Stock assessment of a commercially harvested northern pike (*Esox lucius*) population in Waterhen Lake, Manitoba

Tim Pellissier

Supervisor: Dr. Scott Forbes

A thesis submitted in partial fulfillment of the Honours Thesis Course (05.4111/6)

Department of Biology

University of Winnipeg

2012

Abstract

Manitoba Fisheries Branch is seeking to make Waterhen Lake the first northern pike fishery in the world to be ecocertified through the Marine Stewardship Council as a fully sustainable enterprise. Ecocertification carries numerous benefits for fishermen, the community, and the environment, but it is contingent upon one fundamental question: *is the fishery sustainable*? I addressed one aspect of that question by determining the age distribution of pike in Waterhen Lake, using opercular bones to estimate fish age. The resulting age structure, combined with data collected on sexual maturity and gill-net selectivity, was used to assess whether pike are vulnerable to harvest before they have an opportunity to reproduce, a typical sign of overfishing. I found that pike on Waterhen Lake appear to reach sexual maturity at a slightly younger age than expected, possibly in response to fishing pressure. The size of mesh used in gill-netting was a significant factor in the capture of smaller pike, but not larger pike. The mesh size regulations currently in place on Waterhen Lake were determined to be sufficient to protect pre-reproductive pike from the fishery. Finally, a strong correlation was found between operculum length and both fish length and mass.

Acknowledgments

I would like to thank Dr. Scott Forbes for giving me the opportunity to work with him this year, and for all his guidance and patience from start to finish. Thanks also to Geoff Klein for his invaluable contribution to this project, providing samples, data, advice and encouragement. I would also like to thank Dr. Jens Franck and Dr. Murray Wiegand for their much-appreciated advice and support throughout the year. Finally, thank you to Marianne Geisler, without whose unending supply of orange juice and good humour this project would not have been possible.

Table of Contents

List of Figures

List of Tables

List of Appendices

Introduction

Overfishing is a growing problem in both marine and freshwater fisheries worldwide (FAO, 2002), and the implementation of more sustainable fishing practices is considered essential to curbing this trend (Peterman, 2002). Globally, one of the largest promoters of sustainable commercial fishing practices is the Marine Stewardship Council (MSC), whose stated intent is to reward sustainable fisheries by providing them with a competitive advantage in the marketplace (MSC, 2011). Through MSC's eco-certification program, fisheries that satisfy a set of pre-determined criteria for sustainability are granted official certification from MSC in recognition of this fact.

The benefits of ecocertification to a fishery are considerable, in both the short and long term. The immediate economic advantages stem from a growing demand for sustainable products, and potentially include both a higher dollar-value for eco-labeled fish and an increased market share as suppliers and retailers move toward providing eco-certified products for their customers (Peterman, 2002). Long-term benefits include: 1) reduced likelihood of overfishing leading to a fishery collapse; 2) better ecological conditions not just for the fishery itself, but also for the surrounding ecosystem (Gulbrandsen, 2005); and 3) increased awareness of the certification process in particular, and sustainable development in general, among the public, potentially paving the way for certification of other fisheries in Manitoba.

Several important criteria for certification involve understanding basic demographic information about the target stock (MSC, 2010). This includes the age, size and sex structure of the population, as well as the age of maturity of the stock and the age of recruitment to the fishery (MSC, 2012). The fundamental aim of this project was to obtain this demographic information for northern pike *(Esox lucius*) in Waterhen Lake as a preliminary step toward the ecocertification of this fishery.

Growth & Recruitment Overfishing

Overfishing is a clear threat to the sustainability of any fish stock, and pike are no exception. However, "overfishing" is a broad and sometimes ambiguous term, and it is often more useful to break it down into a number of related but distinct concepts (FAO, 1996). Growth overfishing, for example, occurs when fishing intensity is too high to allow fish to grow to an ideal size before being harvested (Pauly, 1983). An "ideal" size can be defined as the size which maximizes overall harvest biomass, and is generally larger than the size at first maturity (Froese, 2004). In populations experiencing growth overfishing older and larger year-classes are absent, meaning that the fishery must either reduce its yield, or else rely solely on smaller, younger fish, which tends to reduce harvest biomass (Froese, 2004). Large females, in addition to being more commercially valuable than smaller fish, produce more and often higher-quality eggs than smaller females (Trippel, 1998; Raat, 1988) and are thus considered important in maintaining the reproductive capacity of the population.

Recruitment overfishing occurs when this reproductive capacity is not maintained. More specifically, it occurs when fishing mortality reduces the spawning population to the extent that not enough new fish are produced to regenerate the diminishing parent stock (Pauly, 1983). This type of overfishing can have serious consequences, including fishery collapse if left unchecked (Froese, 2004). The protection of sexually immature fish from harvest is considered an essential component of preventing recruitment overfishing, as any fish removed before it reaches spawning age will obviously not be able to contribute to the regeneration of the stock (Froese, 2004; FAO, 1996). In a modeling study, Myers and Mertz (1998) found that the likelihood of maintaining reproductive capacity significantly increased when all fish in a population were allowed to spawn at least once before being recruited into a fishery, and recommended that management policies should aim for this situation.

Various methods have been proposed for detecting recruitment overfishing before a fishery collapse. Froese (2004) proposed that the proportion of immature fish in the catch as well as declines in old, reproductively valuable age classes are useful indicators. Peterman (2002) suggested that population age structures can also serve as indicators of recruitment overfishing. Specifically, if the age structure of a population skews toward very young age classes over time, this can indicate a reduction in the spawning population and, depending on the age of maturity, possible pre-reproductive harvest (see also FAO, 1996). Thus, the age structure of a stock provides fisheries managers with a valuable metric for monitoring harvested stocks over time. An assessment of the age structure of northern pike on Waterhen Lake has not previously been carried out.

Life History

The northern pike is a valuable commercial and sport fish both in Manitoba and throughout the northern hemisphere (Stewart, 2004). It is the most widely distributed member of the *Esocidae* family, with managed populations throughout Europe, Russia and North America (Scott and Crossman, 1998). The species also plays a key ecological role as a top predator, and has been introduced as a control predator in eutrophic lakes (Berg *et al.*, 1997; Scott and Crossman, 1998).

Spawning tends to take place soon after ice melts in April or early May, in water temperatures ranging from 6 to 14 degrees Celsius (Raat, 1988). Spawning behaviour involves a series of repeated mating acts (Fabricius and Gustafson, 1958) in shallow, vegetated areas (Frost and Kipling 1967). The spawn are not subsequently guarded, and mortality is very high throughout the larval stage, first growing season and first winter (Raat, 1988; Scott and Crossman, 1998). Hatchlings are susceptible to predation by insects and larger predatory fish, including other pike (Craig 2008). Frost and Kipling (1970) noted that cannibalism could play a large role in pike population dynamics, as smaller pike are more likely to be cannibalized in high-density populations. Growth occurs rapidly during the first several growing seasons, but slows after the onset of sexual maturity as energy allocation shifts from somatic to gonadal growth (Scott and Crossman, 1998).

The age of onset of sexual maturity in pike is a variable trait, and is affected by several factors (Raat, 1988). There is strong evidence for a general effect of latitude, as southern populations frequently mature earlier than northern populations. As latitude increases, growing-degree days per year tend to decrease, resulting in slower growth rates and later maturity (Scott and Crossman, 1998; Frost and Kipling, 1967). Mature one-year-olds, for example, are common in Texas, Missouri and Kansas (Inskip, 1982), while in northern Russia or the Northwest Territories maturity is usually delayed until 5 years of age or later (Raat, 1988). The effect of other factors, particularly long-term fishing pressure, on maturity onset has been investigated (Diana, 1983; Raat, 1988) and a relationship between higher fishing mortality and lowered age of maturity was found.

