

METHODS FOR ESTIMATION OF CYCLIC RECRUITMENT VARIATION IN
PYGMY NORTHERN PIKEMINNOW (*PTYCHOCEILUS OREGONENSIS*) OF
SOUTH CENTRAL BRITISH COLUMBIA

by

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Abstract

A long term study of fish populations on the Bonaparte Plateau, B.C., has revealed the possibility of 2-year cyclic recruitment variation in the pygmy pikeminnow (*Ptychocheilus oregonensis*). This thesis reviews possible causes of the cycle, and evaluates an inexpensive and non-destructive visual survey method to estimate juvenile population numbers over short summer periods while pikeminnow juveniles are recruiting to the lakes and dying rapidly, for use in future studies of the cyclic pattern. To provide an index of the abundance of juvenile pikeminnow, strip-transect surveys were conducted from shore. Each strip transect area was a full circumference of each of three study lakes, and extended from shore to a distance of up to 3 meters offshore. The visual surveys were shown to be accurate and repeatable when estimating the number of fish and the lengths of the fish in a shoal. The strip transects provide an index of abundance for juvenile northern pikeminnow and this index of abundance can be used to calculate daily summer and interannual mortality rates, providing estimates close to those predicted from the Lorenzen model for size-dependent mortality rates of fish in general.. Stationary point surveys were also conducted to investigate juvenile pikeminnow behaviour, and these point surveys reveal a link between sunlight intensity and pikeminnow activity, and provide evidence of direct agonistic interactions between age 0 and age 1 juveniles, which could result in higher mortality rates of age 0 fish when age 1 fish are abundant. Analysis of survey data collected to date over five years from three lakes supports the possibility of a recruitment cycle with lakes out of phase with each other, suggesting that ecological interactions drive the cycles. These interactions are worthy of further investigation.

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Dedication

For Meghan.

Chapter One: Introduction

1.1 Background

Recreational fishing in British Columbia is a major source of revenue for the province.

The lakes of the interior of British Columbia are the focus of much of the recreational anglers' activity. This important recreational fishery however, is in decline. In recent years the quality of the recreational angler's fishing experience has been diminished.

Stocking programs, seasonal closures, the implementation of catch and release regulations, and other management activities have long been used to remedy the decline in size and numbers of fish caught in order to maintain a reasonable level of user satisfaction.

Some lakes in British Columbia have several species of fish, with typically a smaller "forage" fish and a larger rainbow trout strain. The rainbow trout are desired by anglers, while the forage fish are considered a nuisance and contribute nothing to angler satisfaction. Such systems can be dominated by rainbow trout and produce large numbers of trout; but may undergo a regime shift under high angling pressure and become dominated by the forage species, with the trout showing severely depressed recruitment (but often unusually high growth rates of older fish). Such shifts have been attributed to a mechanism called "cultivation-depensation" (Walters and Kitchell, 2002).

The cultivation-depensation hypothesis has been the focus of long-term research in a complex of lakes on the Bonaparte plateau North and West of Kamloops, British Columbia. As part of this investigation I examined the populations of northern pikeminnow (*Ptychocheilus oregonensis*), a forage fish in these lakes. The northern

pikeminnow is a piscivorous, spring spawning minnow of the cyprinid family and is widely distributed in the Columbia and Fraser River system. Typical pikeminnow reach adult length of greater than 300 mm and individuals as large as 600 mm are reported (McPhail 2007, Parker et al., 1995). The population being studied on the Bonaparte plateau is composed of unusually small and slow growing individuals, the largest reported pikeminnow caught in an extensive mark recapture program in 2007 was 240 mm fork length (van Poorten pers comm.) and the maximum length reported by Taylor (2005) for northern pikeminnow in these populations is 210 mm. As a result this population has been dubbed the pygmy northern pikeminnow (Taylor 2005). At the start of the research, some of the lakes were thought to be trout dominated and some to be minnow dominated. I attempted to estimate juvenile survival of the pikeminnow, and better understand the early life history of this fish in the study lakes. In the course of this investigation, I discovered an interesting pattern of abundance in the youngest age classes of pikeminnow: the lakes appear to exhibit cyclic recruitment variation, with alternating years of strong and weak recruitment. This alternation of strong and weak year classes suggests that there is some strong density dependent or environmental effect on the recruitment dynamics of the pikeminnow.

The aim of this thesis is to evaluate the use of visual census methods for estimating recruitment rates of pikeminnow in the Bonaparte plateau study areas. The possibility of a recruitment cycle affecting the northern pikeminnow populations of the Bonaparte plateau requires the development of an inexpensive and non-destructive way to estimate juvenile population numbers for a large number (10) of lakes, over short summer periods while pikeminnow juveniles are recruiting to the lakes and dying rapidly. This

monitoring technique will be used to examine the stock-recruitment function for pikeminnow, as the long term study proceeds. Gathering information on recruitment rates will allow me to determine whether there is a recurring recruitment cycle.

Visual surveys might be an excellent tool for evaluating juvenile northern pikeminnow abundance, because the small size of the juveniles and their habitat choices make them immune to most sampling gear. The juveniles concentrate at some times in very shallow water (<10cm depth), a behavior that concentrates them in habitat that is accessible to visual survey techniques. Development of shore based visual monitoring of the juvenile pike minnow and the results of that preliminary study form the basis of this thesis. A follow up study to investigate the cyclic recruitment pattern observed will be carried on in the future, hopefully forming the basis of a Doctoral thesis.

The thesis is organized in four chapters. Chapter 2 provides a review of fish population studies where cyclic recruitment has been observed, and hypotheses that have been proposed to explain the cyclic patterns. Chapter 3 describes the Bonaparte field site and the visual survey methods used in this study. Chapter 4 presents results of the two summers of visual surveys conducted to date, along with tests of how survey results are affected by factors including time of day, sunny versus cloudy days, and season. Chapter 5 discusses the study findings in relation to longer term studies of cyclic recruitment variation of northern pikeminnow

Chapter Two: A Review of Cyclic Recruitment Patterns in Fish Populations

A recruitment cycle is a regular pattern of strong and weak cohorts, with strong cohorts occurring more regularly than would be expected by chance. True cyclic recruitment phenomena are rare in fish populations. Cycles are not often evident in fish populations most likely because there are a large number of external and internal factors affecting recruitment (Townsend 1989). Abiotic and biotic factors act on most fish populations and usually mask each other so as to result in complex recruitment dynamics and patterns (Pitcher and Hart 1982, Mills and Mann 1985). Research to date has found that cycles usually appear in populations only when there is a single particularly strong factor affecting recruitment (Townsend 1989).

Populations of fish are often studied to examine the underlying relationships between stock and recruitment. What is interesting about populations that exhibit cyclic recruitment pattern is that recruitment rate is apparently driven by one overriding factor, rather than a complex of environmental and biotic interactions that produces a correspondingly complex pattern of recruitment variation over time. By studying cyclic populations, biologists may be able to see how particular factors act to help determine stock recruitment relationships.

2.1 Cyclic Fish Populations in Nature: Examples and Mechanisms

Several populations of ocean, lake, and stream resident fish have been shown to exhibit stable population cycles, including but not limited to pink and sockeye salmon (*Oncorhynchus gorbuscha*, *O. nerka*) as well as barramundi (*Lates calcifer*). The driving factors behind these cycles have been identified and in many cases supported by data or modeling. The anadromous salmon examples are mentioned in this chapter only briefly

because the populations in question generally exhibit cycles with period equal to the life cycle duration, so that large parental abundances produce large recruits and low adult numbers produce low recruitments; in such cases there may be linkages across “cycle lines” that cause abundances to remain low for the weak lines, but the dominant factor causing cyclic variation is simply adult abundance. The barramundi are described in more detail below, explaining their complex life history and outlining a model used to predict the recruitment of this highly cyclic species.

Arctic char (*Salvelinus alpinus*), roach (*Rutilus rutilus*), brook and rainbow trout (*Salvelinus fontinalis*, *O. mykiss*), vendace (*Coregonus albula*) (Townsend 1989) and brown trout (*Salmo trutta*) (Borgstrom et al 1993) are all species of fish that have lake populations that have been reported to exhibit stable populations cycles. Vendace and brown trout are two species that have been described in detail in the literature, with examinations of potential causal mechanisms; as a result these examples are discussed in more detail in this chapter. The reason for addressing these two species in more detail is to show how examining the cyclic recruitment of populations can lead to conclusions about the mechanisms that drive stock-recruitment relationships.

A population of Vendace in Lake Pyhajarvi in south-west Finland has been the subject of ongoing study for many years. This population exhibited a stable 2-year cycle (Helminen et al 1997). A brown trout population in Lake Skavatn in Norway has also been the subject of intense study and has also shown a stable 3 – year recruitment cycle (Borgstrom et al 1993).

2.2 Anadromous Salmon

Some pink salmon stocks exhibit a two-year cycle, which is a result of their being semelparous and having a life cycle lasting two years. This results in two separate stocks or “cycle lines” that share a habitat but use it in alternate years. The pink salmon cycles are thought to result from irregular random disturbances that create a strong or weak year which is reflected forward through time every two years (Townsend 1989).

Some sockeye salmon populations show a four year cycle, and like the pink salmon this corresponds to the age of maturity and breeding at four years (Ricker 1950). The Sockeye cycle is thought to be caused by a random event and reinforced by extreme inverse density dependent fishing mortality (Ricker 1950, Walters and Staley 1987, Eggers and Rogers 1987). However, there is also growing evidence of negative linkages among the cycle lines, based on statistical regression modeling of how recruitment rates vary not only with parental abundance but also with abundance of spawners in pre-parental years (Walters and Staley 1987; Cass 1994). Ward and Larkin (1964) speculated that these negative effects could be due to predator responses to changing juvenile abundance and to interannual carryover effects of depletion of zooplankton food supplies.

2.3 Barramundi

Roland Griffin in the Northern Territory in Australia has reported a violent 2-year cycle in the age-1 and age-0 barramundi population of a study reach in the Mary River (Walters and Martel 2004). Barramundi are a catadromous, protandric, hermaphroditic species of fish. Spawning takes place in coastal ocean areas near river mouths, then juveniles migrate upstream to rear in freshwater rivers and ponds. In the Mary River it appears that cannibalism and food competition between age-1- and age-0 barramundi leads to a 2-year

cycle in recruitment. This cycle can be modeled by representing cannibalism/competition effects using a modified Beverton-Holt recruitment equation.

$$R_t = (N_{ot} * e^{-a_1 P_t}) / 1 + (N_{ot} * a_2 (1 - e^{-a_1 P_t}) / A_t) \quad (2.1)$$

Where a_1 and a_2 are predation and behavioural ecology scaling parameters, A_t is the habitat size, and P_t is the predation risk. To account for density dependent, cannibalistic predation of age 1 on age 0 barramundi, the predation risk is expressed as a function of a constant background predation risk plus the recruitment of barramundi from the year before.

$$P_t = P_o + R_{t-1} \quad (2.2)$$

These two equations can be combined into a simple population model for the abundance of older fish where the number of age 1 and older fish each year is the surviving fish from last year plus the new recruits predicted by equation (2.1) above.

$$N_t = S N_{t-1} + R_t \quad (2.3)$$

A model combining equations (2.1), (2.2), and (2.3) can easily replicate the fluctuating population observed in Mary River. Gaming with the model produces a few interesting effects (Walter and Martell 2004), the most important of which is that the violent cycling of these population requires high cannibalism rates, i.e. the effect of R_{t-1} must be large relative to P_o in equation (2.2). Stability in the model is increased when the non-cannibalistic risk factors are increased or when the reproductive rate is high. Thus instability appears to require heavy intercohort density dependent mortality and a low reproductive rate (Walters and Martell 2004).

2.4 Vendace

A decade long study of vendace in south-west Finland by Helminen and other researchers (Helminen et al 1997) shows some interesting recruitment variability that argues for certain density dependence factors causing cyclic recruitment. Vendace is an important commercial freshwater fish in Finland; as a result they have been studied very intensely in Lake Pyhajarvi from 1971 to the present. Vendace of age 0 and older are caught in a winter seine fishery, although the fishery is most efficient at catching age 2 fish. A study in 1993 by Helminen and Sarvala established that the final numbers of vendace in each year was determined by an interaction between a density dependent factor and a density independent factor. The density dependent factor was determined to be the driving force behind the cycle, while the density independent factor helped to establish the actual numbers in each age category. Using a least squares linear regression model Helminen and Sarvala were able to explain the population abundance of the vendace in Lake Pyhajarvi prior to 1993, and claimed good fit to this model as evidence of inter-cohort competition as the main driver of the cycle. They were able to explain 77% of vendace year class variation as resulting from inter-annual competition and summer temperature of the water.

Helminen and Sarvala argue that the density dependent factor that drove the cycle was asymmetric competition for food resources, between the age 0 and age 1 fish (Helminen and Sarvala 1993). A strong year class of age 0 fish will compete with the existing age 1+ fish. This will result in poor reproductive success for the age 1 fish because they are denied food during the gonad ripening period. The vendace fishery efficiently removes all fish of age 2+ so the primary reproductive cohort is the age 1 fish. The essence of this

argument is that a strong age 0 cohort will put the age 1 fish at a disadvantage so that they will produce a weak age 0 cohort the following year. This weak cohort will not compete successfully with the age 1 cohort and the age 1 cohort will reproduce successfully, leading to a strong age 0 cohort and beginning the cycle anew (Helminen and Sarvala 1993).

