lake. Our dependent variable is the response of the northern pike population to fishing mortality. I measured this response by recording fish abundance and the mean length across the fish populations with varying mortality. The effects of the mortality regulation were compared to determine if there is a significant difference in the abundance and size of fish with no mortality or high mortality with t-tests and ANOVA. The results were further investigated to determine the correct level or mortality to have the best catch per unit effort (CPUE) and largest size for sport in the fishery.

RESULTS:

When taking the Von Bertalanffy growth curve, our K value (growth rate) calculated was 0.31578. The amount K fluctuates when affected by changes in the fish population density is unknown. Therefore, the growth model was calculated with three varying ranges of sensitivity to fish mortality. K- (K*0.75) was the strictest parameters not allowing K to range far with increasing density allowing for the least amount of sensitivity for the northern pike population. K- (K*0.25) was the most liberal parameter allowing K to have a large range with the greatest sensitivity to mortality with increasing density.

Several two-factor t-tests were run amongst the highest level of mortality (71%) and the lowest (CR fishing 0%) while utilizing different sensitivity levels or K values in the fish population. For simplicity, I present the ages 1, 2, 4, and 5 for t-tests. Age 1 was chosen as this population is not in the fishery and is largely affected by birth rates of larger fish. Age 2 was chosen as it is the first-year fish enter the fishery and experience the effects of fishing. Ages 4 and 5 was chosen as larger fish sizes over the age of sexual maturity and the most likely to be fished for sport. Using an α 0.05, there was significant differences found in all the abundance of fish with different levels of mortality (**Table 1)**. There was a significant difference across lengths of northern pike with different mortality levels. Lengths of northern pike at age 4 were significantly different all but in the K- (K*0.75) trial (**Table 1**). Similarly, lengths of northern pike at age 5 were significantly different all but in the K- (K*0.75) trial (**Table 1**). The northern pike at age 1 and age 2 followed an expected pattern of growth as hypothesized with previous literature. Overall a higher mortality of older, larger northern pike leads to a low mortality of younger small fish. There was no difference in the models tested against varying growth rate responses to changes in fish density except in age 4 fish and age 5 fish at K- (K*0.75) trial. Using an ANOVA there was a significant difference found in the mortality rate in regard to fish abundance (**Table 2**). Using an ANOVA, it was found that there is a significant difference in the interaction terms of mortality percentage and the model as well as the model and mortality rate separately in each trial in regard to the length of the fish (**Table 3**).

The level of mortality of northern pike is most effective when it is at 45% mortality for age 2 fish populations (**Figure 7**). For age 4 fish populations, the level of mortality of northern pike is most effective when it is at catch and release level or 37% mortality (**Figure 8)**. The abundance of fish at age two under catch and release is 4.6 per hectare at 45% mortality (**Figure 7**). At age four, the most beneficial mortality is at catch and release level or 0% mortality as it allows for an abundance of 2 northern pike per hectare while any mortality above 45% is at near zero abundance.

DISCUSSION:

Our hypothesis proved true, that increased northern pike density at low levels of fishing mortality (CR fishing) results in smaller sized individuals at a given age when compared to populations with higher levels of fishing mortality (partial harvest). In every model of sensitivity level, it was shown that mortality affected the abundance or length of northern pike in populations (**Table 1**).

There are some outliers in the t-tests that do not fit the hypothesis like in the K- (K*0.75) trials where the lengths of age 4 and age 5 northern pike are not statistically different. This is most likely because of a lack in response to fish mortality in the K- (K*0.75) trials. These trials had the lowest sensitivity to fishing, which is expected. When the K range is increased there is a significant difference therefore, the only difference is the low sensitivity to changes in fish density. Further tests were run on these specific t-tests to see if the upper outliers in high abundance populations correlate to those outliers found in shorter length northern pike; however, no correlation was found within the specific data points (**Figure 4; Figure 5)**. Age 1 northern pike showed significant difference in their lengths and abundances across all growth models. This is likely because of rapid growth in the northern pike's first year as well as the cumulative effects of fishing seasons is not as present in a 1-year old fish as in a 2, 4 or 5-year-old as these fish are absent from the fishery. During the first year of development, northern pike grow to avoid the gape of their predators in their aquatic biome (Margenau et al. 2003). The northern pike has also shown not to show signs of stunting until it reaches the age of three and over 457 mm (Diana et al. 1987).

When comparing the models across levels of sensitivity to increasing density, I found the models do not produce differing results. This was proven using an ad Hoc (Tukey) test on fish length with increasing mortality rates. Ideally, it would make sense for a greater sensitivity to have a difference in the size of northern pike in older age fish when compared to the less sensitive northern pike populations. For example, the K- (K*0.25) model should have significant differences in sizes between the two levels of mortality because the population is more sensitive to changes in fish density. This is also true that K- (K*0.75) model should not show significant differences in sizes between the two extremes of mortality because the population is less sensitive to change. However, our model results suggested that this is false, there is not a difference in significance found across the various models of sensitivity to fish mortality except at age 4 and age 5 lengths (**Table 1**).