Growth rate and longevity have also been correlated with latitude: northern populations have been found to grow slower and live longer than southern ones, implying that temperature plays a role in pike life history (Scott and Crossman 1998). Pike aged 10 years or older are not uncommon in Canadian populations (Scott and Crossman, 1998; Inskip, 1982) while populations in the mid- and southern United States often have a maximum age of just 4 years (Inskip 1982). Patterns in year-class strength are variable and generally unpredictable; Kipling and Frost (1970) found that the only reliable indicator of the strength of a given year class was temperature at the end of its first year of growth.

The operculum is the largest bone covering the gills of ray-finned fishes. Like several other calcified structures including scales, fin rays and cleithra, opercula develop annuli, or lines of visibly denser bone laid down in winter when the growth rate of pike slows dramatically (Scott and Crossman 1998). An estimate of the age of a pike can be obtained by counting these annuli. Frost and Kipling (1959) compared age estimates for pike from opercula and scales and concluded that opercular bones give a more reliable estimate of age. They subsequently used opercula to obtain age estimates for a series of studies on pike in Lake Windermere, England (Frost and Kipling, 1967; Kipling and Frost, 1970).

Project Goals

Five specific research questions were addressed in this study:

1) What are the age distributions of male and female northern pike in Waterhen Lake?
2) At what age do male and female pike in Waterhen Lake first reproduce?
3) What is the effect of varying gill-net mesh size on the vulnerability of pike to capture?
4) Are fishery regulations currently in place on Waterhen Lake sufficient to prevent the commercial harvest of pre-reproductive pike?
5) What is the relationship between the length of the operculum and body length in pike, and how do back-calculated ages from opercula compare amongst age classes?

Questions one to four aim to address whether the fishery is in danger of overfishing (particularly recruitment overfishing). Question five is aimed at addressing possible effects of fishing mortality on the population, as well as examining the possibility of deriving future fisheries data from fishery waste rather than labour-intensive test-netting. All of these questions are aimed, ultimately, at addressing various aspects of the larger question: *is the northern pike fishery on Waterhen Lake sustainable?*

Methodology

Sample Area

Waterhen Lake (52.08°N, 99.58°W) is located near Lake Manitoba and Lake Winnipegosis in central Manitoba, Canada. Its primary inflow is from Lake Winnipegosis via the Waterhen River, which then flows into Lake Manitoba (Last, 1982). Approximately 20 licensed commercial fishermen operate on the lake, primarily targeting walleye (*Sander vitreus*) and pike (Geoff Klein, pers. comm.), and income from this fishery is an important part of the local economy (Manitoba Water Stewardship, 2010). Waterhen Lake is one of a small number of fisheries in Manitoba in which northern pike are specifically targeted for harvest and sale (Geoff Klein, pers. comm.).

Sample Collection

With the cooperation of Manitoba Fisheries Branch, a sample of 51 pike was obtained from Waterhen Lake between September 11th and 13th, 2011. Each fish was given a unique identification number, and for each the following data was recorded: mass (grams), total length from the snout to the end of the caudal fin (mm), sex (male/female), and maturity (mature/immature). Sex and maturity were determined by a fisheries biologist, through observation of gonad type and development. The head of each fish (with opercula attached) was removed, sealed in a plastic bag along with its identification number, and the 51 heads were transported to the University of Winnipeg and kept in freezers until operculum extraction began.

Operculum Extraction

I followed the technique for operculum extraction and age estimation described by Frost and Kipling (1959). Frozen pike heads were partially thawed under warm water, and both opercula were removed with flesh attached and placed in boiling water for 1-2 minutes. After this time, any remaining flesh could be easily removed with a paper towel, and the bare opercula were rinsed in cool water and left to dry for several minutes. They were then placed in envelopes along with their identification number and allowed to dry further for several weeks, by which point annuli were readily visible.

Age Estimation and Validation

Opercula were examined under a dissecting microscope at low magnification to count annuli. In general reflected light was sufficient for this, although transmitted light was also used when annuli appeared faint or obscured. On the opercula of some older fish, the first annulus was obscured by a layer of spongy tissue, a problem also observed by Frost and Kipling (1959). However opercular growth was consistent enough across the sample that this could be accounted for by assuming a hidden annulus for those opercula for which the first visible annulus corresponded to the second visible annulus on similarly sized unobscured opercula. Greater than 95% agreement was found between age estimates for left and right opercula, and between estimates for left opercula made separately by myself and another reader. Opercula for which there were discrepancies in age estimation were re-examined by both readers and final age estimates were agreed upon.

Assessment of Mesh Size Effects

To assess the effect of varying gill-net mesh size on the vulnerability of pike to capture, test-netting data were supplied by Manitoba Fisheries Branch. These data included 79 pike from Waterhen Lake and two nearby lakes (Lake St. Martin and Lake St. Andrews) for which total length was recorded along with the mesh size in which each fish was caught. I performed three linear regressions to test relationships between total length and mesh size of capture for 1) all 79 pike in the dataset, 2) only the largest pike caught in each mesh size, and 3) only the smallest pike caught in each mesh size. The latter two regressions aimed to test for differences in the effect of mesh size variation between large and small pike.

Back-Calculation

To assess the validity of the operculum as a tool for back-calculation of pike length at previous ages, a reduced major-axis (RMA) regression was performed with operculum length as the independent variable and total length of pike as the dependent variable. Reduced major-axis regression is preferable to standard least-squares regression in this case, as it accounts for random error in both the *x* and *y* axes (McArdle, 1988). I used the program RMA Software For Reduced Major Axis Regression created by Andrew Bohonak (2004) to conduct RMA analyses in this study.

Operculum lengths were obtained through the measurement of scanned images of each left operculum with ImageJ image analysis software. A Canon CanoScan LiDE 210 scanner was used to generate the images, and measurements were taken from the origin of each operculum to each annulus and to the most distal edge of the bone. The origin of the operculum was defined, following Frost and Kipling (1959), as the midway point between two indentations visible on either side of the articulating surface of the bone. The axis of measurement was perpendicular to the line connecting those indentations.

I estimated the length of each pike at previous ages by 1) dividing the distance to each annulus by the total length of the operculum, and 2) multiplying this value by the total length at capture. Back-calculated lengths based on the distance to the end of a given annulus are considered to provide an approximate length of the fish during the spring of the corresponding growing season, as this is when annulus formation is completed (Raat, 1988).

Results

Age Structure

Five age classes of pike were present in the sample (Figure 1), with a range from 0 to 6 years, and 86% of the sample was aged between 2 and 4 years old. Males and females differed in both abundance and age structure, with females more numerous, generally older and showing a wider range of ages: mean age at capture was 2.5 and 2.8 for males and females, respectively. One-year-olds were entirely absent, and only one pike older than 4 years was obtained.