The density independent factor was summer temperature of the water after ice out. The summer water temperature has two major effects on the Lake ecosystem and these contribute to the final numbers of fish in each cohort. Summer water temperature affects predator density and the vendace larval growth rate. In this lake ecosystem the major predator of juvenile vendace larvae is age 2 perch (*Perca fluviatilis*), Helminen and Sarvala (1993) established an index of age 2 perch abundance using the summer temperature 2 years earlier. Summer water temperatures in the year that perch were hatched determined the final size of the age 2 perch cohort. The age 2 perch cohort in each year had a strong predatory effect on the vendace larvae. This effect was shown using a linear regression model to predict the total number of vendace in each year, and was shown to not be strong enough to overwhelm the cycling effect caused by intercohort competition between age 0 and age 1 vendace.

The linear regression model indicated that the other density independent factor was larval growth rate. Bigger larvae have a better survival rate and the warmer the summer temperature the better the larvae grow.

It is unclear why Helminen and Sarvala did not consider the possibility that age 1 fish are in fact competitively superior (in contest and food competition) to age 0 fish, and drive down age 0 survival when they are abundant. This would produce the same cyclic

pattern. Further, they do not explain how it could be that the numerically much less abundant age 1 fish the year after a weak age 0 cohort has been produced, could then produce a strong cohort of age 0 fish as observed, no matter how good the growth (and hence fecundity) conditions encountered by those low abundance fish.

Since 1993 there has been a fishery collapse in Lake Pyhajarvi due to overfishing of the vendace stock, and the two year cycle has disappeared. The stock has exhibited poor recruitment at very low stock sizes with continuing fishing pressure holding stocks at low numbers, leading to continuing very low recruitment; no cycling has been observed from 1993 to the last reported study (Helminen et al. 1997). This observation further argues against the possibility that weak age 1 cohorts were ever able to produce strong age 0 recruitment as Helmen and Sarvara had argued.

2.5 Brown Trout

Several investigators have studied interaction between cohorts of brown trout in several anadromous populations, and they show evidence of competition for habitat driving a cycle (Townsend 1989). These are not as directly relevant to my situation as the work of Borgstrom, et al. (1993), which investigates the cycling of brown trout populations in a lake based freshwater ecosystem. Borgstrom et al (1993) undertook a four year study of the brown trout population of Lake Skavant in eastern Norway. The study identified seven repeating patterns of dominant year classes at three year intervals between 1976 and 1992, data were collected from otoliths collected by seine net, gill net and electrofishing along with scale samples collected from gill netting conducted by the Federal Fisheries Management Branch of the Eastern Norway Region.

First the study determined that over the three years of the four year study , a single cohort of fish dominated the littoral habitat of the lake. The age 1 year class was dominant in 1989. In 1990 this same cohort was dominant in the littoral as the age 2 year class. Again in 1991 this same cohort (now age 3) dominated the littoral. While this cohort dominated the littoral there was little or no age 0 recruitment to this habitat. More support for a cycling population was found by this study when the numbers of fish of each year class that were caught in the gill net, beach seine, and electrofishing sampling conducted from 1989 to 1991 were examined. These data showed that the majority of fish caught came from only four year classes. They found that cohort years, 1979, 1982, 1985, and 1988 made up the greatest part of their catches and were much more numerous than neighbouring year classes. The gill net catch record provided by the Federal Fisheries Management Branch of the Eastern Norway Region for 1977 showed that the 1976 and 1973 cohorts were more numerous than other neighbouring year classes. Given this pattern of dominance with very regular peaks every three years, Borgstrom et al. hypothesize that the population cycle is a result of competition for habitat between cohorts of young brown trout. Juvenile brown trout normally rear in the outlet streams, but in Lake Skavant there is a very limited stream area suitable for rearing juvenile brown trout in the outlet stream of the lake, and the occurrence of age 0 fish in the littoral of the lake suggests early immigration to the lake in this stock. Brown trout adult prey upon juvenile brown trout and this could trap early immigrants in the littoral area of the lake. Borgstrom et al. surveyed the littoral areas of the lake and noticed that this area had very limited habitat suitable for rearing juvenile brown trout. When this limited habitat area is already occupied by a strong year class of older juvenile brown trout, they would drive

juveniles from younger age classes into marginal habitat where they would suffer much higher predation mortality. Until the abundant older age class move of juvenile habitat any following years would be heavily impacted by predation from adult brown trout and this could lead to the observed population cycle.

2.6 Causes of Cyclic Recruitment

The investigations of salmon, barramundi, vendace and brown trout, combined with theoretical work (Townsend 1989), has identified 3 main causes of population or recruitment cycles. First, external environmental factors can establish a strong or weak year class in a semelparous species, which when acted upon by the normal predation or fishing effects remains strong or is kept depressed. Second, recruitment effects whereby certain year classes have regular recruitment failures, as exemplified by the vendace in Lake Pyhajarvi, could possibly occur where competition for resources with age 0 fish retards the development of gonads in age 1 fish, provided the weak age 0 cohorts are still able to produce strong age 1 cohorts when they do mature. Finally intercohort competition within a species can lead to cycles when older juveniles are competitively superior to age 0 juveniles. This competition can take the form of direct contest competition for limited habitat for rearing (brown trout, vendace), reduction in food availability to younger juveniles, or direct cannibalism of one cohort on another (barramundi). It is not clear that the competition and cannibalism hypotheses can or should be considered distinct, in the sense that it really does not matter whether older juveniles eat the age 0 juveniles directly, or instead drive those age 0 fish to exhibit behaviours (habitat use patterns) that expose them to higher predation risk by older conspecifics or even other species.

Chapter Three: Study Area and Field Methods

This chapter details the study area and methods used for development of a visual survey method for juvenile pikeminnow. The watersheds that make up the study area on the Bonaparte plateau are briefly discussed. I first review the literature on visual surveys then explain the methods used in this study. Possible causes of variation and bias in visual surveys are discussed and related to the uses to which the observations are put, including estimates of abundance made by this project and observation of pikeminnow activity.

3.1 Study Area

Northern pikeminnow populations are resident in a small complex of lakes on the southern edge of the Bonaparte plateau located approximately 100 km north of Kamloops in the south-central interior of British Columbia. This is the site of an ongoing investigation of cultivation-dependence effects in eight small lakes (Fig 3.1). The lakes range in size from 2.7 to 8.4 hectares and are all located within 3.5 kilometres of one another. Each lake contains two species of fish: rainbow trout (*Oncorhynchus mykiss*) and northern pikeminnow. The northern pikeminnow inhabit all of the lakes in this complex, but juvenile recruitment occurs exclusively in lakes downstream of lake outlet spawning sites (Taylor 2005). Hence juvenile recruitment dynamics was studied only in three “nursery” lakes. These nursery lakes are known as Dad’s Lake, Moose Pasture Lake, and Cath Lake. These lakes are spread across two watersheds, with Dad’s Lake in the western Deadman watershed and Moose Pasture and Cath Lakes in the eastern Thompson watershed (Fig 3.1).

Several of the lakes in the study area have been manipulated by Brett van Poorten, David O'Brien, and Dr. Nathan Taylor as part of their graduate research into cultivation-dependence hypotheses. These students have conducted experimental reductions of the northern pikeminnow populations in Cath Lake in 2006 (van Poorten, in press) and Moose Pasture Lake in 2003 (Taylor 2005), with stocking rainbow trout into Dads, Moose Pasture and Cath Lakes so as to generate both decreases in pikeminnow abundance and increases in trout abundance. Body growth and abundance of both rainbow trout and northern pikeminnow are being monitored by an ongoing program of gill net and fyke net (trap) sampling. This monitoring includes both mark-recapture and depletion estimators of abundance (van Poorten, pers comm.).

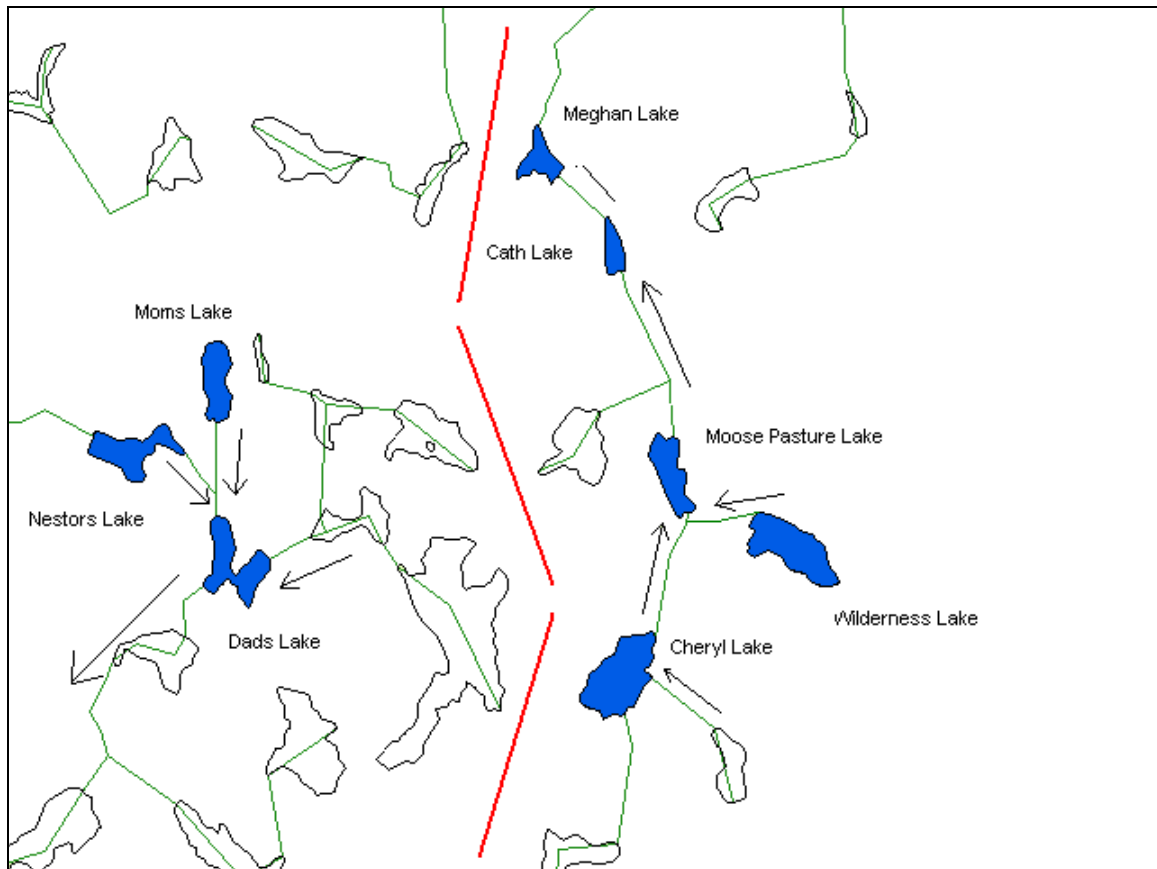


Figure 3.1 Map of study area with line showing east-west divide of watersheds and arrows showing direction of flow (from Taylor 2005).

3.2 Literature Review of Visual Survey Methods

Visual surveys are an alternative to traditional mark-recapture, catch-per-effort or other population sampling methods for absolute or relative abundance. They are most often

employed when there are logistic problems that prevent using a more traditional study type, for example inability to capture and mark very small fish effectively using nets and conventional tagging methods. When properly conducted, visual surveys can provide important ecological information including species richness, distribution and abundance (Sale 1997).

Visual Surveys usually take the form of either point counts or transect surveys, and have been a technique most often used to evaluate the abundance and diversity of species in hard-bottom aquatic habitats (Sale 1997, Samois and Carlos 2000). Since being introduced by Brock (1954), underwater visual census has been used for the evaluation of reef fish populations in a non-destructive manner. Much of the fisheries literature discussing visual surveys is very specifically related to coral reef ecosystems (Sale 1997, Samois and Carlos 2000, Colvocoresses and Acosta 2007). Many studies have shown that visual surveys are a useful tool for rapidly estimating abundance, biomass, and length frequency distribution of reef fish. Visual census both underwater and from shore have also been used routinely in conjunction with mark-recapture studies to estimate the abundance of salmon stocks and other fish in lake and river waters.

3.2.1 Transect Studies

Three types of transect studies are discussed in the ecological literature (Eberhardt 1978, Sale 1997): the line-intercept transect, the strip-transect, and the line-transect. Strip-transects and line-transect are used to estimate the number or density of organisms in a study area. In both cases the major challenge with these methods is in determining the proportion of organisms that are present, but are not counted. The line-intercept method is used only for large, sedentary organisms.

3.2.2 Line-Intercept Transect

The first of these methods, line-intercept transects, is based on the idea of counting individuals that intercept a line; the method depends on the observed organisms being large and stationary. The major application of this method is the analysis of plant communities and estimating cover where the proportion of the line that is intercepted by organisms is assumed to be proportional to the total area covered by the organisms (Eberhardt 1978). Line intercept transects are not suitable for the study of motile organisms and were not used in this study.

3.2.3 Strip-Transect

When conducting strip-transects the goal is to count only the organisms in a fixed width strip. This technique works best when the organisms being surveyed are easily spotted and abundant. This methodology is widely used and the fundamental question to be addressed when conducting these surveys is how to account for organisms present in the transect area, but not seen by the observer (Eberhardt 1978). This problem of uncounted organisms is addressed by a multitude of empirical methods that generate a frequency of detection function (as a function of distance from the transect line) and apply it to the number of individuals observed (Eberhardt 1978). Biases in strip transects are a result of the observer having difficulty seeing the organisms, or difficulty in accurately identifying and recording the numerical details of organisms seen (Sale 1997). Strip transects are used extensively in underwater visual surveys of reef fishes; as a result a number of studies have been conducted to evaluate their effectiveness. Though the use of strip-transects in underwater visual survey has become widespread in ecology, there has been no standard of method (Sale 1997, Colvocoresses and Acosta 2007, Samoilys and Carlos

2000). Since there is no standard methodology the biases must be carefully evaluated for each study.