The study presented here has some limitations. The first of which is the lack of northern pike collected in Morris Lake. Unfortunately, there were not enough collected so it was necessary to supplement the data from Wisconsin DNR surveys, but this can easily be overcome with greater resources and methods like electrofishing (Benike 2004). Morris lake is also a rarely used recreational lake when compared to many Wisconsin recreational fisheries so that could have affected our data analysis when supplementing with data points from more heavily targeted fisheries. The three models were also used as an estimation for the true reaction and sensitivity to fish mortality. In the future, it would be necessary to calculate the actual K value found in the northern pike populations of each lake. However, to do this in the field requires multiple lake locations with different fishing mortalities or long-term data for one lake with different fishing mortality over a long period of time. In the future, the model could also alter fish populations by including size selective removal of fish by anglers and age specific natural mortality rates. This would improve the general rate of mortality applied to all fish in the population studied. The model also doesn't take into account the sheer number of Yellow Perch (*Perca flavescens*) found within Morris Lake when compared to any other species. As an apex predator, the northern pike in Morris Lake would perhaps have a greater density problem with Yellow Perch than intraspecies competition. In the future it would be interesting to fluctuate the density of Yellow Perch and see how that affects the abundance and length of northern pike at various ages and percentages of mortality. It would also be interesting to see how the enforcement of various fishing regulations of northern pike affect their populations across the jurisdiction. For example, Wisconsin has three levels of regulation for northern pike ranging from a bag limit of 5 fish of any size to a limit of 660 mm and a bag limit of 2 fish (Wisconsin DNR, 2019). According to Margeneau et al 1998, the northern pike increases rapidly in length the first two years, but in the third year as the organism enters sexual maturity, there is faster growth in the overall girth of the organism when compared to its length. Therefore, the weight or the girth of each fish should also be recorded and compared as the fish ages if I want to compare the stunting of the organism as a whole. These measurements would be more invasive and ultimately lack interest in the angling population but are imperative to fully understand the northern pike's growth rate in a more holistic view.

In conclusion, our hypothesis was true, the lower the fish mortality in a northern pike population, the smaller the fish appear due to the density dependent effects of fish growth. There were, however, a few deviations most likely because of the stochasticity of our model with the upper asymptotic fish length, fish growth coefficient, and natural mortality which reflect how these systems actually behave. There was no difference between the models observed in varying levels of sensitivity leading our population model to be sufficient in determining an appropriate level of mortality. This information can be used to explore new management options which may increase CPUE and average fish size for northern pike recreational fisheries in Northern Wisconsin and the Upper Peninsula of Michigan.

FIGURES:

	1-(K*0.25)	1-(K*0.50)	1-(K*0.75)
Abundance 1 Year	<0.00001*	<0.00001*	<0.00001*
Length 1 Year	<0.00001*	<0.00001*	<0.00001*
Abundance 2 Year	0.001218*	0.000359*	0.003353*
Length 2 Year	0.001943*	0.0000953*	0.007792*
Abundance 4 Year	0.0008564*	0.00004252*	0.00006092*
Length 4 Year	0.0005713*	0.01464*	0.1213
Abundance 5 Year	0.0001257*	0.00009532*	0.002369*
Length 5 Year	0.00005282*	0.008954*	0.3353

Table 1: T-tests comparing catch and release and 71% mortality rates in northern pike simplified P values.
A T-test was compared between a catch and release mortality rate of 0% and a 71% mortality rate. This t-test was run with three levels of sensitivity to the K factor of growth rate with 0.75 being the least sensitive and 0.25 being the most sensitive to mortality. The test was run on an abundance model and a growth model of northern pike fish populations. When compared to an α ($P<0.05$) significant difference is shown with asterisks.

	Df	Sum Sq.	Mean Sq.	F value	Pr(>F)
Age 1: Mortality	1	253421	252421	2982.275	<0.0001*
Age 1: Model	2	5	3	0.031	0.969
Age 1: Mortality:Model	2	5	3	0.031	0.970
Age 1: Residuals	594	25591	43.1		
Age 2: Mortality	1	1455	1454.8	33.766	<0.0001*
Age 2: Model	2	31	15.6	0.362	0.697
Age 2: Mortality:Model	2	31	15.6	0.361	0.697
Age 2: Residuals	594	25591	43.1		
Age 4: Mortality	1	253421	253421	2982.375	<0.0001*
Age 4: Model	2	5	3	0.031	0.969
Age 4: Mortality:Model	2	5	3	0.031	0.970
Age 4: Residuals	594	50474	85		
Age 5: Mortality	1	1455	145.8	33.766	<0.0001*
Age 5: Model	2	31	15.6	0.362	0.697
Age 5: Mortality:Model	2	31	15.6	0.361	0.697
Age 5: Residuals	594	25591	43.1		

Table 2: ANOVA abundances comparing catch and release and 71% mortality rates in northern pike.

An ANOVA was compared between a catch and release mortality rate of 0% and a 71% mortality rate. This t-test was run with three models of sensitivity to the K factor of growth rate with 0.75 being the least sensitive and 0.25 being the most sensitive to mortality. The test was run on an abundance model and a growth model of northern pike fish populations. When compared to an α ($P<0.05$) significant difference is shown with asterisks

	Df	Sum Sq.	Mean Sq.	F value	Pr(>F)
Age 1: Mortality	1	3500996	350996	2797.1	<0.0001*
Age 1: Model	2	100351	50176	399.8	<0.0001*
Age 1: Mortality:Model	2	63602	31801	253.4	<0.0001*
Age 1: Residuals	594	74539	125		
Age 2: Mortality	1	3928	3928	31.674	<0.0001*
Age 2: Model	2	1078	539	4.345	0.0134*
Age 2: Mortality:Model	2	748	374	3.014	0.0499*
Age 2: Residuals	594	73669	124		
Age 4: Mortality	1	350996	350996	2797.1	<0.0001*
Age 4: Model	2	50176	50176	0399.8	<0.0001*
Age 4: Mortality:Model	2	31801	31801	253.4	<0.0001*
Age 4: Residuals	594	74539	125		
Age 5: Mortality	1	3928	31.674	31.674	<0.0001*
Age 5: Model	2	539	4.345	4.345	0.0134*
Age 5: Mortality:Model	2	374	3.014	3.014	0.0499*
Age 5: Residuals	594	73669	124		

Table 3: ANOVA lengths comparing catch and release and 71% mortality rates in northern pike.