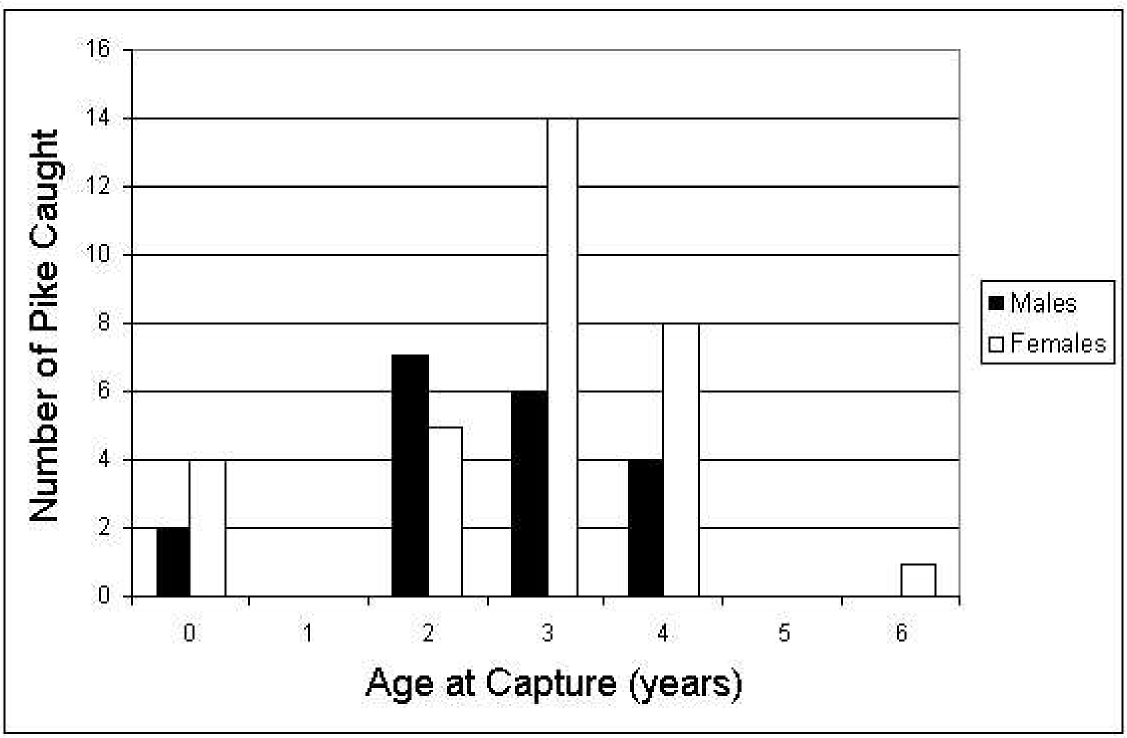


Figure 1: Age distributions of male (n=19) and female (n=32) pike from Waterhen Lake.

Length-mass Relationship

The general length-mass relationship of pike can be described by the formula $\log M = b \log L + \log A$, in which M = mass, L = length, A = some constant and b = an exponent term. (Frost and Kipling, 1967). Figure 2 shows that pike in Waterhen conform to this pattern, irrespective of sex or maturity. A reduced major-axis regression on log-transformed mass and length data (Table 1) yielded estimates of 2.96 for *b* and -5.13 for log*A*. The estimate for *b* did not differ significantly from 3 (t = 1.14, df = 49, p = 0.26), indicating isometric growth (Sangun *et al.*, 2007).

Table 1: Reduced major-axis regression of log-transformed data for pike body weight (g) on total length (mm) in Waterhen Lake (n=51).

	Intercept (log*A*)	**Slope (*b*)**	**R^2**
Estimate	-5.13	2.96	0.99
Standard Error	0.10	0.035	
t	51.3	1.14	
P	<0.001	0.26	

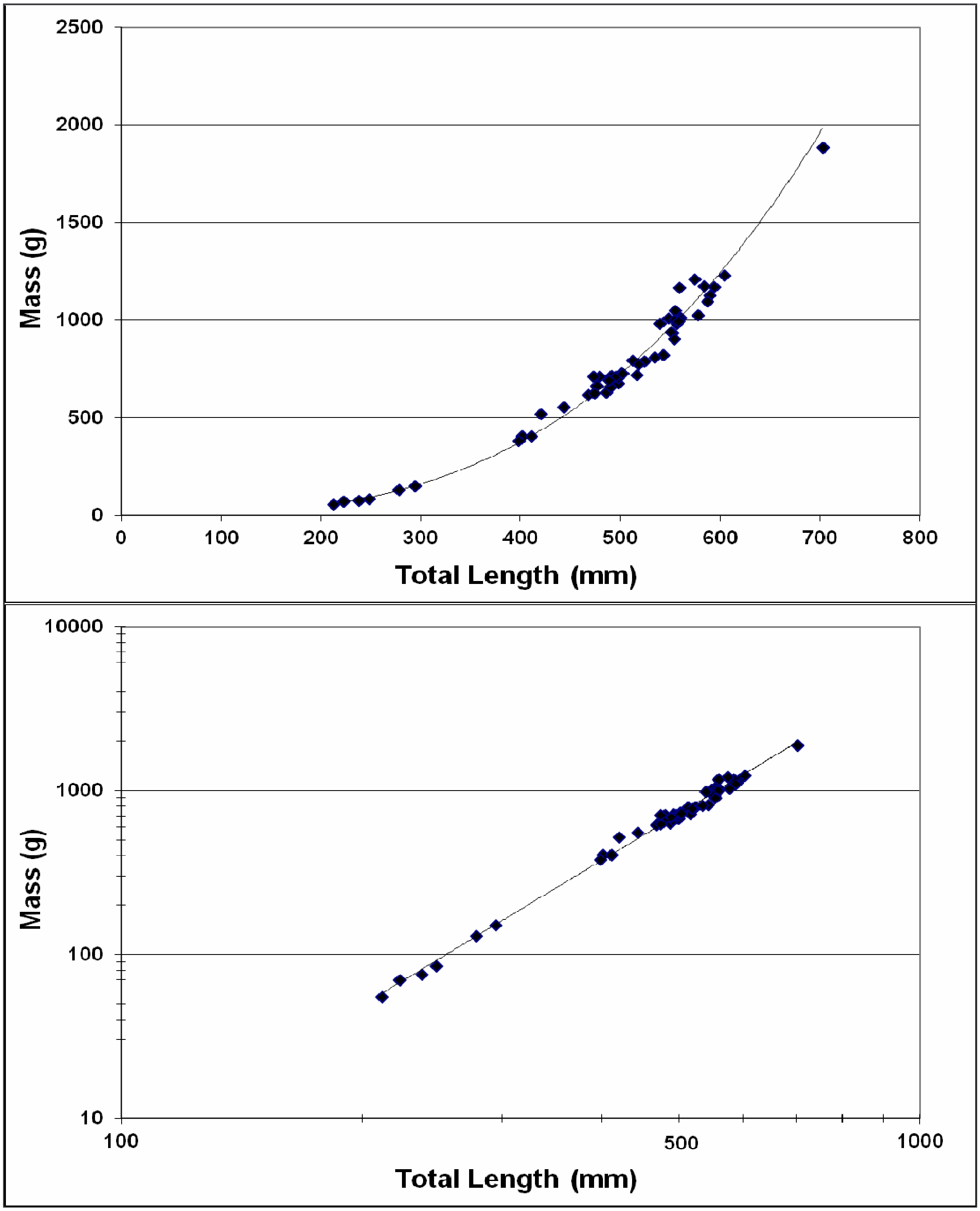


Figure 2: Length-mass relationship of pike in Waterhen Lake, plotted on an arithmetic scale (above) and a logarithmic scale (below). $R^2 = 0.99$ for the logarithmic regression.