3.2.4 Line-Transect

A line-transect is very similar to a strip transect, but rather than evaluating the fish in a strip of fixed width, all organisms are recorded that are sighted from a transect line, along with their distances from that line. There is a breakdown of line-transects into two subtypes; surveys of animals that react to the observer or “flush”, and organisms that are not affected by the observer (Eberhardt 1978). If the organisms flush or have a conspicuous reaction to the observer, then the abundance estimates are based upon the probability of an animal flushing based on the distance between the observer and the animal (Eberhardt 1978, Quinn and Gallucci 1980). If the organisms do not flush then a probability model must be created to determine the odds of seeing an organism at varying distances from the transect line, and these probabilities are combined with the actual observer counts and distances in order to generate an estimate of abundance (Eberhardt 1978). The biases in this case are similar to those of a strip-transect: observer visibility, identification and accurately enumerating the study organisms, but with an added uncertainty of estimating the distance from the line at which each organism is observed (Eberhardt 1978, Quinn and Gallucci 1980).

3.2.5 Point Surveys

A point survey is a specialized strip-transect survey where the “transect” is a small fixed area rather than the usual long strip. The fish within a specific area are counted for a fixed period of time. As long as the full area of the stationary survey is visible from the observation point, the procedure is relatively simple: easily spotted organisms are

counted first and the borders are watched for incoming and outgoing mobile organisms while the area is searched in detail for hidden organisms (Eberhardt 1978, Sale 1997).

Bias in point surveys is a result of the same issues of visibility, identification and estimating size and numbers of fish as for transect surveys (Eberhardt 1978, Sale 1997). Using a small area which is totally exposed to the observer allows the observer to view a higher fraction of organisms present (Eberhardt 1978, Sale 1997), but mobile organisms can enter the study area, artificially inflating the numbers observed (Sale 1997).

3.2.6 Addressing Biases in Survey Design

A number of authors have explored the problems of visual survey design in order to address the biases inherent in this type of study (Sale 1997, Samois and Carlos 2000, Colvocoresses and Acosta 2007). Visual surveys are considered a useful tool so long as a study using visual surveys explicitly recognizes that the surveys do not count all of the organisms present (total abundance), but instead a properly designed visual survey can make a precise estimate of a consistent fraction of the total numbers of organisms present (Eberhardt 1978, Sale 1997). That is to say, visual surveys can provide an index of abundance that is proportional to the actual abundance, when the biases inherent in the method are recognized and corrected so far as possible. The literature suggests that bias in visual surveys arises because of two main reasons, observer effects and study design effects (Sale 1997). The literature advises that there is no standard methodology, and that addressing each of the sources of bias is necessary when the investigator designs a visual survey (Sale 1997).

3.2.6.1 Observer Effects

“Observer effects” is a catch all phrase, in this case used to indicate a variety of possible biases that can be introduced by the observer while conducting a visual survey. Observer survey experience has been directly linked to number of fish and number of species counted per survey (Williams et al. 2006, Edgar et al. 2004). More experienced observers have been shown to see a higher proportion of the organisms in a survey area and are more likely to identify more species of organisms in a survey (Williams et al. 2006). Research has also shown that the accuracy of estimates of fish length is also closely linked to observer experience, after a certain threshold of experience the accuracy of estimates of length increased (Edgar et al. 2004).

3.2.6.2 Study Design

Study design can introduce bias by neglecting to account for changes in visibility and by not fitting the survey to the biology of the organisms being studied (i.e. by not stratifying the observation process in relation to temporal and spatial patterns of habitat use and related behavioural changes that can influence visibility). An obvious source of bias is that changes in visibility of organisms must not be confused with changes in abundance; visibility is usually a function of weather and time of day (Eberhardt 1978, Sale 1997). When surveying fish, water quality is also an important factor, in particular changes in water clarity can affect visibility of fishes (Sale 1997) and changes in temperature, oxygen concentration etc. can affect both behaviour and fine-scale distribution of individuals relative to survey points or transects. Additional consideration must be given to ensuring that the survey design incorporates the various types of habitat that the organism uses. Many organisms have a preferred habitat and display patchy distribution,

so the survey must be scaled or stratified to account for patches of high and low density (Sale 1997, Samois and Carlos 2000). Organism behaviour can have a confounding effect and the survey should account for movement of the organisms. Care must be taken to avoid a design which either underestimates abundance because organisms that are flushed out of the survey area are not counted, or that overestimates abundance because of double counting organisms that move into the survey area more than once (Sale 1997).

3.3 Visual Survey Methods for Juvenile Northern Pikeminnow

3.3.1 Strip Transect

Over the course of the three summers of investigation in this study, 112 visual surveys were undertaken. Similar surveys had been carried out in two of the lakes (Dads, Moose Pasture) in two previous years by Taylor (2005), but these were not carefully standardized for fish size when abundances were recorded. In 2005, 8 surveys were conducted to refine the technique of visual surveying from boat and shore. In 2006 and 2007 a series of 104 surveys were conducted from the shore of the three lakes. The following subsections explain the survey method, address the most serious practical problem encountered during the surveys (estimating numbers of fish in large shoals), and discuss the types of bias that will affect the indices of abundance

3.3.1.1 Survey Method

In order to arrive at an index of the abundance of juvenile pikeminnow, strip-transect surveys were conducted from shore. Each strip transect area was a full circumference of the lake and extended from shore to a distance of up to 3 meters offshore (less in areas of steep shoreline where depth and water clarity precluded seeing small fish near the bottom

further than 1-2 m from shore). Shore surveys were carried out by the investigator walking at a slow, steady pace around the circumference of the lake. While walking the investigator recorded the numbers, size, apparent age (based upon length) and species of all fish observed.

A handheld global positioning system (GPS) was used to record the position of each fish (or shoal) seen, and to map all observations. When obstacles or weather conditions prevented observation of the fish, the investigator noted these conditions on the map. In addition the investigator recorded the areas of the lakeshore that were shaded by trees on the map, at the time of day when the transects were conducted. For each transect a map was attached to a data sheet upon which was recorded the time of observation, the GPS coordinates and estimated sizes of northern pikeminnow shoals. Interactions between larger and smaller fish, fish behaviour, and habitat choices were also recorded on the data sheets.

3.3.1.2 Estimating Numbers

The investigator was only able to record crude estimates of numbers of fish when pikeminnow were observed in larger shoals of 10+ individuals. Typically, such shoals of pikeminnow were initially identified by their flight reaction to the investigator.

Behavioural observations over the years (Taylor, pers comm.) have shown that pikeminnow typically gather in shoals segregated by length, and exhibit strong flight responses to movement of people along the shore. The average body length and number of the fish in each shoal was estimated as they fled from the investigator. The investigator then moved forward and recorded the remaining slower moving (usually solitary) fish that did not show a flight reaction. To calibrate the estimates of numbers of

fish in a shoal, whenever possible the investigator would record an estimate of shoal size, then attempt to accurately count the individuals in the shoal. This procedure allows calculation of variability in estimates of numbers of fish in a shoal, and helped the investigator fine-tune his visual estimation skills.

3.3.1.3 Bias

When generating an estimate of abundance from visual surveys, the biases introduced by survey design and observer effects must be taken into consideration. The surveys used in this study are designed to eliminate, where possible, or maintain a constant bias between surveys.

3.3.1.3.1 Design Bias

Eliminating or controlling the sources of design bias means that the surveys should consistently sample the same proportion of the total population, so as to at least allow the surveys to be used as indices of abundance. The use of the full circumference of the lake as a single transect minimizes sources of bias associated with patchy distribution of fishes (assuming small juveniles do not form offshore patches, a phenomenon we never observed even for areas where there was shallow water, <10cm depth, far offshore).

Circumnavigating the lake means that the survey examines the entire habitat spectrum in the lake rather than a set of short transects or small area samples that might non-randomly target aggregations of pikeminnow. To reduce the likelihood of over or underestimating numbers of fish, whenever possible the fish in each shoal were counted as they flushed offshore from the observer (flushed shoals fled offshore and then reformed behind the observer) and only shoals ahead of the observer were counted. The observer moved forward at a consistent rate so that the observer was past the shoal before it returned to

shore. Two surveys were made by two observers with the second observer following behind and counting aggregations of minnows to verify that the minnows that had fled offshore do return to the same locations and to try to determine if there were any shoals missed by the first observer.

The visibility of fish is a function of several factors; weather conditions, light levels, and water clarity are the most important (Sale 1997). To minimize variability due to weather conditions, surveys were only conducted on sunny days with light breezes and no rain. If there was any wind or rain that disturbed the surface of the water, or heavy cloud that reduced light levels, then the survey was halted. To standardize for effects of light levels, surveys were conducted only on days with little or no cloud cover and between 0945 and 1700 hours.

There was also concern about spatial variability in visibility due to emergent and floating macrophyte cover (sedges, water lilies). Juvenile pikeminnow were expected to concentrate in such dense cover areas as a way to avoid predation risk. However, repeated attempts (over at least a dozen inspection periods of 5-20min by the investigator, by Dr. Walters, and by Dr. Taylor) to detect juveniles in such areas, by standing quietly next to or within them and waiting to see movement, resulted in only a few sightings of individual juvenile fish and small (2-10 fish) shoals. It is not possible to rule out downward bias in overall counts due to hiding behaviour in heavy cover, but there are no indications that such behaviour was either common or changed systematically with season or juvenile density.

3.3.1.3.2 Observer Bias

Using the same observer for all visual surveys provided a consistently increasing level of experience. The surveys in 2005 were used to train a single observer to a basic level of experience in visual surveys. Since a single observer was used, a consistent fraction of the fish present should have been vulnerable to observations except for effects of habitat factors or variability in sunlight. The training surveys when combined with consistent handling of fish of various sizes leading up to and during the visual survey process was also expected to increase the accuracy and reduce the variability of the estimates of fish length.

3.3.2 Point counts and Behavioural Observations

In July and August of 2006, behavioural observations were conducted in selected small study areas (as point counts), in order to try to better understand diurnal behavioural patterns in the early life history of the juveniles. These observations were also aimed at evaluating possible sources of bias in counts related to time of day and weather conditions.

3.3.2.1 Survey Method

5 stationary day-long observations of juvenile minnow behavior were conducted on the nursery lakes (2 on Moose Pasture, 1 on Cath, and 1 on Dad's) from July 12th to Aug 24th 2006. On each lake a position on shore was chosen and a survey area was defined. Each such area was a transect of 10 meters length along the shoreline, and had a width of 3 meters from shore into the lake. These point observation dimensions were chosen so that the whole area of the point survey was clearly visible at one time. Habitat details including placement of rocks and debris as well as substrate type and colour were noted

on a map of each area, and the area was subdivided into 2.5 by 1 meter zones. Over the course of the day the investigator recorded all fish observed, noting where (which zone) and when (time of day) the fish were first observed, recording the size of fish observed, and looking for behavioral cues making special reference to direction of travel, speed of travel, feeding behaviors, and interactions between individuals. The investigator recorded weather conditions and changes in light intensity as well as shadows falling on the study area. Observations were made very carefully before, during, and after instances of changes in weather in order to get counts of fish in the study area under different light and water conditions. These surveys were designed to examine pikeminnow activity to look for temporal patterns of activity and for a relation between weather conditions and activity, and to evaluate the effects of weather and other factors on visibility. These surveys were not to be used as an index of abundance of pikeminnow in the study lakes.

3.3.2.2 Bias

Bias in the point surveys was evaluated in a similar manner to the bias in the strip transects. Sources of bias that arise from the design of the survey and observer effects must be addressed when using the data from these surveys.

3.3.2.2.1 Design Bias

These surveys, conducted at fixed points on the shoreline, were not aimed at developing a measure of abundance for the study lakes. The point surveys were designed to make observation of pikeminnow activity and trend in apparent pikeminnow abundance (visibility) at fixed spots over the course of a day. A source of bias in these observations is site selection. The site selected must have a range of habitats, so that visibility and

behaviour of fish can be evaluated in different habitat types, but the site must also be contained so that the observer can see the whole of the study area from one point. Fish movement is another source of bias; fish movement during changes in visibility conditions or movement of fish over time could introduce bias in this survey.

Unobserved movement of fish could change abundance in the survey area during episodes of poor visibility, hence biasing the estimates of visibility tests. To reduce variability in counts associated with temporal movement of fish in and out of the study area, fresh counts were made with every change in visibility conditions.

3.3.2.2.2 Observer Bias

A major potential source of bias in these small-area observations is in estimation of movement speed and distance of fish. Measuring and marking distances in the survey areas before beginning the observations, and evaluating distance traveled as number of grid squares traversed, should have reduced bias in the estimates of speed and distance. Using the same trained observer for all observations should have produced a consistent bias, allowing at least for comparison between surveys.

Chapter Four: Results

The observations of juvenile northern pikeminnow distributions and behavior over 3 summers provided several insights into the life history of this species on the Bonaparte Plateau. The visual survey method was tested and accuracy in estimating lengths and numbers was determined. The repeatability of the visual survey method was also determined, and was found to be surprisingly good. Some visual surveys results are presented in this chapter in addition to the method testing; these results summarize overall observations made while conducting stream surveys of the inlet and outlet areas of the survey lakes, boat surveys of the study lakes, point visual surveys, transect visual surveys, and include data collected by Nathan Taylor and Brett van Poorten.