An ANOVA was compared between a catch and release mortality rate of 0% and a 71% mortality rate. This t-test was run with three models of sensitivity to the K factor of growth rate with 0.75 being the least sensitive and 0.25 being the most sensitive to mortality. The test was run on an length model and a growth model of northern pike fish populations. When compared to an α (P<0.05) significant difference is shown with asterisks.

	1-(K*0.25)	1-(K*0.50)	1-(K*0.75)
Abundance 1 Year	<0.00001*	<0.00001*	<0.00001*

	t=-32.195	t=-33.062	t=-29.61
	df= 99.023	df=99.019	df=99.014
Length 1 Year	<0.00001*	<0.00001*	<0.00001*
	t=33.707	t=31.404	t=36.217
	df=99.678	df=100.83	df=110.89
Abundance 2 Year	0.001218*	0.000359*	0.003353*
	t=3.3307	t=3.6962	t=3.0061
	df=99	df=99	df=99
Length 2 Year	0.001943*	0.0000953*	0.007792*
	t=-3.1807	t=-4.0611	t=-2.7036
	df=102.72	df=103.21	df=127.91
Abundance 4 Year	0.0008564*	0.00004252*	0.00006092*
	t=3.4288	t=4.2844	t=4.1889
	df=99	df=99	df=99
Length 4 Year	0.0005713*	0.01464*	0.1213
	t=-3.5506	t=-2.4745	t=-1.5565
	df=107.67	df=128.66	df=183.45
Abundance 5 Year	0.0001257*	0.00009532*	0.002369*
	t=3.9924	t=4.0681	t=3.1201
	df=99	df=99	df=99
Length 5 Year	0.00005282*	0.008954*	0.3353
	t=-4.1834	t=-2.6453	t=-0.96608
	df=128.49	df=164.28	df=181.66

Table 4: T-tests comparing catch and release and 71% mortality rates in northern pike. A T-test was compared between a catch and release mortality rate of 0% and a 71% mortality rate. This t-test was run with three levels of sensitivity to the K factor of growth rate with 0.75 being the least sensitive and 0.25 being the most sensitive to mortality. The test was run on an abundance model and a growth model of northern pike fish populations. When compared to an α (P<0.05) significant difference is shown with asterisks.