Age of Onset of Maturity

Out of nineteen total male pike, two were young of the year (aged 0+ at capture) and sexually immature (Table 2). All of the remaining males were sexually mature, including nine males aged 2 years. Out of 32 total females, four were young of the year and sexually immature. All five females aged 2 years old were sexually mature, while one of the fifteen females aged 3 years old was sexually immature. One-year-old pike of either sex were not present in the sample. These data suggest that male pike in Waterhen Lake likely reach maturity by the end of their third growing season at the latest, and that females, while generally following the same trend, may in some cases remain sexually immature until the end of the fourth growing season.

Table 2: Percentage of male and female pike in each age class found to be sexually mature at the time of capture (sample size in parentheses).

	Age Class	0	1	2	3	4	5	6
% Maturity	Males	0% (n=2)	N/A (n=0)	100% (n=7)	100% (n=6)	100% (n=4)	N/A (n=0)	N/A (n=0)
	Females	0% (n=4)	N/A (n=0)	100% (n=5)	93.30% (n=14)	100% (n=8)	N/A (n=0)	100% (n=1)

Mesh Size Effects

Only a modest overall relationship was found between mesh size and total length (R^2 = 0.30; Figure 3). An even weaker correlation was found between mesh size and the total length of the largest pike caught in each mesh (R^2 = 0.20; Figure 4), suggesting that the vulnerability of larger pike to capture is not strongly affected by the size of mesh used. However, a much stronger relationship was found between mesh size and the total length of the smallest pike caught in each mesh (R^2 = 0.83; Figure 4), indicating that the vulnerability of smaller pike to capture is dependent on mesh size.

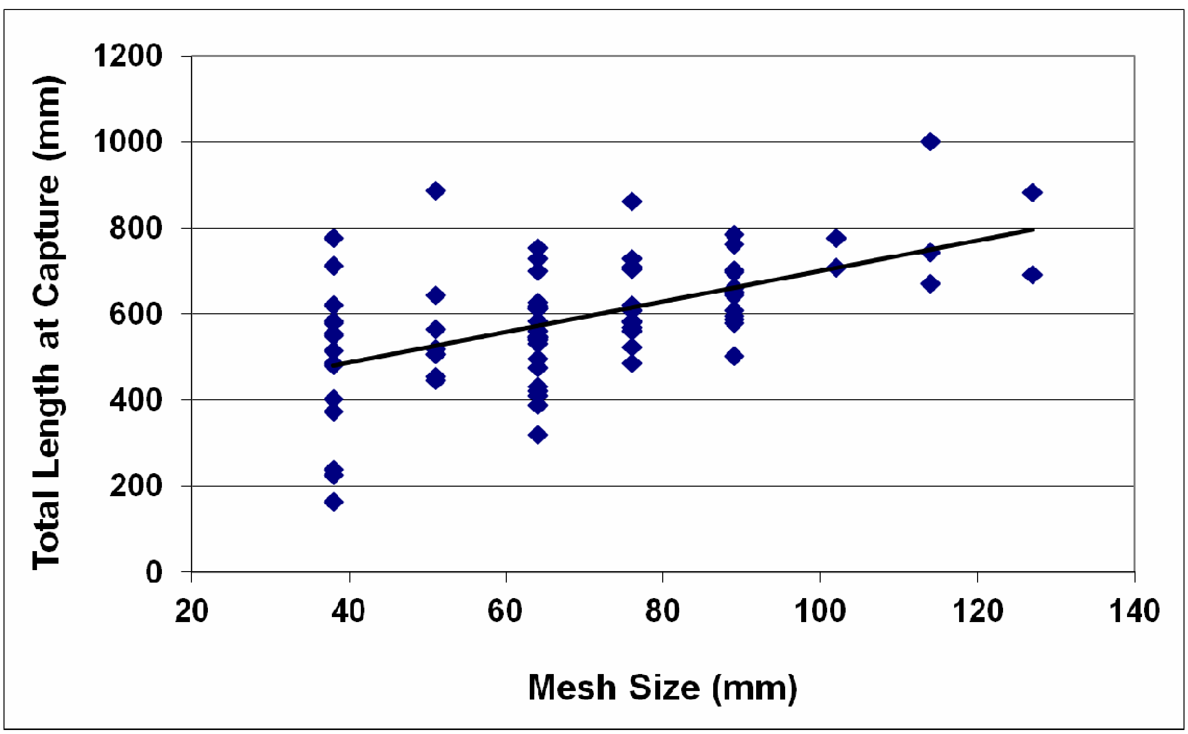


Figure 3: Total length (mm) of northern pike captured in varying gill-net mesh sizes (mm, stretched) on Waterhen Lake, Lake St. Andrews and Lake St. Martin (n=79).

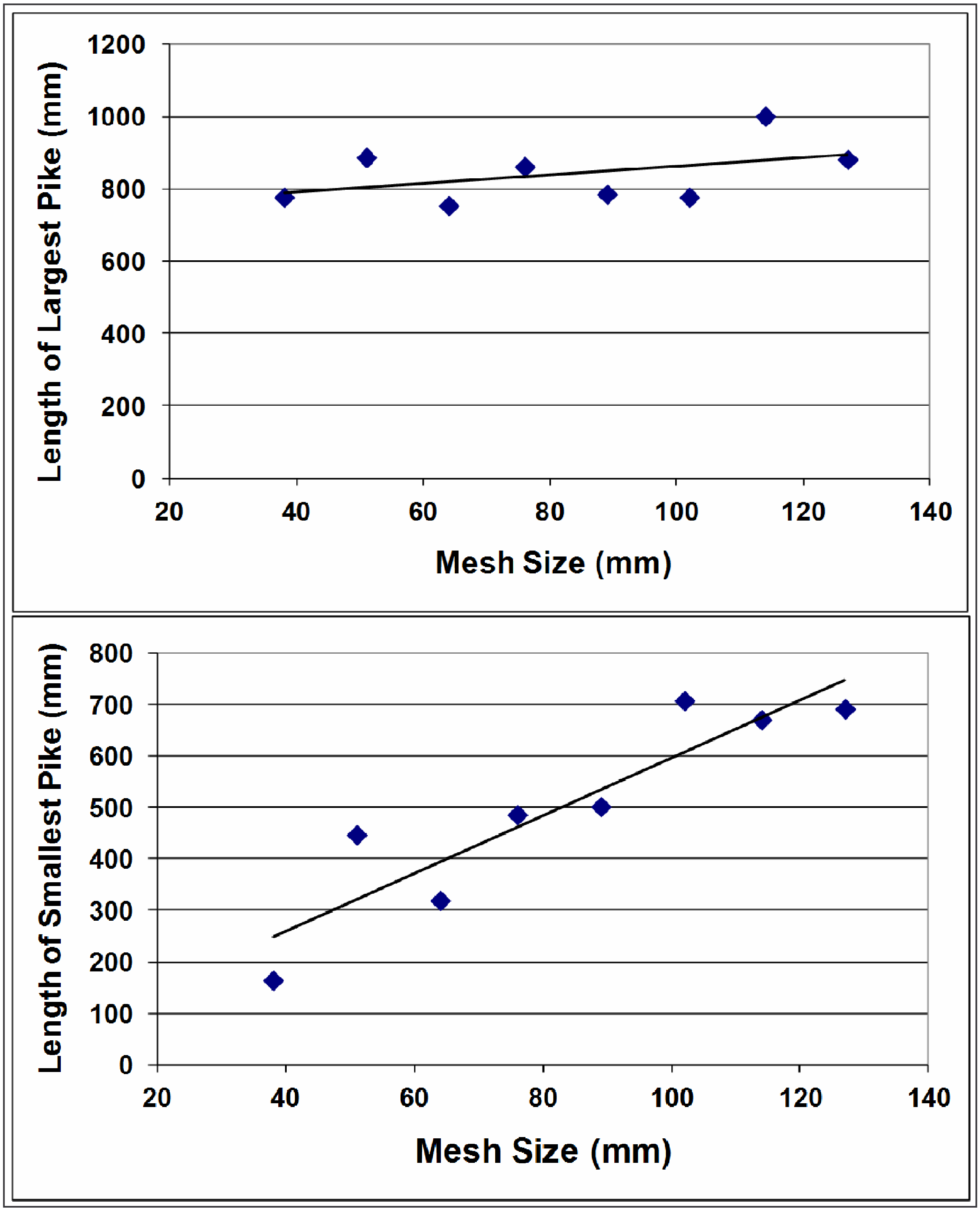


Figure 4: Maximum (above) and minimum (below) total lengths (mm) of northern pike captured in each of 8 gill-net mesh sizes on Waterhen Lake, Lake St. Andrews and Lake St. Martin.