Transect visual surveys undertaken in 2006 and 2007 show some very interesting patterns of abundance that may indicate cyclic recruitment of juvenile northern pikeminnow in the lakes of the study area. Transect visual surveys also show a decline in abundance of juveniles over the course of the summer which can be used to approximate the survival rates of these juveniles.

The point surveys and other surveys show that juvenile northern pikeminnow have specific habitat preferences and two interesting behavioural patterns. The behaviour patterns observed are a positive correlation between activity level and sunlight, and intercohort aggressive behavior. Northern pikeminnow in the age 0, 1, and 2 years were observed in the point and transect surveys. Individuals of the age 1 cohort (but not age 2) were observed in the point survey and transect surveys to show aggressive behaviour towards individuals of the age 0 cohort. The results of the point surveys in particular

provide important clues that will help to determine the cause of the recruitment cycle should that cycle prove to be persistent in future years.

4.1 Accuracy and Repeatability of Visual Surveys

4.1.1 Estimating Numbers and Length

4.1.1.1 Estimating Numbers

Estimating the number of fish in a shoal is a well studied practice in visual surveys, and it has been shown that an experienced observer can accurately estimate the number of fish in a school provided school size is not too large, e.g. <100 fish (Williams et al. 2006, Edgar et al. 2004). To reinforce these findings and evaluate the effectiveness of the observer conducting the pikeminnow visual surveys, whenever possible the estimate of numbers in a shoal was followed up with a more detailed count of the exact number of fish in that shoal. This provided an estimated and an actual number of fish in 85 shoals in 2006, and 45 shoals in 2007). This information is summarized as graphs of estimated numbers in a shoal graphed against the actual numbers in the shoal (Figure 4.1 and 4.2). In these graphs a line of slope 1 extending from the origin is included to demonstrate what a perfect estimate for each actual shoal size would be. In 2006 (Figure 4.1) it is obvious that the estimates were fairly tight but tended to overestimate at larger shoal sizes. The mean of the ratio of estimated counts to actual counts is 1.05 suggesting a slight upward bias. Presentation of this information in the form of a histogram of ratios of estimated shoal size divided by actual shoal sizes suggest that the estimates tend to be slightly biased upwards. But if the area under the histogram above 1.0 (44) is compared to the area under the histogram below 1.0 (43) it is obvious that in 2006 there was only a

slight tendency to overestimate numbers in a shoal, that mainly due to several very large overestimates of 1.5-1.7 times.

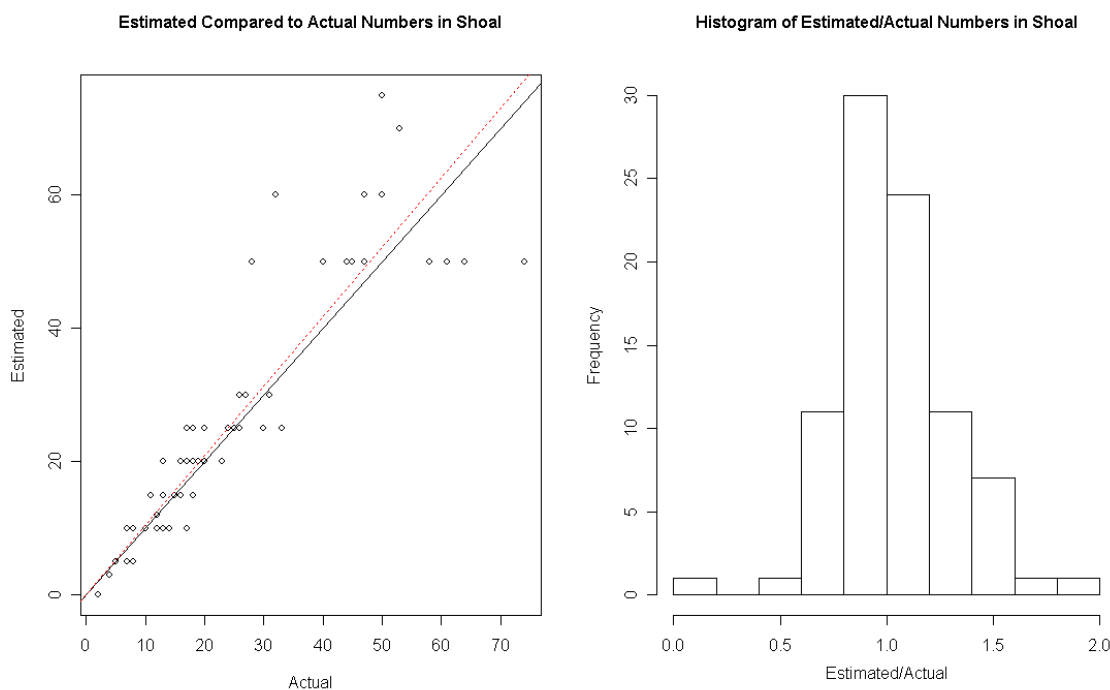


Figure 4.1 Estimated versus actual (complete count) numbers of fish in shoals, 2006 data from all lakes. The solid line on left hand graph is a 45 degree line from the origin while the dotted line is an estimated regression line with a zero intercept.

In 2007 (Figure 4.2) as in 2006 estimated and actual numbers of fish in shoals were collected whenever possible in order to verify that the estimates of numbers were reasonably accurate. In 2007 there was a smaller sample size than 2006 ($n=45$ compared to $n=87$), but as in 2006 the estimates of numbers of fish in a shoal were surprisingly accurate. The mean of the ratio of estimated counts to actual counts is 1.02 suggesting a slight upward bias. Presentation of this information in the form of a histogram of ratios of estimated shoal size divided by actual shoal sizes suggest that the estimates tend to be slightly biased downwards the area under the graph above 1.0 (20) is compared to the

area under the graph below 1.0 (28). This shows how close the estimates are to the actual numbers observed in 2007.

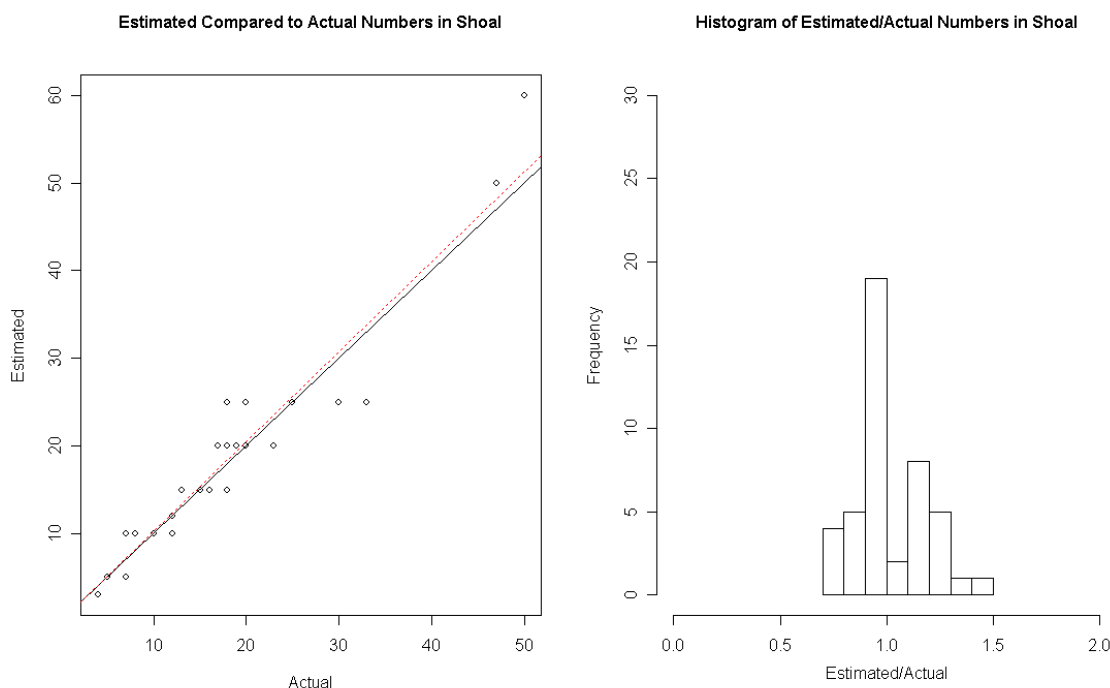


Figure 4.2 Estimated versus actual (counted) numbers of fish in shoals, 2007. Data from all lakes combined. The solid line on left hand graph is a 45 degree line from the origin while the dotted line is an estimated regression line with a zero intercept.

4.1.1.2 Estimating Lengths

Estimating the lengths of fish in the visual survey is an important part of this study, since the length data are used to identify abundances of age 0, 1, and 2 juveniles. Because the juvenile northern pikeminnow are invulnerable to most gear types and because there is a fairly substantial overlap in lengths-at-age for the older (age 1 and 2) fish, it is hard to quantify the accuracy of estimating lengths. When examining age 0 age northern pikeminnow, I found sharp distinctions in morphology (color, head size relative to body size) and total length that allow this age category to be accurately distinguished from all other age categories. In the study lakes, age 0 northern pikeminnow emerge from the egg

as 5 mm larvae and appear in littoral habitat as a translucent larvae of between 12-17 mm. They grow several mm over the course of the summer, and end the growing season have total lengths between 22 and 30 mm. Towards the end of the season, they change colour, are no longer translucent and have a fully developed body. Age 1 fish are also quite easy to distinguish from age 2 fish because they have a very tight length distribution at the beginning of the growing season, near the length where they ended the previous season as age 0s.

Age 2 and older fish are harder to distinguish because there is a fair amount of overlap in the length-age distribution of these fishes. Nathan Taylor analyzed the length-age relationship of the northern pikeminnow in this system as a part of his doctoral thesis (Taylor 2005; results summarized in Fig. 4.3). He collected and aged 945 lapilli otoliths and used these data to evaluate five different methods of fitting a vonBertalanffy growth curve. Taylor also indicates that because of various biases inherent in the methods used to collect fish for otoliths because of size selective mortality, there is a bias towards overestimating the lengths of younger fish. In addition his data show a great variability in length at all age categories.

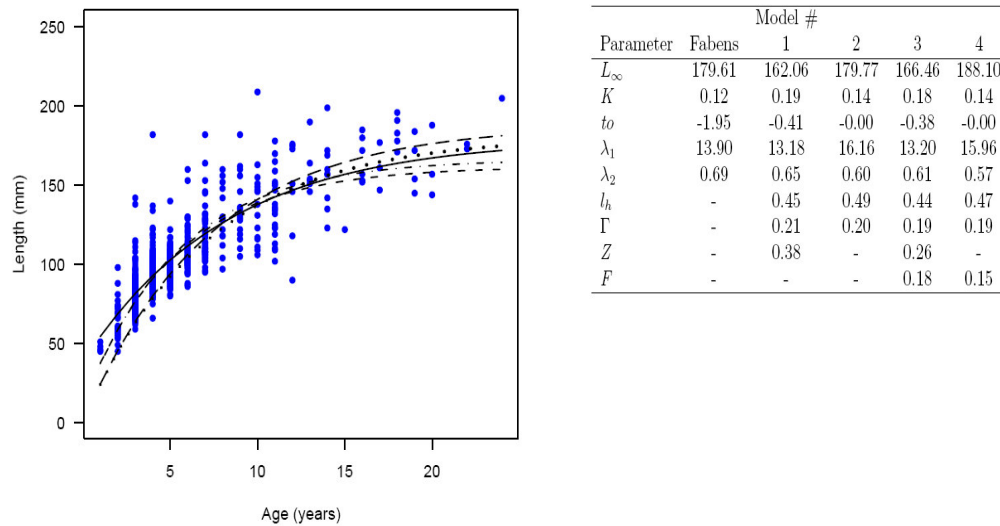


Figure 4.3: Growth curves fit to northern pikeminnow data by Nathan Taylor, using 5 estimation methods: solid=Fabens, dashed=full likelihood (1), dotted=reduced likelihood (2), dotdash=full likelihood with Fishing (3), longdash=reduced likelihood with Fishing (4). (from Taylor 2005). Note that the few age 1 fish included in Taylor's sample were collected in a fall depletion netting, when these fish had reached nearly their age 2 spring size; further, only the largest age 1 individuals could be captured by the nets used in the depletion (net mesh size allowed escape of smaller individuals).

A series of hand net captures of fish were carried out to determine whether the fish being observed as being a certain length and age category (0, 1, 2+) were actually of that same length and age. Fig. 4.4 shows estimated lengths and actual lengths distributions as well as length at age of fish captured by hand netting. There is a good agreement between estimated length and actual lengths for age 0 fish, while age 1, age 2 and age 3 fish show considerable overlap in body length. The captured fish were examined in detail while collecting otoliths for later preparation; these examinations showed considerable morphological differences separating the age 0, and age 1 fish, from the age 2 and age 3 fish the lengths of the age 1 fish collected overlap with those of the age 2 and 3 fish

because these fish were collected late in the summer and as a result had undergone most of that seasons growth.