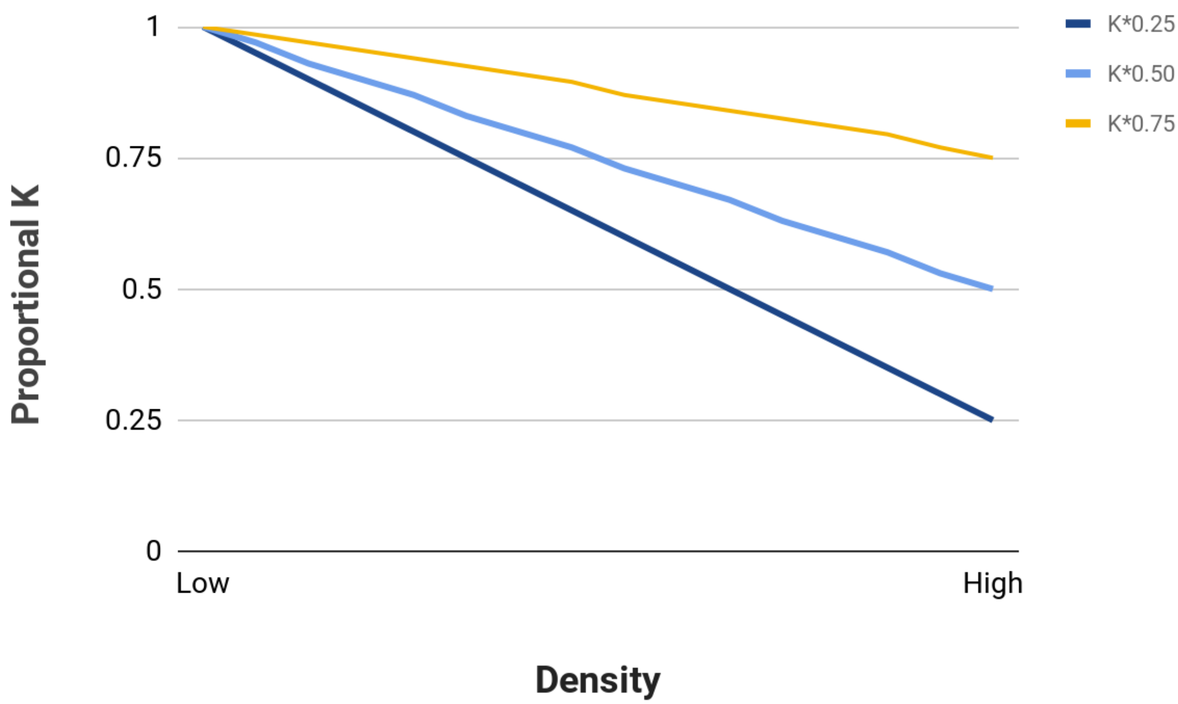

Figure 1: The growth factor of northern pike over differing sensitivities to fish mortality in the population.
Theoretical graph of K value with its range of sensitivity to levels of northern pike mortality rates. K*0.25 is the most liberal interpretation which responds with the greatest sensitivity for northern pike mortality causing the greatest effect as density increases. K*0.50 is a moderate interpretation allowing for moderate sensitivity to the mortality rates while K*0.25 is the strictest interpretation allowing for the lease sensitivity to increasing mortality when compared to increasing density.

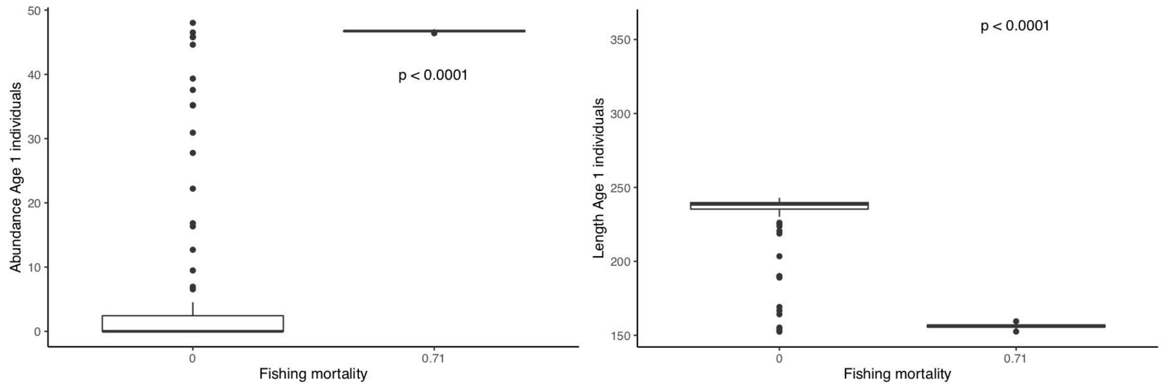

Figure 2: Abundance and Length of Age 1 northern pike (*Esox Lucius*) with K=0.25 with t-test compared between 0% and 71% mortality rates.
A T-test was compared between a catch and release mortality rate of 0% and a 71% mortality rate. This t-test was run with K*0.25 sensitivity growth rate. The test was run on an abundance model and a growth model of northern pike fish populations. When compared to an α (P<0.05). There is a significant difference in abundance or length in high and low mortality populations.

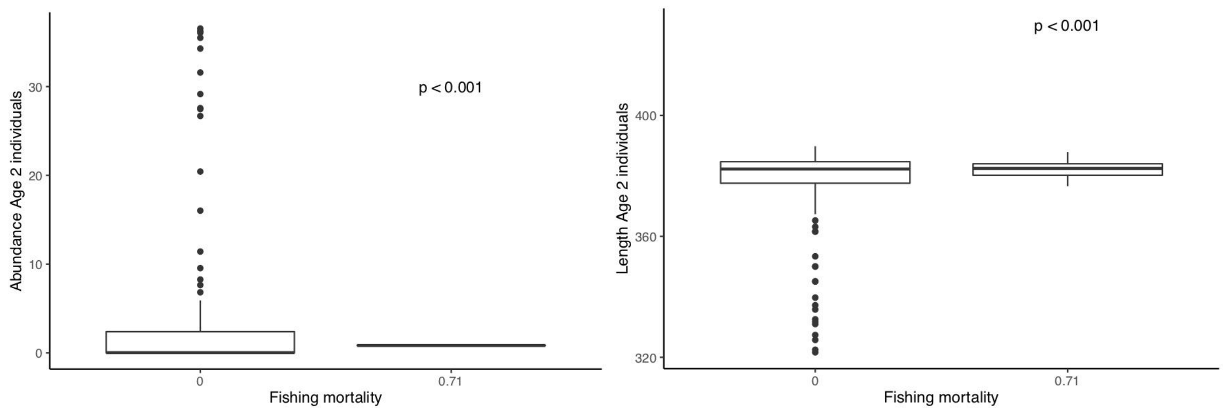

Figure 3: Abundance and Length of Age 2 northern pike (*Esox Lucius*) with K=0.50 with t-test compared between 0% and 71% mortality rates.
A T-test was compared between a catch and release mortality rate of 0% and a 71% mortality rate. This t-test was run with K* 0.50 sensitivity growth rate. The test was run on an abundance model and a growth model of northern pike fish populations. When compared to an α (P<0.05). There is a significant difference in abundance or length in high and low mortality populations.