Back-Calculation of Length-at-Age

A strong linear relationship was found between operculum length and body length (Table 3), with an intercept not significantly different from zero ($t = 0.12$, df = 49, $p = 0.91$). A similarly strong logarithmic relationship was found between operculum length and body mass (Table 4). Due to the strong and direct operculum-body length relationship, the distance to annulus a_n over total opercular length was taken to be equivalent to body length at age n over body length at capture. From this, average total length of males and females at the beginning of every previous growing season was estimated for each year class (Tables 5 & 6).

Table 3: Reduced major-axis regression of pike body length (mm) on operculum length (mm) (n=51).

	Intercept	Slope	R^2
Estimate	-1.58	22.9	0.96
Standard Error	13.7	0.625	
t	0.12	36.6	
P	0.91	<0.001	

Table 4: Reduced major-axis regression of log-transformed data for pike body mass (g) on operculum length (mm) (n=51).

	Intercept	Slope	R^2
Estimate	-1.17	3.0	0.97
Standard Error	0.10	0.08	
t	11.7	37.5	
P	<0.001	<0.001	

Table 5: Mean back-calculated length at the beginning of previous growing seasons for each age class of female pike in Waterhen Lake (standard deviation in parentheses).

		Back-Calculated Length (mm) at Age:					
		1	2	3	4	5	6
Age At Capture	2 (n=5)	237.6 (16.9)	368.4 (42.6)				
	3 (n=14)	250.7 (24.9)	366.9 (34.1)	462.4 (26.1)			
	4 (n=8)	242.6 (24.6)	339.5 (26.1)	435.5 (19.0)	514.2 (19.2)		
	6 (n=1)	249.9 (N/A)	336.9 (N/A)	413.7 (N/A)	516.4 (N/A)	610.9 (N/A)	665.7 (N/A)

Table 6: Mean back-calculated length at the beginning of previous growing seasons for each age class of male pike in Waterhen Lake (standard deviation in parentheses).

		Back-Calculated Length (mm) at Age:			
		1	2	3	4
Age At Capture	2 (n=7)	237.6 (17.1)	368.4 (40.3)		
	3 (n=6)	250.7 (8.4)	366.9 (15.1)	462.4 (20.1)	
	4 (n=4)	242.6 (28.9)	339.5 (30.8)	435.5 (32.9)	514.2 (33.6)

Discussion

The results of this study provide the basic demographic information needed to begin the process of ecocertifying the Waterhen Lake pike fishery. Knowledge of the age structure, growth characteristics, age of maturity and the age/size of new recruits to the fishery are all important criteria for sustainability, as they allow fishery managers to monitor changes to the stock over time (MSC, 2012). New data can also be added to these results over time to provide a more complete understanding of the biological characteristics of this population.

Age Estimation

Opercula proved to be an effective aging structure for northern pike, as there was high inter-reader reliability (>95% agreement) in age estimates once readers had gained sufficient experience with the technique. This result is consistent with other studies that found opercula to be a valid and efficient method of age estimation for pike (Frost and Kipling, 1959). Otoliths are commonly used aging structures in many fishes (Campana, 2001), however otoliths extracted from this sample proved impossible to age due to indistinguishable annuli, suggesting that opercula are the more effective aging structure for this species. Other structures including the cleithrum (Laine *et al.*, 2011) and metapterygoid bone (Sharma, 2007) have successfully been used to age pike, and it may be worthwhile to investigate the level of agreement between age estimates from these structures and from opercula.

Age Structure

Frost and Kipling (1967) suggested that for females younger than 4 years and males younger than 6 years in Windermere Lake, age distributions in gill-netted pike samples were strongly dependent on gill-net selectivity, and did not necessarily represent the actual age distribution of the population itself. Given that the large majority of pike in this sample fall into this age range, it is probable that the distribution presented in Figure 1 does not reflect the actual age distribution of young pike in Waterhen Lake. Rather, the absence of 1-year-olds of either sex in the sample is likely reflective of the fact that very young pike are vulnerable only to the very smallest mesh sizes, and thus this represents a reduced sampling effort for the youngest age classes. On the other hand, the presence of young-of-the-year pike in the sample is likely a reflection of the relatively large proportion of this year-class in the lake, since at the time of sampling this age class had not yet been through a winter, when young-of-the-year mortality is very high (Scott and Crossman, 1998).

The absence of pike older than six years from the sample may reflect a deficit of older fish in the population, but this is not necessarily the case. While studies of other pike populations have frequently found pike of 10 years of age or older (Scott and Crossman, 1998 and Raat, 1988), such studies usually involve larger sample sizes than was obtained from Waterhen Lake (eg. Frost and Kipling, 1967, and Mosindy and Mucha, 2006). Older, larger fish normally comprise a small proportion of a fish population (Frost and Kipling, 1967), and a larger sample size may be required in order to accurately account for the older, less numerous year classes. Despite comprising a small fraction of the population, older pike often account for a large proportion of the reproductive capacity of pike populations (Raat, 1988), so further research to assess the status of older pike in Waterhen Lake would be beneficial.

Age of Maturity

The age of onset of sexual maturity is often defined as the age at which the majority of fish have developed functioning gonads (Mosindy and Mucha, 2006). The absence of 1-year-olds in this sample makes it impossible to pinpoint the age of maturity precisely, but based on the very high percentage of mature fish in every age class at or above 2 years, the onset of maturity can be estimated at 2 years or younger for males and 2-3 years or younger for females. This places the age of maturity for pike on Waterhen Lake slightly below what was expected based on latitude alone, particularly for females (Scott and Crossman 1998). For example, in Flathead River, Montana, and Lake Oahe, North Dakota, the majority of female pike did not reach maturity until at least 3 years, despite these populations being found considerably to the south of Waterhen Lake (DosSantos, 1991; Raat, 1988). A more geographically comparable population in Waskesiu Lake, Saskatchewan matured at 4 and 4-6 years for males and females, respectively (van Engel, 1940). On the other hand, pike of both sexes in Lake of the Woods, Ontario were found to reach maturity at 2 years. It was noted that the pike population in this lake had previously been under substantial fishing pressure (Mosindy and Mucha, 2006).

The role of fishing mortality in the determination of the onset of maturity was investigated by Diana (1983), who found that in three Michigan pike populations, earlier maturation was associated with higher angling pressure and greater fishing mortality, irrespective of latitude and temperature variables. Similar responses to sustained fishing pressure have been found in other fishes (Jorgensen, 2009), and reflect the evolutionary advantage of producing offspring as soon as possible in conditions where the probability of mortality for larger fish is increased. Given that pike in Waterhen have been locally harvested for many years, this appears to be a sound explanation for the early onset of maturity found in this study. While this indicates that fishery-induced mortality on Waterhen Lake is having an impact on the pike population, it also suggests that pike in this lake have been able to adapt to the fishery so as to maximize their reproductive output under the current conditions.