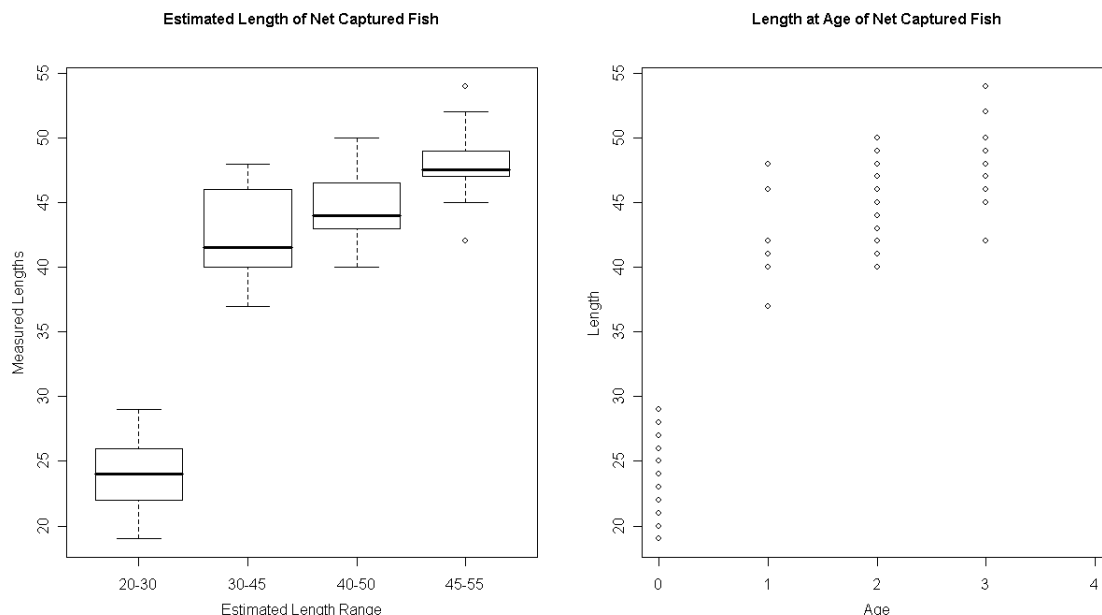


Figure 4.4 Lengths and estimated ages of juvenile pikeminnow: mean lengths, standard deviations and 95% Confidence Intervals for estimated length Ranges, and length-age plot for estimated ages. Estimated lengths are by visual examination before capturing and measuring the fish. Note age 0 and age 1 fish are easily distinguished by length.

When estimating ages of northern pikeminnow in shoals during the main period when visual surveys were conducted there was considerable overlap in length of age 1, 2, and 3 pikeminnow which meant that length alone was not a sufficient metric for age, body depth and maturity were also considered when estimating length. In the surveys conducted age 0 fish are semi-translucent fish of 20-30 mm in length, while age 1 fish are thinner bodied fish between 30 and 45 mm, and age 2 fish are full bodied fish of between 40 and 50 mm. Age 3 fish are deep bodied fish of between 45 and 55 mm. The deep-bodied fish appeared visually similar to sexually mature adult northern pikeminnow.

4.1.2 Repeatability of Observations

To test the repeatability of the visual survey observations of juvenile pikeminnow, two surveys were conducted with two observers, one following the other. These surveys were conducted the 30th of July 2007 on Moose Pasture Lake and the 31st July of 2007 on Dads Lake. In the first set of observations, the observers compared the number of age 0 northern pikeminnow that they observed in short sections (50-100m) of the visual survey transect of Moose Pasture Lake. The second set of observations was conducted on Dads Lake where the two observers compared the number of shoals of pikeminnow they observed in sections of the visual survey transect. These observations (Fig 4.5) showed that there was good agreement in numbers of age 0 fish seen in Moose Pasture Lake, and numbers of shoals of older fish (mainly age 1 and 3) seen by the two observers in Dad's Lake.

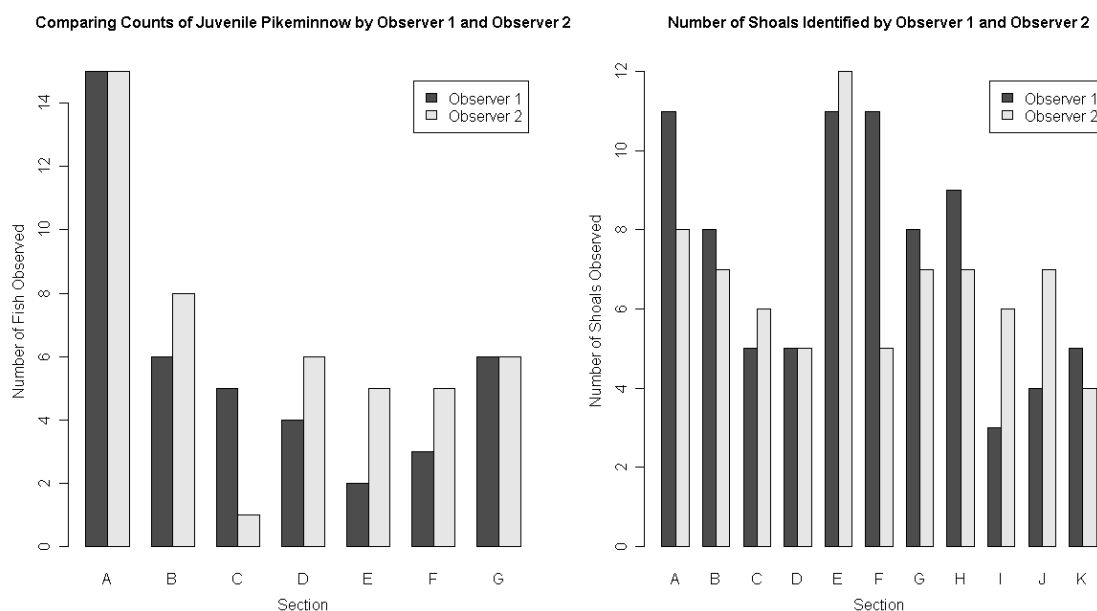


Figure 4.5 Fish counts in sections of a transect of Moose Pasture Lake (left) and shoal counts in sections of Dads Lake (right), by two observers counting each section independently. Sections were 50-100m lengths of shoreline, designated by letters.

The two observers were separated in time by approximately 1/2 hour; shoals definitely returned to shore after being scared by the first observer, and in most cases were obviously the same shoals as spotted by the second observer. Applying a t-test to examine the observations in both cases shows that there is not a statistically significant difference between the two sets of observations ($p=0.72$ for counts of juvenile pikeminnow, and $p=0.51$ for counts of number of shoals).

4.2 Pikeminnow Behaviour

4.2.1 Habitat Preferences

Habitat types used by the juvenile northern pikeminnow were recorded as part of the transect surveys throughout 2006. The information collected in 2006 show that the juvenile northern pikeminnow have very specific habitat preferences (Fig. 4.6). Habitat types were defined in various manners considering several habitat characteristics including water depth, density of emergent grass or other vegetation, and the presence or absence of woody debris. Water depth was evaluated as either deep or shallow, with deep being 10 cm and deeper. Density of vegetation was evaluated as either low or high density depending on the distance between clumps of grass or plants around the spot where the pikeminnow observation was taken. Vegetation density was considered to be low if there was on average more than 30 cm between plant stems.

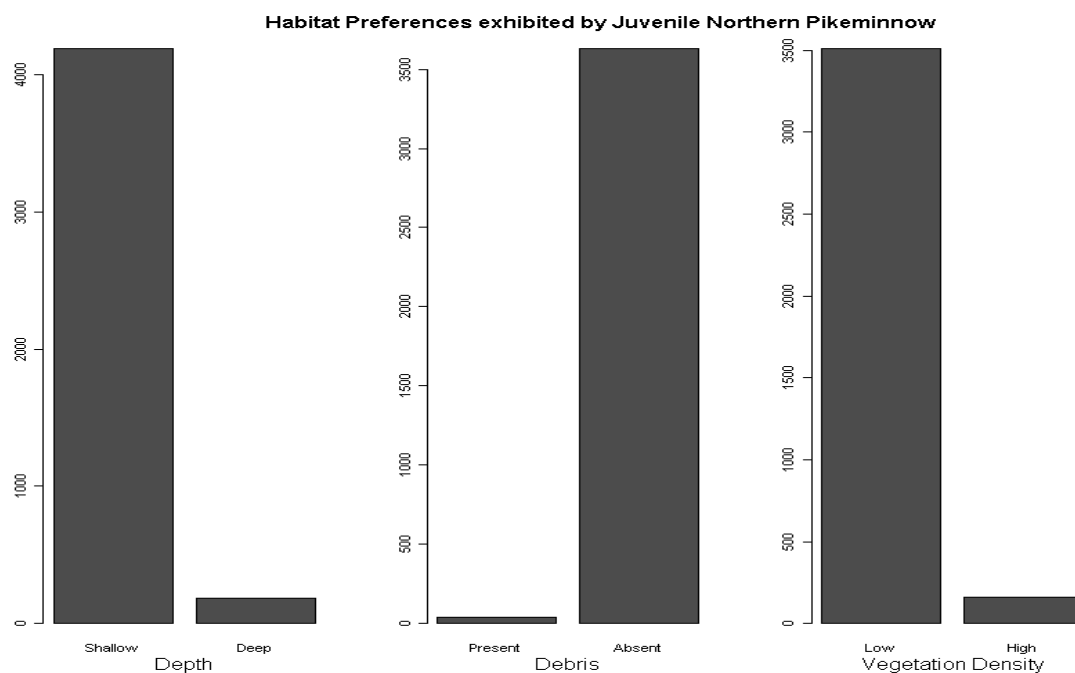


Figure 4.6 Numbers of juvenile pikeminnow observed by depth-debris-vegetation habitat types. Data are totals over both point and line transect samples.

Chi-squared tests were used to confirm that there are significant differences in the habitat preferences observed ($P = < 2.2e-16$ for depth, $P = < 2.2e-16$ for debris, $P = < 2.2e-16$ for vegetation). It is obvious from Fig. 4.6 that juvenile northern pikeminnow prefer shallow water to deep water, low density of vegetation to high, and habitat without woody debris. As noted earlier, considerable time was spent watching dense vegetation sites to determine whether juvenile pikeminnow might simply be less visible in such sites, and such observations consistently failed to detect large numbers of juveniles.

4.2.2 Temperature Gradients

Noting that the juvenile pikeminnow have a preference for shallow water and that this preference might be driven by thermal preference rather than predation risk avoidance, a series of temperature observations was taken to examine the temperature gradient

between the offshore and shallow inshore areas of the study lakes. Temperature gradients of between 1.0 and 10.5 degrees Celsius were observed under different conditions on all three lakes, i.e. the shallow water was as much as 10 degrees warmer than adjacent deeper water. The temperature gradients observed all had a similar structure. Water was warmest on shore, and water temperature declined, often sharply (as a strong vertical thermocline or thermal bar), as distance from shore increased. The thermocline distance from shore appears to be a function of water mixing rates, sunlight intensity, and water depth; this relationship needs to be investigated in greater detail. More study of the effect that this temperature gradient has on juvenile pikeminnow has yet to be completed. The following figure illustrates the temperature gradient as a function of distance from shore. A series of 24 sets of temperature measurements were taken between the 14th and 24th of August 2007 on the three study lakes. In 14 sets of measurements a difference in temperature was observed between the shoreline and deeper water.

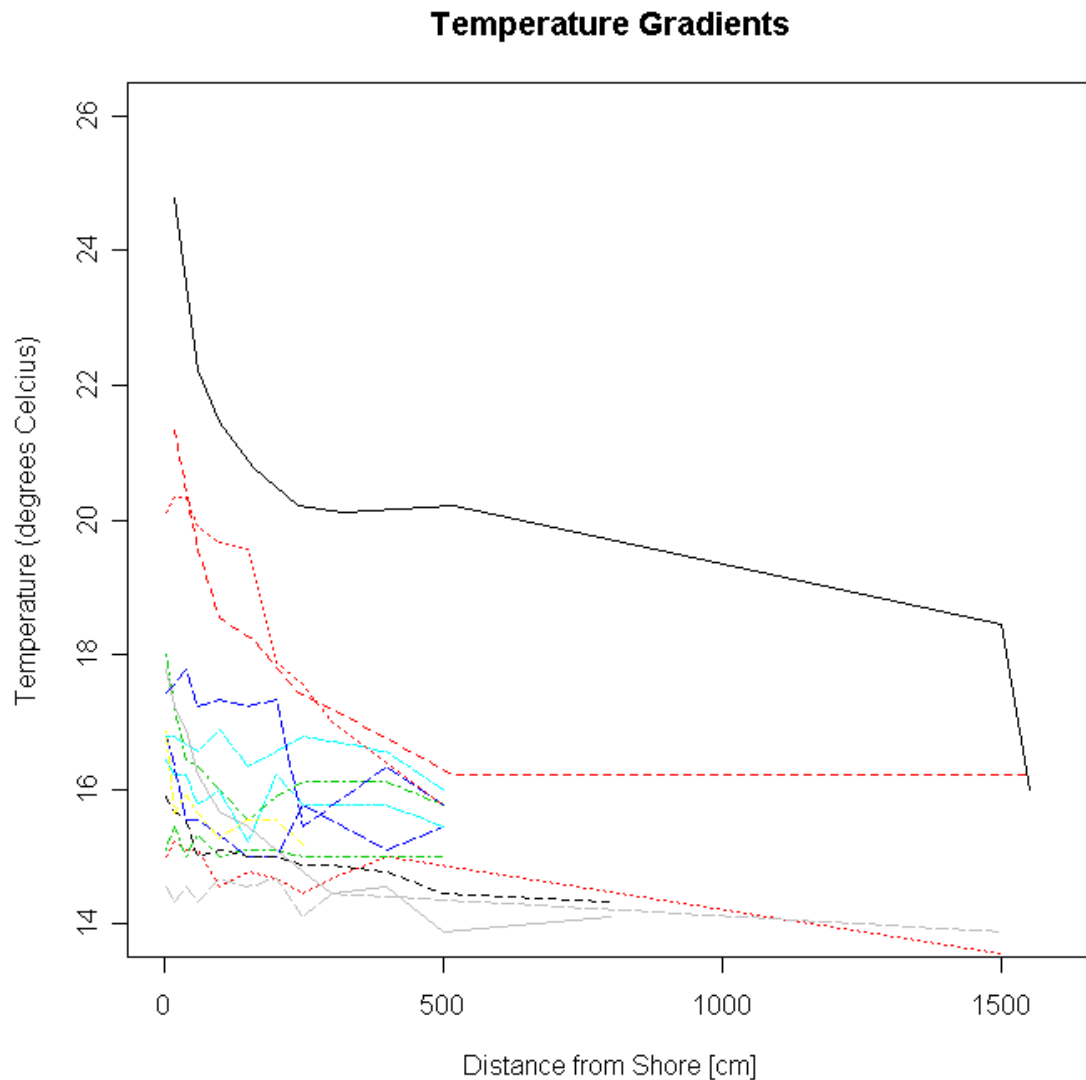


Figure 4.7 Water temperature gradients measured in late August 2007. Each line on the figure corresponds to a measured temperature gradient.