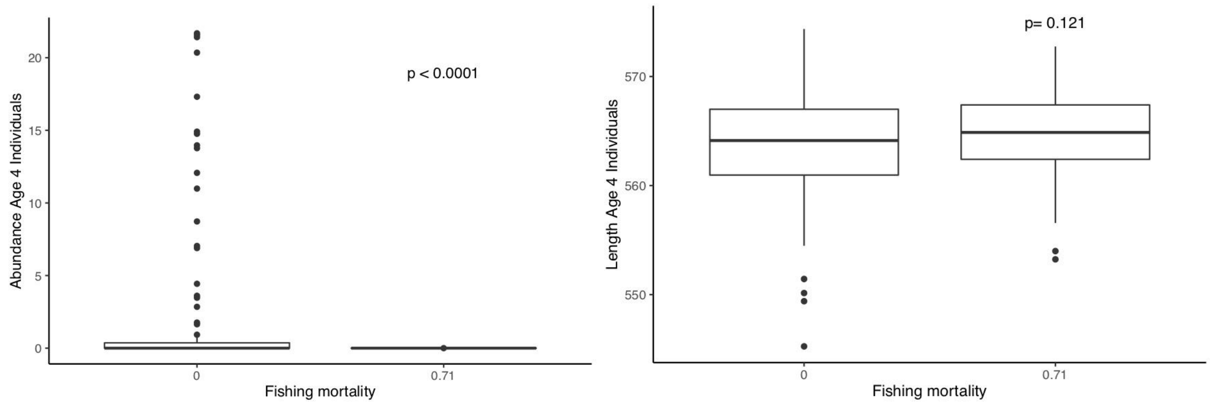

Figure 4: Abundance and Length of Age 4 northern pike (*Esox Lucius*) with K=0.75 with t-test compared between 0% and 71% mortality rates.
A T-test was compared between a catch and release mortality rate of 0% and a 71% mortality rate. This t-test was run with K* 0.75 sensitivity growth rate. The test was run on an abundance model and a growth model of northern pike fish populations. When compared to an α (P<0.05). There is no significant difference in abundance or length in high and low mortality populations.

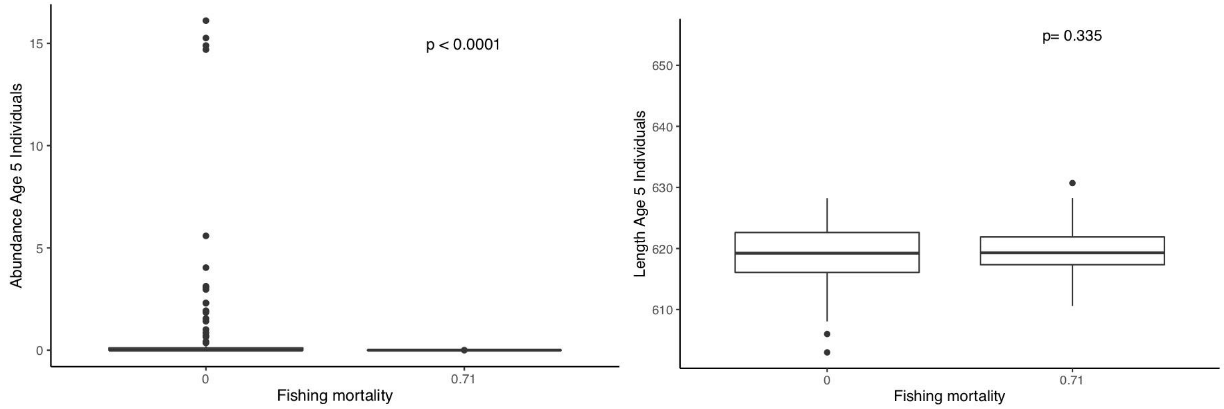

Figure 5: Abundance and Length of Age 5 northern pike (*Esox Lucius*) with K=0.75 with t-test compared between 0% and 71% mortality rates.
A T-test was compared between a catch and release mortality rate of 0% and a 71% mortality rate. This t-test was run with K* 0.75 sensitivity growth rate. The test was run on an abundance model and a growth model of northern pike fish populations. When compared to an α (P<0.05). There is no significant difference in abundance or length in high and low mortality populations.