An alternative explanation for the results in Table 2 is that immature 2-year-old pike, which tend to be smaller than mature pike of the same age class (Mann, 1975), were less susceptible to capture due to their size and thus the apparent reduction in the age of maturity may be the result of sampling bias toward mature fish. To test this possibility, back-calculated ages at the beginning of the third growing season were compared between 2-year-olds and older pike, to see whether the 2-year-olds caught tended to be unusually large for their age class (Table 7). One-tailed t-tests showed no significant difference in size for females ($t = 0.85$, df = 100, $p = 0.20$), while male 2-year-olds were larger than the back-calculated length of older males at a 0.10 significance level ($t = 1.41$, df = 100, $p = 0.081$). Given the modest sample sizes obtained in this study, the statistical power of these comparisons is low (Peterman, 1990).

Table 7: Results of one-tailed Student's t-tests on the back-calculated lengths at the beginning of the third growing season for 2-year-old pike and older pike (sample size in parentheses).

	Males		**Females**		**All**	
Age at Capture	**2 years**	**3+ years**	**2 years**	**3+ years**	**2 years**	**3+ years**
Mean back-calculated length at age 2 (mm)	362.8 (n=7)	340.9 (n=10)	368.4 (n=5)	354.2 (n=23)	365.2 (n=12)	350.1 (n=33)
t	1.41		0.85		1.37	
P	0.081		0.20		0.09	

This result does suggest that sampling bias in favour of larger (and thus more mature) 2-year-olds is a possibility, at least for males. However it should be noted that smaller back-calculated lengths of older fish are also expected to occur as a result of Lee's phenomenon (Ricker, 1975), in which the larger members of each class experience higher mortality resulting in lower than expected back-calculated lengths for the smaller survivors. Additional research using small-mesh gill-nets, electrofishing or other sampling protocols targeting young fish would be useful in eliminating this potential bias and obtaining a more precise estimate of maturity onset in this population (Goffaux *et al.*, 2005).

Mesh Size Effects

The difference between small and large pike in the effect of mesh size on vulnerability to capture was not unexpected. Frost and Kipling (1967) also regularly caught large pike in small-mesh nets, although this was attributed to the use of loose gillnets in which larger pike became entangled rather than gilled. While gillnets used on Waterhen Lake were not loose, capture through entangling may be part of the explanation for this result. It seems probable that large pike are drawn to the net, or "baited" by the presence of small, gilled fish in small meshes. In attempting to eat gilled fish, pike will often either swallow the net itself, or their teeth and jaw may become entangled (Geoff Klein, pers. comm.).

Assessment of Mesh Size Restrictions on Waterhen Lake

The strong relationship between mesh size and total length for smaller fish is important in assessing the effectiveness of fishing regulations aimed at protecting pre-reproductive pike. This relationship implies that there should be a mesh size threshold that protects smaller, immature pike from the fishery without negatively impacting the harvest of larger, commercially valuable pike. Figure 5 shows that 95mm (3.75") is likely a good estimate of where that threshold lies for this population. Specifically, no pike less than 600mm were caught in mesh sizes above 95mm , while sub-600mm fish made up a significant portion of the catch in all smaller meshes. If 600mm is thus taken to be an estimate of the size at which pike are recruited into the fishery, this indicates that almost all pike aged four and below are protected from harvest (Figure 5). Given the estimated age of maturity (2 or younger for males, 2-3 or younger for females), it is probable that pike on Waterhen Lake are protected for at least 1-2 spawning seasons before they are recruited into the fishery.

A protected spawning population is an important component in avoiding recruitment overfishing (FAO, 1996; Abrosov, 1969). A mesh size limit lower than 95mm would begin to target 500mm pike, which could include 2-year-olds that had just reached maturity. Thus, the current mesh size restrictions in place on Waterhen Lake appear to be effective given the current biological characteristics of the pike population.

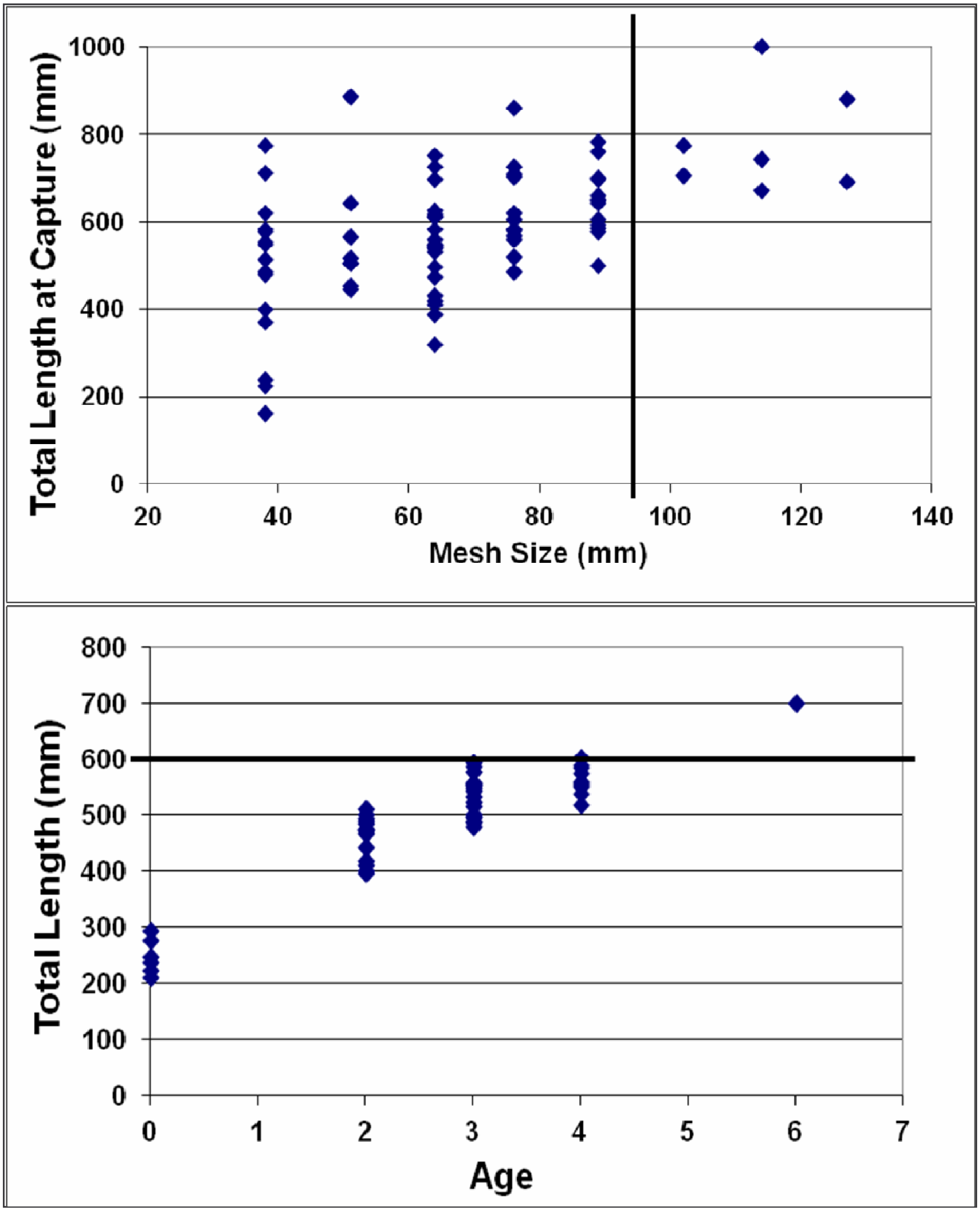


Figure 5: Relation of the 95mm mesh size restriction to age and growth data. Above: Total length (mm) of northern pike captured in varying gill-net mesh sizes (mm) on Waterhen Lake, Lake St. Andrews and Lake St. Martin, with a vertical line representing the division between illegal (<95mm) and legal (>95mm) mesh sizes. Below: Total length of pike (mm) by age class, with a horizontal line at 600mm representing an estimated threshold for likely recruitment into the fishery.