It is important to note that in all cases the warmest water is in the shallowest habitat closest to shore. Few transects were carried out but some patterns did appear. The warmer water was invariably associated with intense, direct sunlight. Several transects were taken over the course of a day at the same locations and in particular two sets of transects clearly show this pattern. In Figure 4.8 the effect of cloud cover on the inshore

water temperature is shown, and Figure 4.9 shows the difference in temperature when shoreline trees are shading the transect area.

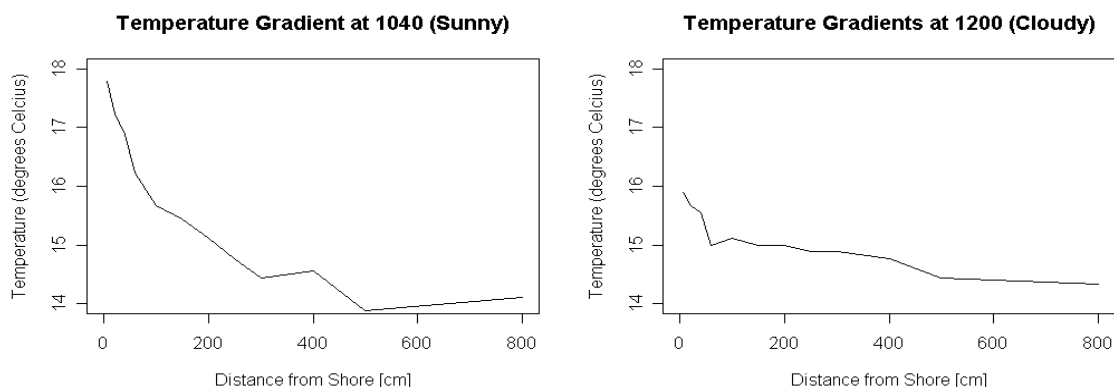


Figure 4.8 Temperature gradients taken at the same location on August 21st 2007 in Moose Pasture Lake. The gradient on the left was taken at 10:40 am and shows a 3.6 degree Celsius change from onshore to offshore. The temperature gradient on the right was taken later that day and shows a 1.5 degree Celsius change from onshore to offshore. The air temperature and weather conditions were constant between the two transects but the second gradient was taken during a period when the transect site had been shaded by cloud cover for at least 30 minutes.

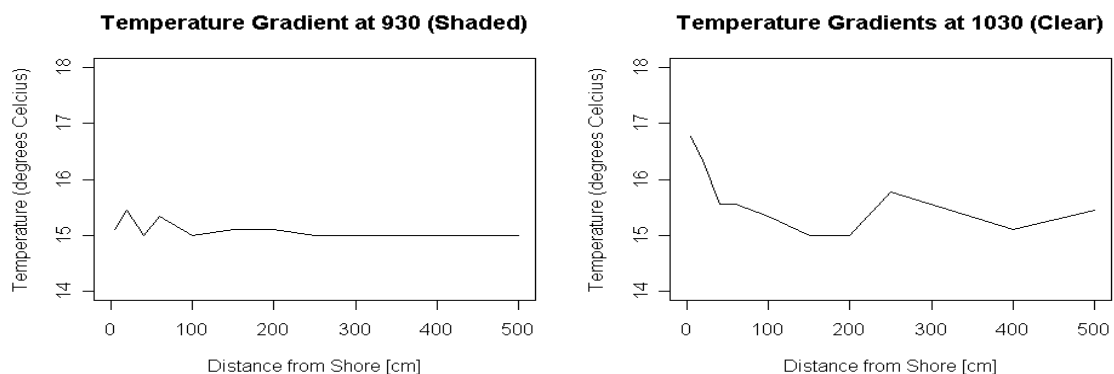


Figure 4.9 Temperature gradients taken at the same location on August 17th 2007 in Moose Pasture Lake. The gradient on the left was taken at 9:30 am and shows a 0.2 degree Celsius change from onshore to offshore. The temperature gradient on the right was taken an hour later that day and shows a 1.3 degree Celsius change from onshore to offshore. The air temperature and weather conditions were constant between the two transects but the first gradient was taken during a period when the transect site had been shaded by trees.

4.2.3 Activity and Sunlight

While conducting a total of five point surveys around the three study lakes in 2006, an interesting observation about the activity levels of juvenile northern pikeminnow was made. It appears that activity levels of juvenile northern pikeminnow are directly influenced by sunlight and/or the rapid inshore temperature change that accompanies sunny conditions. During the course of the point surveys the investigator had the opportunity to watch the behaviour of shoals of fish over an extended period. Given the small size of the point survey area there was a great deal of movement of fish in and out of the survey area, but there were also long periods of time where the investigator was able to observe the behaviour of shoals of juvenile pikeminnow in different lighting conditions. The main result from these observations is that when the sunlight intensity was lowered by partial or full cloud cover, activity by the juvenile pikeminnow decreased markedly and often stopped, with the pikeminnow settling to the lake bottom and resting. As the light intensity increased when the sun emerged from behind clouds, there was a delay of up to several minutes, and then activity resumed (fish moved up from the bottom, moved about apparently in search of food). During the mid-day and early afternoon when there was the most intense sunlight on the study areas, there was the greatest amount of activity with juvenile northern pikeminnow engaging in a variety of energetic behaviours. These behaviours included digging in the substrate of the lake, rising to the surface and rapidly swimming through the study plots.

The same general response to sunlight was noticed in making around-lake transect walks on days when cloud cover varied greatly. Very few fish were seen moving actively in the water column and avoiding the observer during early morning (before 10 AM) and

cloudy conditions. This response to light intensity was also noticed in areas of the study lakes that became shaded in the afternoon (after 2 PM). Areas of the study lakes that were in full sunlight during the morning were thrown into shade in the afternoon and the number of fish observed moving in the water column or displaying a flight reaction to the observer decreased as an area was shaded.

Moose Pasture Lake is the one lake in the study area in which the whole lake is free from shade for at least part of the day; as a result it shows the strongest evidence for the relationship between sunlight intensity and activity levels. Moose Pasture Lake is roughly oval and 5.9 hectares in area; it is 556 meters long and 203 meters wide. The lake is oriented with its long axis running from north to south, and since the lake is ringed by tall trees there is a dramatic difference in the amount of shade along the shoreline of the lake depending on the time of day. In the mornings the eastern shore of the lake is in shade while the western shore is in direct sunlight, at mid-day the whole lake is free from shade, and in the afternoons the western shore of the lake is shaded while the eastern shore is in direct sunlight (Fig. 4.10). The north and south ends of the lake are swampy areas that have much less tree cover than the western and eastern shores, as a result some parts of these areas are in sunlight for the whole day.

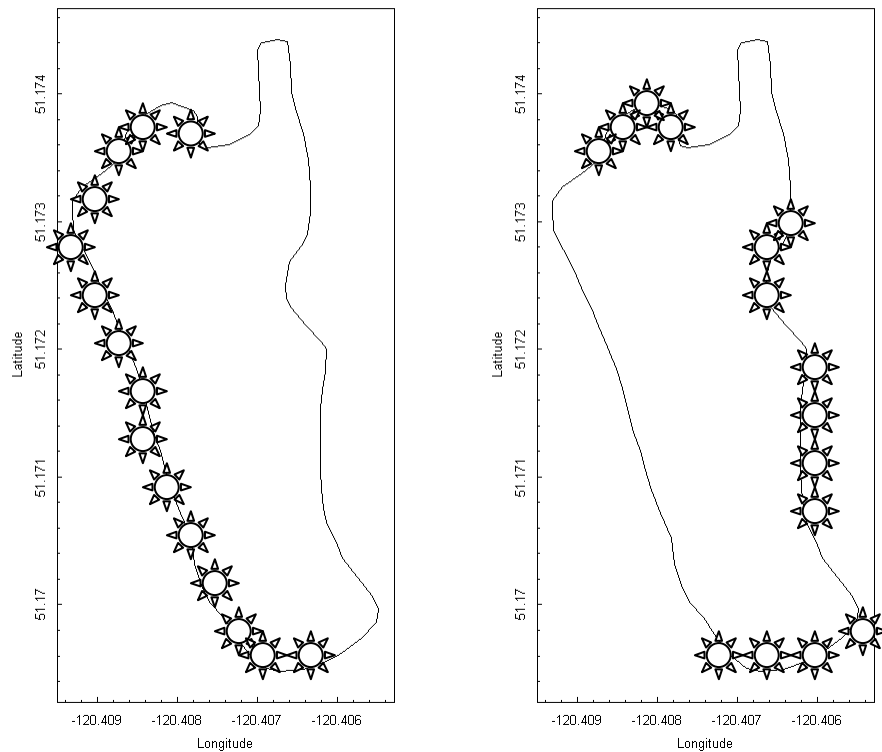


Figure 4.10 Maps of Moose Pasture Lake showing sunlight patterns. The left hand graph shows areas where sunlight strike the lakeshore in the morning, and the right hand graph shows areas where the sunlight strikes the shore in the afternoons.

The juvenile activity pattern (as measured by number of fish actively moving in the water column and hence visible to be counted) observed in relation to this shading pattern (Fig. 4.11) is that as an area comes out of shade, the number of juvenile northern pikeminnow counted rises, and as the day continues the count of northern pikeminnow drops once the edge habitat becomes shaded.

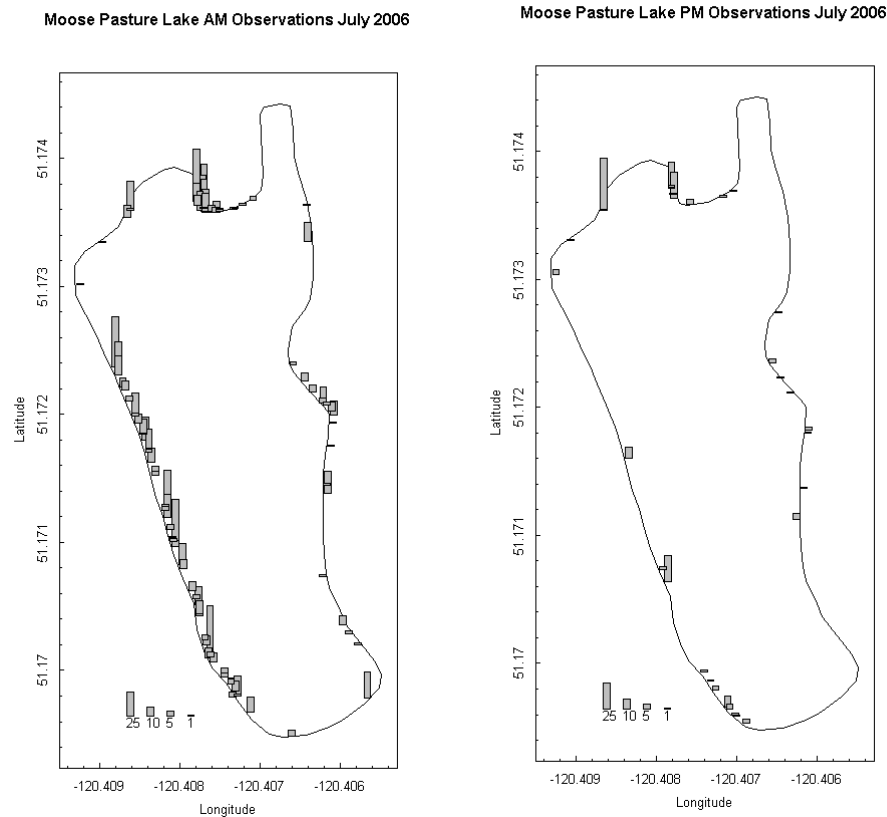


Figure 4.11 Plot of age 0 northern pikeminnow counts from transects in relation to time of day for locations on Moose Pasture Lake. Note that many fewer observations of age 0 fish were made on the shaded western shore in the afternoon

4.2.4 Chasing Behaviour

Encounters between age 1 and age 0 fish were occasionally observed in the habitat that the age 0 fish prefer, scattered over the various visual surveys. These encounters were especially evident in the point observations. In almost all cases the encounters consisted of chases or attacks, where the larger age 1 fish chased the smaller age 0 fish. During the point observations of Moose Pasture, Dads, and Cath Lake, there were 20 recorded encounters between age 0 and age 1 fish. In 15 cases age 0 fish fled or were chased from the vicinity of the age 1 fish. Encounters between age 0 and age 2, 3 and older fish were

observed more rarely; 11 encounters between age 0 and larger fish were observed, and only 2 of these were interactions in which age 0 fish were chased or attacked. In the other 9 encounters the older northern pikeminnow and the age 0 northern pikeminnow swam in proximity to each other and no attack or flight reaction was observed.