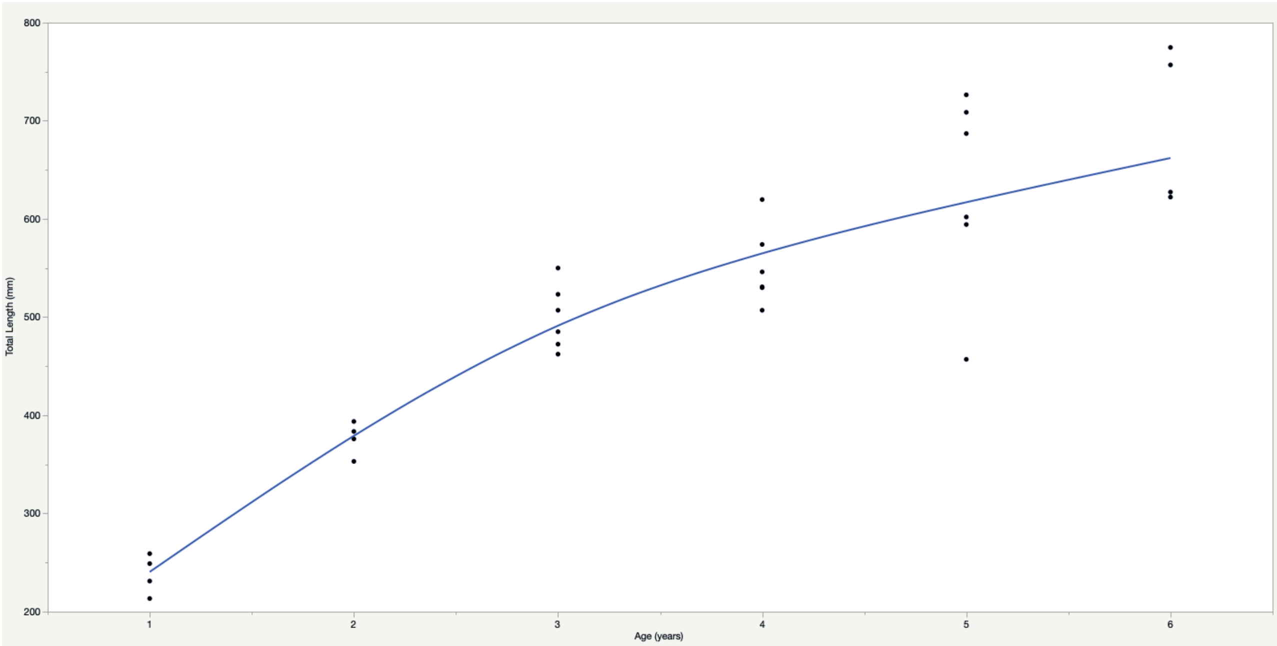

Figure 6: Von Bertalanffy growth curve for northern pike (*Esox lucius*) in northern Wisconsin fisheries.

The growth curve of northern pike when total length (mm) is compared to discrete age (years). From this model the upper asymptotic fish length, fish growth coefficient, and natural mortality were randomly drawn each year of the simulation from a normal distribution centered on the means were calculated from the field data. The data was supplied from Morris lake in Land O'Lakes Wisconsin and from the Wisconsin DNR database.

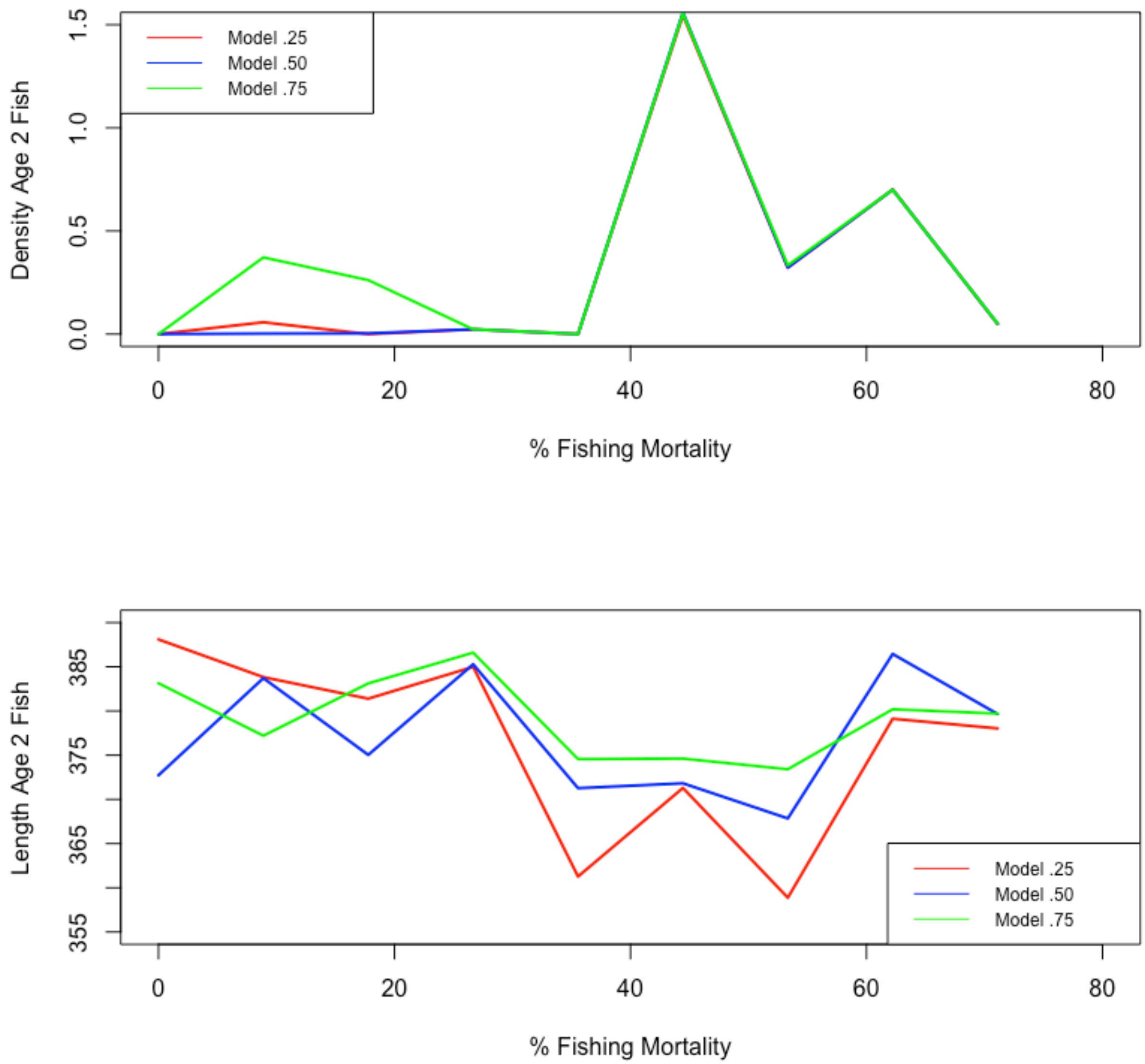

Figure 7: The abundance and length of age 2 northern pike (*Esox lucius*) populations with increasing mortality rates across three levels of sensitivity of growth rate (K) to increasing density.