Operculum-Growth relationship and Back-calculation

The strong relationships between operculum length and both the total length and mass of pike indicates that opercula alone could likely be used to accurately estimate pike length and mass using the regression parameters in Table 3 and Table 4. This opens the possibility of using opercula from fishery waste to add to the data in this study, rather than relying on time- and labour-intensive test-netting by Manitoba Fisheries Branch (Scott Forbes, pers. comm.). However, it would be necessary that both the sex and maturity of each pike be recorded at the time of capture, as this information cannot currently be obtained from opercula alone.

As mentioned earlier, there is evidence for the occurrence of Lee's Phenomenon (Ricker, 1975; Lee, 1912) in this population based on the evident decrease in back-calculated length at ages 2 and 3 as age at capture increases (Tables 5 & 6). That is, older fish in the sample tended to have smaller back-calculated lengths in their third and fourth growing seasons than did younger fish. This suggests that those pike that survive to older ages on Waterhen Lake tend to be the smaller members of their age class, in turn indicating that mortality rates are higher for the larger members of each age class. Frost and Kipling (1967) found similar results for pike in Windermere Lake that had experienced consistent fishing pressure for many years. The existence of fishery-induced Lee's Phenomenon in this population could thus be taken as an indicator of fishing pressure (Ricker, 1975), which seems reasonable given the evidence for a lowered age of maturity. However, the possible conflation of the effects of 1) fishery-induced mortality of larger members of older age classes, and 2) sampling bias favouring the larger members of younger age classes, warrants further investigation. Fuller representation of the lower end of the age distribution in the sample would mitigate the effects of sampling bias, allowing for a more conclusive assessment of both the presence of and explanations for Lee's Phenomenon in Waterhen Lake pike.

Conclusions

1) The operculum is a reliable aging structure for northern pike in Waterhen Lake.
2) Male pike in Waterhen Lake appear to reach sexual maturity at 2 years of age or less; females at 2-3 years of age or less. Age of maturity is lower than was expected based on latitude alone, possibly representing an adaptation to fishing pressure.
3) Gill-net mesh size does not significantly affect the vulnerability of larger pike to capture, but it does significantly affect the vulnerability of smaller pike to capture.
4) Mesh size regulations currently in place on Waterhen Lake appear to be sufficient to prevent the harvest of pre-reproductive pike on Waterhen Lake.
5) The length of the operculum is strongly associated with both the total length and body mass of pike.
6) Lee’s Phenomenon is apparent in this population, possibly indicating the effect of the fishery on pike mortality.
7) Further research targeting 1- and 2-year-old pike, as well as an assessment of the status of older age classes of pike on Waterhen Lake, is recommended.

References

Abrosov, VN. 1969. Determination of commercial turnover in natural bodies of water. Problems of Ichthyology 9:482:489.

Berg S, Jeppesen E, Sondergaard M. 1997. Pike *(Esox lucius* L.) stocking as a biomanipulation tool 1. effects on the fish population in Lake Lyng, Denmark. Hydrobiologia 342:311-318.

Bohonak, AJ. 2004. RMA Software for Reduced Major Axis Regression (version 1.17).

Campana SE. 2001. Accuracy, precision and quality control in age determination, including a review of the use and abuse of age validation methods. Journal of Fish Biology 59:197-242.

Carlson SM, Edeline E, Vollestad LA, Haugen TO, Winfield IJ, Fletcher JM, James JB, Stenseth NC. 2007. Four decades of opposing natural and human-induced artificial selection acting on Windermere pike (*Esox lucius*). Ecology Letters 10:512-21.

Casselman, JM. 1990. Growth and relative size of calcified structures of fish. Transactions of the American Fisheries Society 119:673-688.

Casselman, JM. 1996. Habitat requirements of northern pike (*Esox lucius*). Canadian Journal of Fisheries and Aquatic Sciences 53:161-174.

Craig JF, editor. 1996. Pike: Biology and exploitation. Cambridge, England: Chapman & Hall. 299 p.

Craig JF. 2008. A short review of pike ecology. Hydrobiologia 601:5-16.

Diana JS. 1983. Growth, maturation and production of northern pike in three Michigan lakes. Transactions of the American Fisheries Society 112:38-46.

DosSantos JM. 1991. Ecology of a riverine pike population. *In:* Cooper, LC and Hamre, RH, editors. Warmwater Fisheries Symposium I. Fort Collins, CO: US Department of Agriculture, Forestry Service. p 155-159.

Enberg K, Jorgensen C, Dunlop ES, Heino M, Dieckmann U. 2009. Implications of fisheries-induced evolution for stock rebuilding and recovery. Evolutionary Applications 2:394-414.

Engel WAV. 1940. The rate of growth of the northern pike, *Esox lucius* Linnaeus, in Wisconsin waters. Copeia 1940:pp. 177-188.

Fabricius E and Gustafson K. 1958. Some new observations on the spawning behaviour of the pike, *Esox lucius* L. Report of the Institute of Freshwater Research, Drottningholm 29:57-99.

[FAO] Food and Agriculture Organization of the United Nations. 1996. Precautionary approach to capture fisheries and species introductions. Rome: FAO Technical Guidelines for Responsible Fisheries, 2. 60 p.

[FAO] Food and Agriculture Organization of the United Nations. 2002. The state of world fisheries and aquaculture 2002. Rome: FAO Fisheries Department. 150 p.

Froese R. 2004. Keep it simple: Three indicators to deal with overfishing. Fish and Fisheries 5:86-91.

Frost WE and Kipling C. 1967. A study of reproduction, early life, weight-length relationship and growth of pike, *Esox lucius* L., in Windermere. Journal of Animal Ecology 36:651-693.

Frost WE and Kipling C. 1959. The determination of the age and growth of pike (*Esox lucius* L.) from scales and opercular bones. Journal Du Conseil / Conseil International Pour l'Exploration De La Mer 1959:314-41.

Goffaux D, Grenouillet G, Kestemont P. 2005. Electrofishing versus gillnet sampling for the assessment of fish assemblages in large rivers. Archiv Für Hydrobiologie 162:73-90.

Gulbrandsen LH. 2005. Mark of sustainability? Challenges for fishery and forestry eco labeling. Environment 47:8-23.

Harvey B. 2009. A biological synopsis of northern pike (*Esox lucius*). Canadian Manuscript Report of Fisheries and Aquatic Sciences 2885. 31 p.

Inskip, PD. 1982. Habitat suitability index models: northern pike. Washington, DC: US Department of the Interior, Fish and Wildlife Service. 40 p.

Jorgensen C, Ernande B, Fiksen O. 2009. Size-selective fishing gear and life history evolution in the northeastern arctic cod. Evolutionary Applications 2:356-70.