4.3 Visual Survey Results

4.3.1 Spatial Distribution

The visual survey transects conducted in 2006 and 2007 show a pattern of spatial distribution demonstrating that juvenile pikeminnow restrict themselves to specific, predictable areas of the three study lakes. This pattern is shown by the plots of juvenile pikeminnow counts made during the transect observations on the study lakes.

4.3.1.1 Spatial Distribution

The distribution of juvenile pikeminnow in the study lakes is patchy. There are areas of the lakes that appear to be preferred habitats. These areas are particular locations along the shallow shorelines of the lake, which have concentrations of the preferred habitat type described above (shallow, relatively open bottom without much woody debris). Maps of point sightings of individuals and shoals (Fig. 4.12-4.17) show the limited habitat used by juveniles.

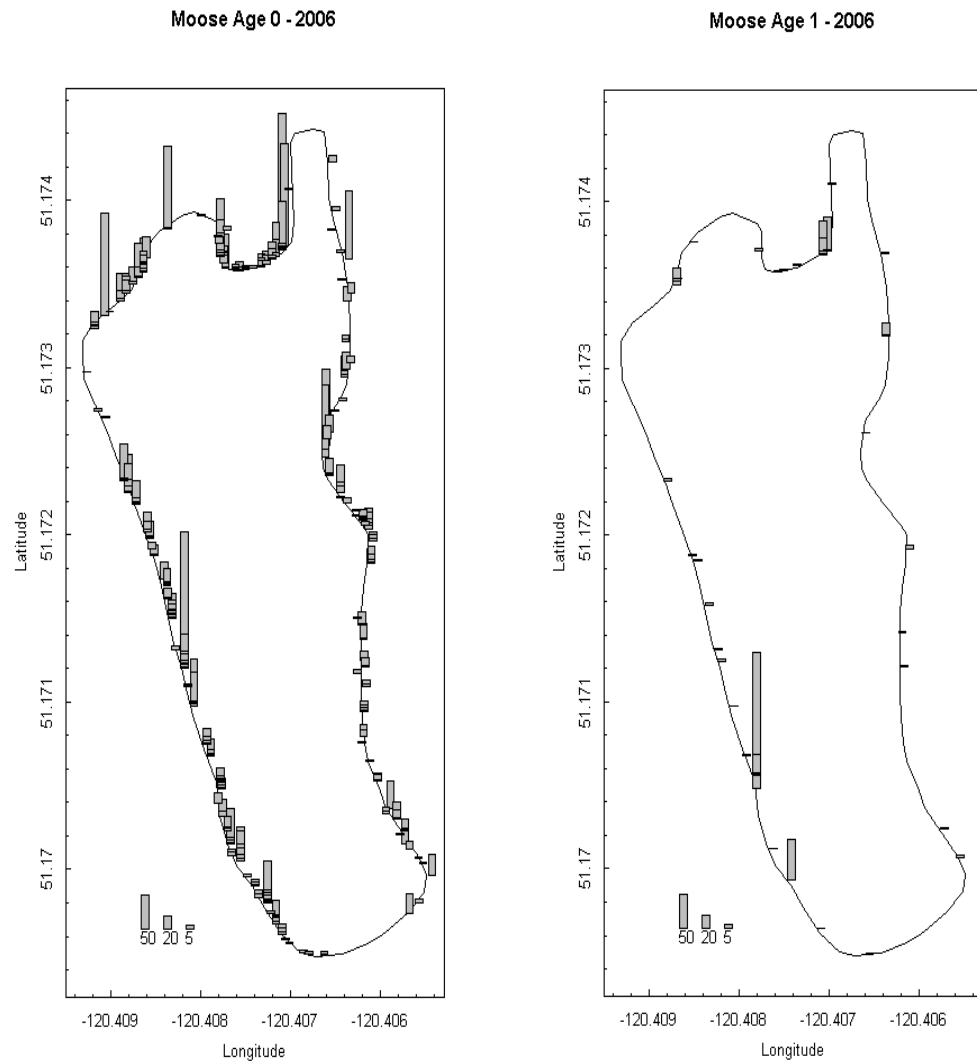


Figure 4.12 Visual survey results from Moose Pasture Lake in 2006. Each bar corresponds to an observation of a shoal of age 0 (left graph) or age 1 (right graph) northern pikeminnow, the height of the bar is proportional to the size of the shoal. Note the heavy concentration of age 0 observations on the western shore and in certain regions of the northern end and eastern shore of the lake. Low counts along much of the eastern shore are associated with steeper banks and little or no water less than 10cm deep.

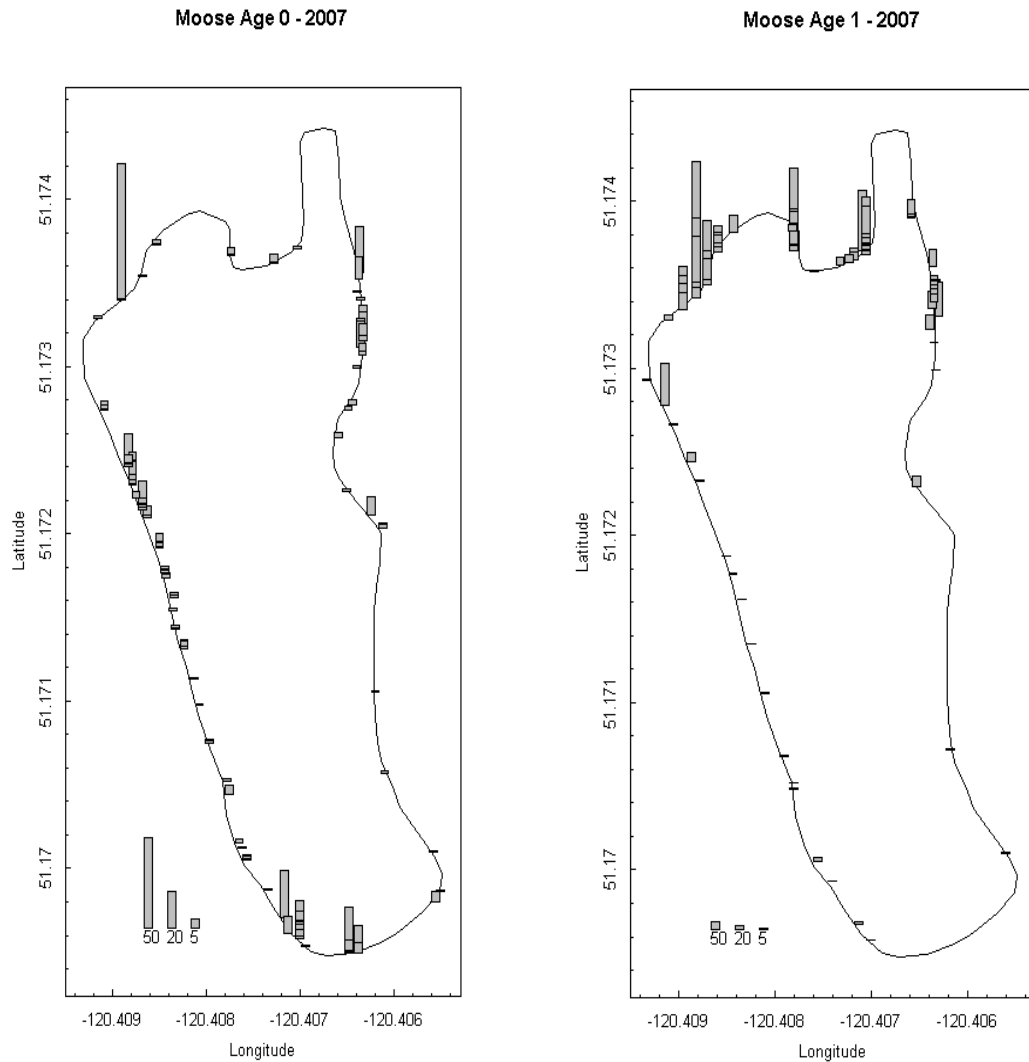


Figure 4.13 Visual survey results from Moose Pasture Lake in 2007. Each bar corresponds to an observation of a shoal of age 0 (left graph) and age 1 (right graph) northern pikeminnow, the height of the bar is proportional to the size of the shoal (Note the difference in scale between left and right graph). Note that there are many fewer observations of age 0 fish than 2006, but that they are concentrated in the same regions of the lake (western shore and specific areas in the northern and eastern shores) as the 2006 observations.

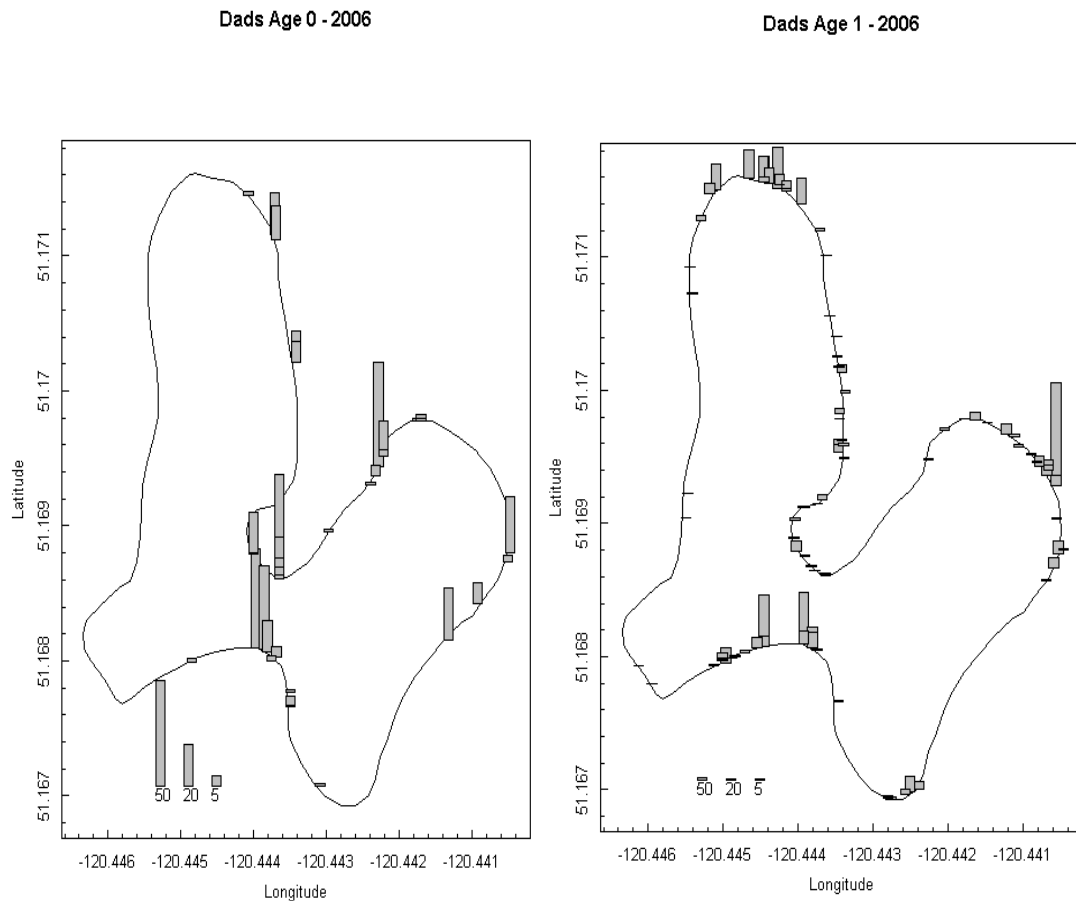


Figure 4.14 Visual survey results from Dads Lake in 2006. Each bar corresponds to an observation of a shoal of age 0 (left graph) or age 1 (right graph) northern pikeminnow, the height of the bar is proportional to the size of the shoal (Note difference in scale between left and right graph). Note the concentration of observations at the narrow band of water between the two larger lobes of the lake.