The northern pike population reactions to increasing mortality rates across various growth models. The ideal mortality rate for a low CPUE and long length is at 43% because of increased abundance. The length fluctuates more than 30 mm providing a greater benefit to sport anglers.

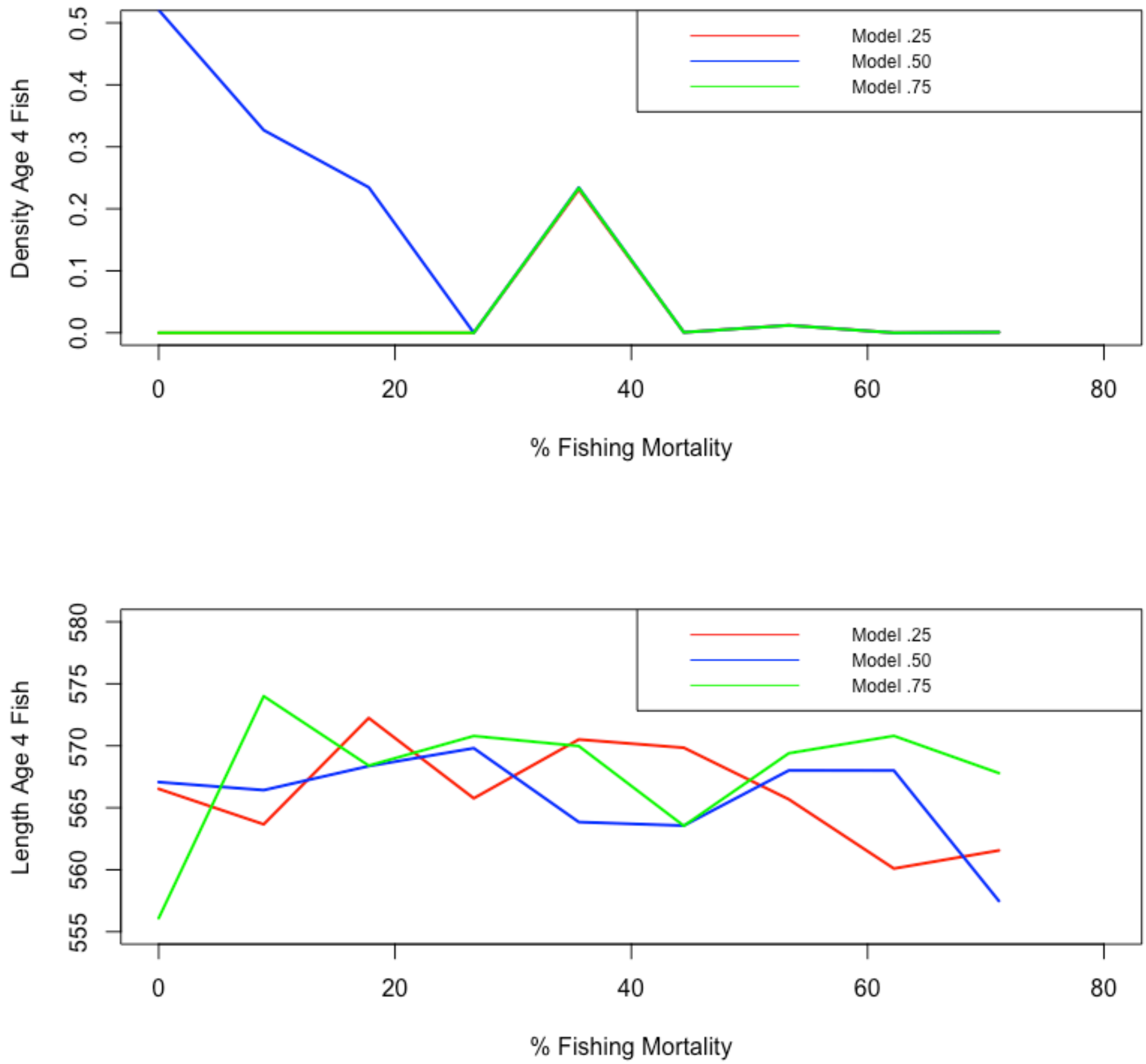

Figure 8: The abundance and length of age 4 northern pike (*Esox lucius*) populations with increasing mortality rates across three levels of sensitivity of growth rate (K) to increasing density.

The northern pike population reactions to increasing mortality rates across various growth models. The ideal mortality rate for a low CPUE and long length is at catch and release levels of mortality (0%) or at 37% because of increased abundance. The length never fluctuates more than 20 mm providing little benefit to sport anglers at such a large.

ACKNOWLEDGEMENTS:

I would like to thank Colin Dassow for his immense patience, support, guidance and counseling in the development and performance of this experiment. Big thanks to Matthew Gerber, Sylvie Martin-Eberhardt, Michelle Nowak, and Mark Ellman for their help with fike nets and fish population surveying in the field. I would also like to thank Dr. Michael Cramer, Dr. Garry Belovsky, and the rest of the UNDERC- East 2019 staff in always supporting mine and other students' projects. I would also like to thank Dr. Sean T. Berthrong, Dr. Shelley Etnier, and Dr. Carmen Salsbury at Butler University for nurturing and developing a love for our aquatic biomes and biological ecology studies. A final big thank you to the Bernard J. Hank Family Endowment for their funding which without, this study would not have been possible.