Kipling C and Frost WE. 1970. A study of the mortality, population numbers, year class strengths, production and food consumption of pike, *Esox lucius* L., in Windermere from 1944 to 1962. Journal of Animal Ecology 39:115-157.

Laine AO, Momot WT, Ryan PA. 1991. Accuracy of using scales and cleithra for aging northern pike from an oligotrophic Ontario lake. North American Journal of Fisheries Management 11:220-5.

Langhorne AL, Neufeld M, Hoar G, Bourhis V, Fernet DA, Minns CK. 2001. Life history characteristics of freshwater fishes occurring in Manitoba, Saskatchewan and Alberta, with major emphasis on lake habitat requirements. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2579. 170 p.

Last WM. 1982. Holocene carbonate sedimentation in Lake Manitoba, Canada. Sedimentology 29:691-704.

Lee RM. 1912. An investigation into the methods of growth determination in fishes. Conseil Permanent International Pour l'Exploration De La Mer 63:1-35.

Mann RHK. 1976. Observations on the age, growth, reproduction and food of the pike *Esox lucius* (L.) in two rivers in southern England. Journal of Fish Biology 8:179-97.

[MSC] Marine Stewardship Council. 2010. MSC Fishery standard: Principles and criteria for sustainable fishing. 8 p.

[MSC] Marine Stewardship Council. 2011. MSC Annual Report 2010-2011. London: MSC Head Office. 25 p.

[MSC] Marine Stewardship Council. 2012. Guidance to the MSC certification requirements. London: MSC Head Office. 203 p.

McArdle BH. 1988. The structural relationship: Regression in biology. Canadian Journal of Zoology 66:2329-39.

Mosindy T. and Mucha J. 2006. Fall Walleye Index Netting of South Sector 5, Lake of the Woods, Ontario: 1997 and 2002. Ontario Ministry of Natural Resources, Northwest Science and Information NWSI Technical Report TR-137. 23 p.

Myers RA and Mertz G. 1998. The limits of exploitation: A precautionary approach. Ecological Applications 8:S165-S169.

Ontario Ministry of Natural Resources. 2006. Guidelines for managing the recreational fishery of northern pike in Ontario. Ontario Ministry of Natural Resources, Fish and Wildlife Branch, Fisheries Section.

Pauly D. 1983. Some simple methods for the assessment of tropical fish stocks. Rome: FAO. 52 p.

Peterman RM. 1990. Statistical power analysis can improve fisheries research and management. Canadian Journal of Fisheries and Aquatic Sciences 47:2-15.

Peterman RM. 2002. Ecocertification: An incentive for dealing effectively with uncertainty, risk, and burden of proof in fisheries. Bulletin of Marine Sciences 70:669-681.

Raat AJP. 1988. Synopsis of biological data on northern pike (*Esox lucius* Linnaeus, 1758). Rome: FAO. 178 p.

Rawson DS. 1932. The pike of Waskesiu Lake, Saskatchewan. Transactions of the American Fisheries Society 62:323-30.

Ricker WE. 1969. Effects of size-selective mortality and sampling bias on estimates of growth, mortality, production and yield. Journal of the Fisheries Research Board of Canada 26:479-541.

Ricker WE. 1975. Computation and interpretation of biological statistics of fish populations. Fisheries Research Board of Canada Bulletin 191. 382 p.

Ricker WE. 1984 Computation and uses of central trend lines. Canadian Journal of Zoology 62:1897-1905.

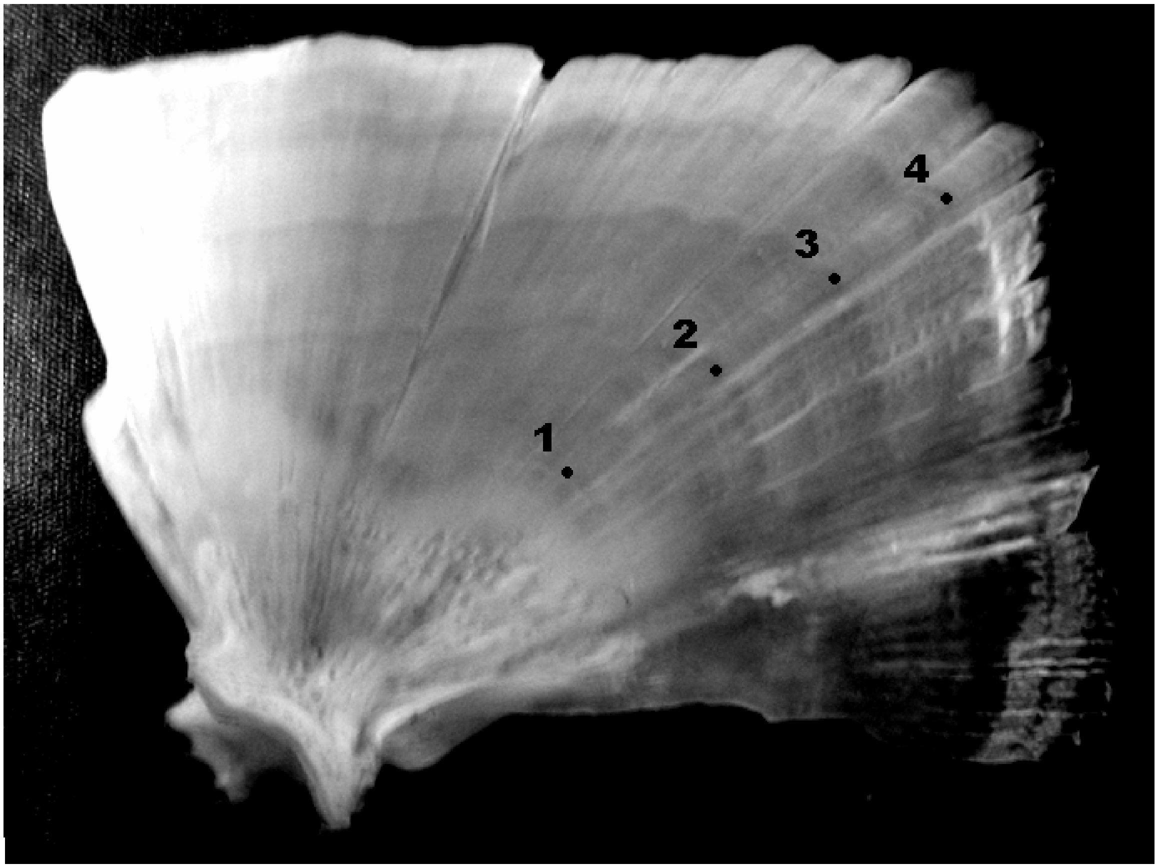
Sangun L, Akamca E, Mustafa A. 2007. Weight-length relationships for 39 fish species from the north-eastern Mediterranean coast of Turkey. Turkish Journal of Fisheries and Aquatic Sciences 7:37-40.

Scott WB and Crossman EJ. 1998. Freshwater fishes of Canada. Oakville, Canada: Galt House Publications Ltd. 966 p.

Sharma CM and Borgstrom R. 2007. Age determination and backcalculation of pike length through use of the metapterygoid bone. Journal of Fish Biology 70:1636-41.

Stewart KW and Watkinson DA. 2004. The freshwater fishes of Manitoba. Winnipeg, Canada: University of Manitoba Press. 278 p.

Trippel EA. 1998. Egg size and viability and seasonal offspring production of young Atlantic cod. Transactions of the American Fisheries Society 127:339-359.



Appendix 1: Left operculum of a northern pike aged 4 years, with annuli marked. The first annulus is frequently obscured by spongy tissue, but is visible under transmitted light.