REFERENCES:

Arlinghaus, R., Mehner, T. & Cowx, I. G. Reconciling traditional inland fisheries management and sustainability in industrial countries, with emphasis on Europe. *Fish Fish.* **3**, 261–316 (2002).

Benike, H. M., & Region-Barron, N. (2004). Evaluation of a 32 Inch Minimum Length Limit for Northern Pike Largon Lake, Polk County, WI. MWBIC Code:(2668100).

Charnov, E. L. 2010. Comparing body-size growth curves: the Gallucci- Quinn index, and beyond. Environmental Biology of Fishes 88:293–294.

Cox, S. P., & Walters, C. (2002). Modeling exploitation in recreational fisheries and implications for effort management on British Columbia rainbow trout lakes. *North American Journal of Fisheries Management*, *22*(1), **22**, 21-34.

Daniel L. Oele, Andrew L. Rypel, John Lyons, Paul Cunningham & Tim Simonson (2016) Do Higher Size and Reduced Bag Limits Improve Northern Pike Size Structure in Wisconsin Lakes?, North American Journal of Fisheries Management, 36:5, 982-994, DOI: 10.1080/02755947.2016.1184199

Diana, J. S. (1987). Simulation of mechanisms causing stunting in northern pike populations. *Transactions of the American Fisheries Society*, *116*(4), 612-617.

Gilbert, S. J. & Sass, G. G. Trends in a northern Wisconsin muskellunge fishery: results from a countywide angling contest, 1964-2010. *Fish. Manag. Ecol.* **23**, 172–176 (2016).

Hansen, J. F. *et al.* Largemouth Bass Management in Wisconsin: Intraspecific and Interspecific Implications of Abundance Increases. *Black bass Divers. Multidiscip. Sci. Conserv.* **82**, 193–206 (2015).

Jackson, Jeremy BC, et al. "Historical overfishing and the recent collapse of coastal ecosystems." *science* 293.5530 (2001): **635**, 629-637.

Kaufman, S. D., J. M. Gunn, G. E. Morgan, and P. Couture. 2006. Muscle enzymes reveal Walleye (Sander vitreus) are less active when larger prey (Cisco, Coregonus artedi) are present. Canadian Journal of Fisheries and Aquatic Sciences 63:970–979.

Kennedy, P. J., Bartley, T. J., Gillis, D. M., McCann, K. S., & Rennie, M. D. (2018). Offshore prey densities facilitate similar life history and behavioral patterns in two distinct aquatic apex predators, northern pike and lake trout. *Transactions of the American Fisheries Society*, *147*(5), 972-995.

Kornis, M. S., Pankow, K. W., Lane, A. A., Webster, J. L., & Bronte, C. R. (2016). Factors Affecting Prestocking Coded Wire Tag Loss in Lake Trout Tagged by an Automated System. *North American Journal of Fisheries Management*, *36*(3), 670-680.

Lorenzen, K., & Enberg, K. (2002). Density-dependent growth as a key mechanism in the regulation of fish populations: evidence from among-population comparisons. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *269*(1486), 49-54.

Margenau, T. L., Rasmussen, P. W., & Kampa, J. M. (1998). Factors affecting growth of northern pike in small northern Wisconsin lakes. *North American Journal of Fisheries Management*, *18*(3), 625-639.

Margenau, Terry L., Stephen J. Gilbert & Gene R. Hatzenbeler (2003) Angler Catch and Harvest of Northern Pike in Northern Wisconsin Lakes, North American Journal of Fisheries Management, 23:1, 307-312, DOI: 10.1577/1548-8675(2003)023<0307:ACAHON>2.0.CO;2

Murphy, B. R., & Willis, D. W. (Eds.). (1996). *Fisheries techniques* (2nd ed., p. 483-512). Bethesda, Maryland: American Fisheries Society.

Paragamian, V. L., & Bennett, D. H. (Eds.). (2008). Burbot: ecology, management, and culture (Vol. 59). *Amer Fisheries Society*.

Schneider, J.C. 2001. Aging scales of walleye, yellow perch, and northern pike. Fisheries Technical Report 2001: 10-83.

Shaw, S. L., Sass, G. G. & Eslinger, L. D. Effects of Angler Harvest on Adult Muskellunge Growth and Survival in Escanaba Lake, Wisconsin, 1956-2016. *North Am. J. Fish. Manag.* **2**, 1–11 (2019). doi:10.1002/nafm.10260

University of Notre Dame. (n.d.). Lake Information // UNDERC // University of Notre Dame. Retrieved July 17, 2019, from https://underc.nd.edu/underc-east/the-environment/bathymetric-maps/

Von Bertalanffy, L. (1938). A quantitative theory of organic growth (inquiries on growth laws. II). *Human biology*, *10*(2), 181-213.

Winter, S. C., and P. J. May. 2001. Motivation for compliance with environmental regulations. Journal of Policy Analysis and Management 20:675–698

Wisconsin Department of Natural Resources. (2019). *Guide to Wisconsin Hook and Line: Fishing Regulations 2019-2020*.