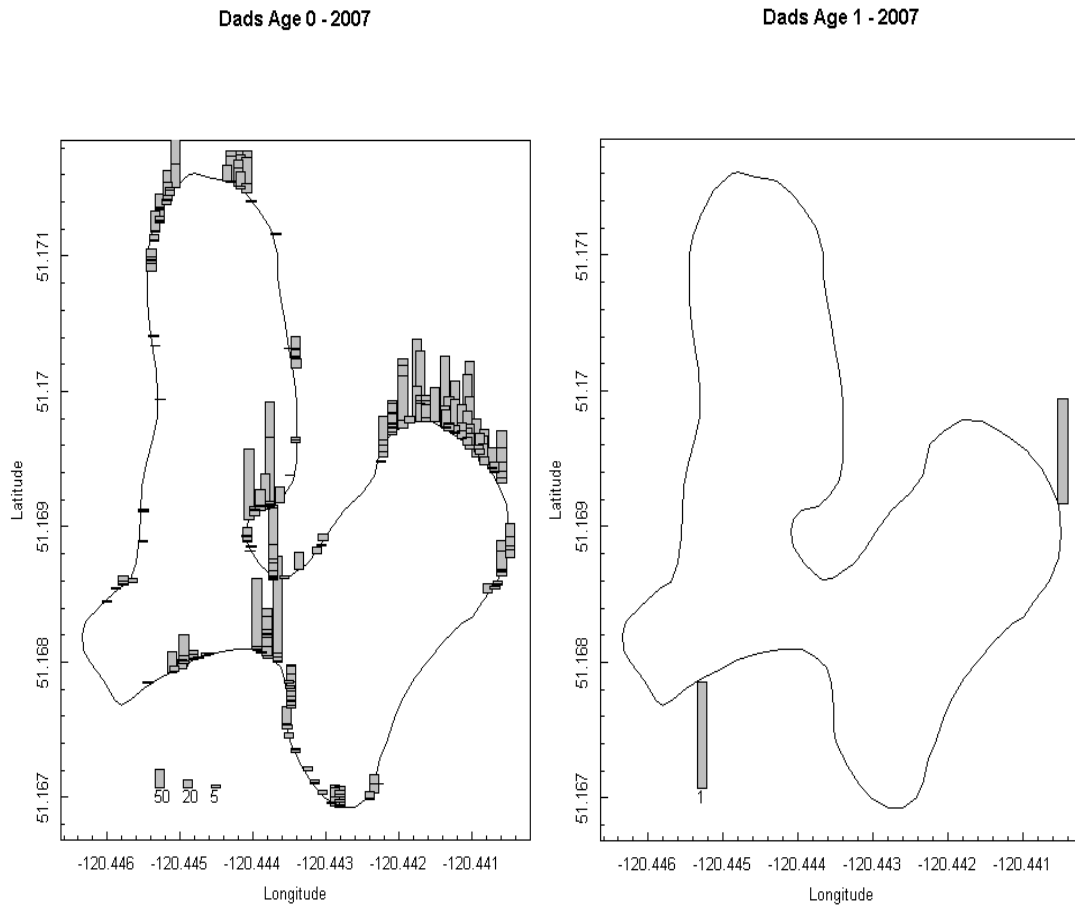


Figure 4.15 Visual survey results from Dads Lake in 2007. Each bar corresponds to an observation of a shoal of age 0 (left graph) or age 1 (right graph) northern pikeminnow, the height of the bar is proportional to the size of the shoal (Note difference in scale between left and right graph). GPS coordinate were retrieved for only 1 observation of age 1 fish at Dads Lake in 2007. Note the concentration of observations at the narrow band of water between the two larger lobes of the lake, and the concentrations of observations in the northern ends of the two lobes of the lake.

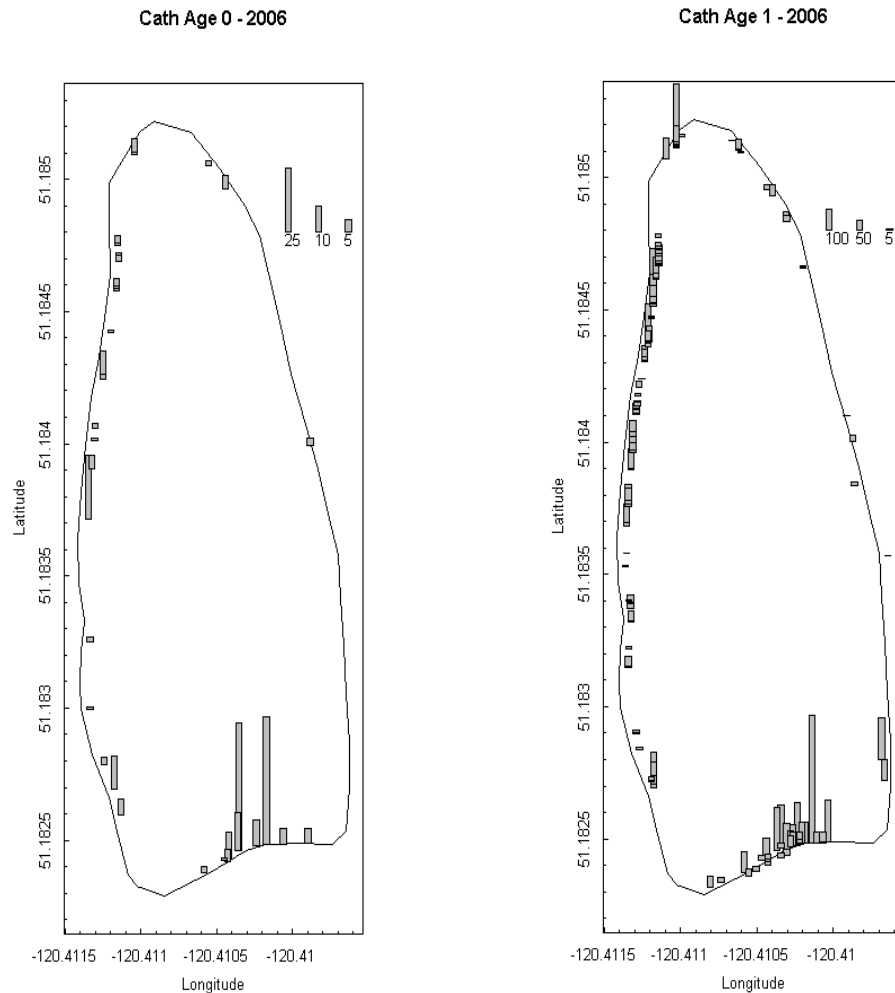


Figure 4.16 Visual survey results from Cath Lake in 2006. Each bar corresponds to an observation of a shoal of age 0 (left graph) or age 1 (right graph) northern pikeminnow, the height of the bar is proportional to the size of the shoal (the scale is different between graphs). Note the concentration of observations on the southern and western shores of the lake.

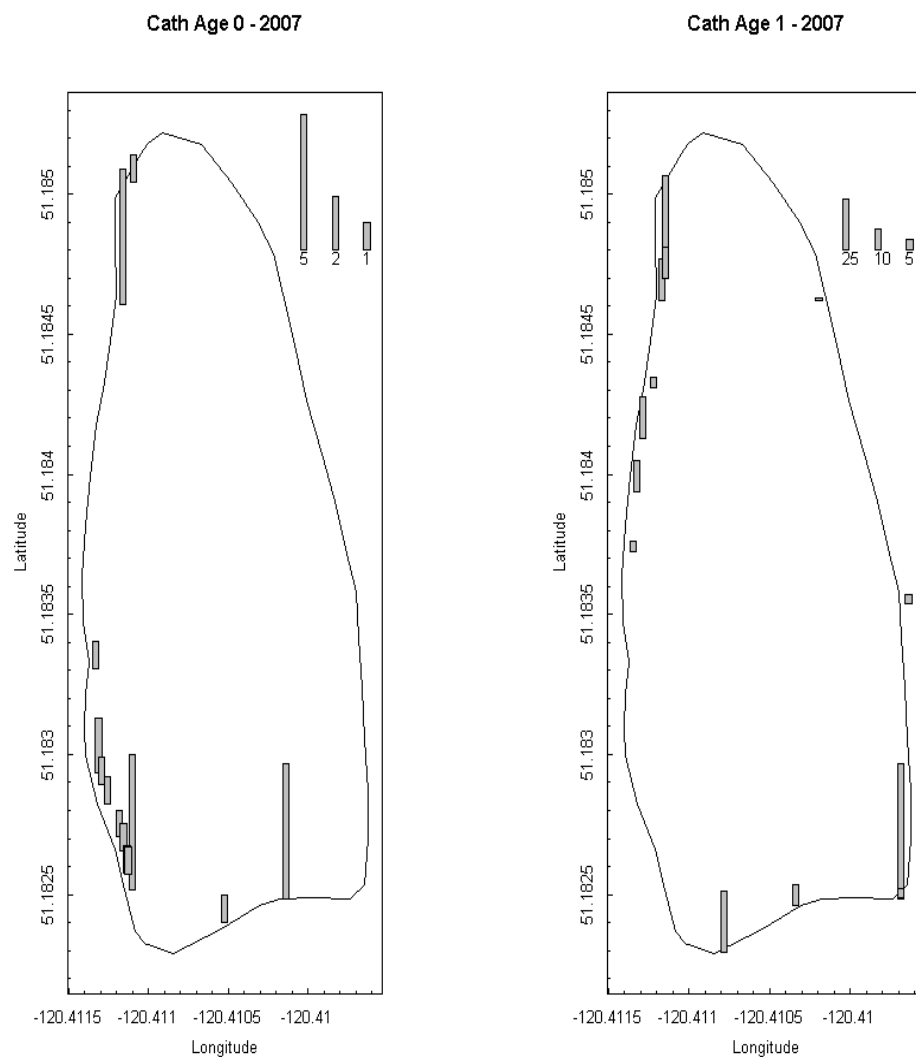


Figure 4.17 Visual survey results from Cath Lake in 2006. Each bar corresponds to an observation of a shoal of age 0 (left graph) or age 1 (right graph) northern pikeminnow, the height of the bar is proportional to the size of the shoal (the scale is different between graphs). Note as in 2006 the concentration of observations on the southern and western shores of the lake.

4.3.2 Survivorship

The visual survey results show a rise in pikeminnow counts in the early part of the summer and then a marked decrease in counts. For age 0 fish, the rise is consistent with the timing of entry of fry to the lake from spawning areas, and for age 1 and older fish the rise is consistent with juvenile activity increasing as the winter ends and spring begins. The decrease in counts as the summer progresses is consistent with natural mortality, and may also involve reduced activity in the latest counts. The pattern of decline can be used to estimate natural mortality rates. The number of juvenile northern pikeminnow in a cohort at the end of the summer is the number of juvenile northern pikeminnow at the beginning of the summer times the survival rate, which in turn can be expressed in terms of instantaneous natural mortality rate. This can be expressed by equation (4.1)

$$N_{t+1} = N_t * e^{-Z_t * t} \quad (4.1)$$

In fisheries population study, the instantaneous total mortality rate (Z) is defined as the sum of the natural mortality rate (M) and the fishing mortality rate (F).

$$Z_t = M_t + F_t \quad (4.2)$$

There is no fishing mortality of juvenile northern pikeminnow in this system and as a result equation (4.1) can be expressed as

$$N_{t+1} = N_t * e^{-M_t} \quad (4.3)$$

The natural mortality is calculated by solving for M_t given observations N_t and N_{t+1} .

$$M_t = \ln(N_t) - \ln(N_{t+1}) \quad (4.4)$$

Examining equation 4.4 it is obvious that the slope of a line fit to the natural logarithms of the observed counts should be an estimate of the average instantaneous natural mortality rate M , over several sampling times t .

It was possible to fit a line through the natural logarithms of the observed counts only for the more abundant year classes (Fig. 4.18-4.20); less abundant classes did not show a pattern of seasonal decline in counts, suggesting either very low mortality rate for such classes, or simply that the low counts are too noisy to show any pattern. In 2006 the instantaneous natural mortality for northern pikeminnow was estimated using the regression method for the age 0 cohort and the age 2 cohort on Moose Pasture Lake. On Dads Lake and Cath Lake in 2006 the instantaneous natural mortality was estimated for the age 1 cohort and the age 3 cohort. In 2007 the instantaneous natural mortality was estimated in the same way for the age 1 cohort and the age 2 cohort on Dads Lake. For Moose Pasture Lake in 2007 the mortality rate was estimated for the age 1 cohort and the age 3 cohort. Cath Lake in 2007 yielded an estimate of instantaneous mortality for the age 2 cohort, but there was no pattern of declining counts that could be used to estimate natural mortality of the age 0 cohort.

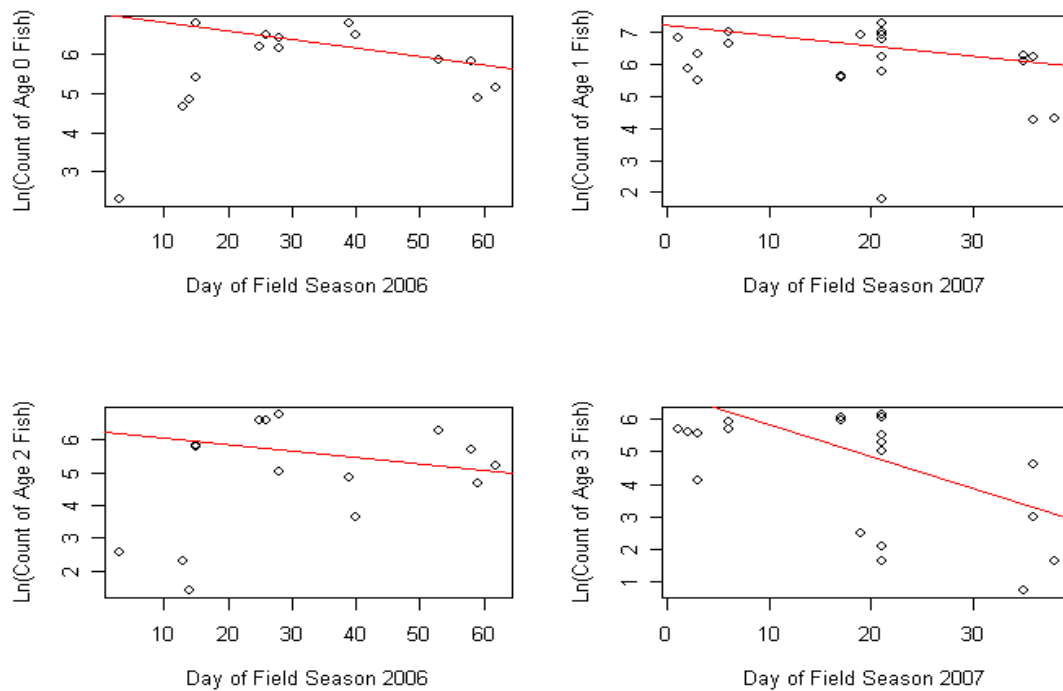


Figure 4.18 Natural logarithms of counts of juvenile northern pikeminnow in Moose Pasture Lake for 2006 and 2007 with fitted lines whose slope corresponds to the instantaneous natural mortality rate. Note the age 0 counts start low then reach a peak and eventually decline. When fitting lines to age 0 counts, only the declining (day 10+) portion of the data was used in order to account for delayed entrance on age 0 fish to the study area.

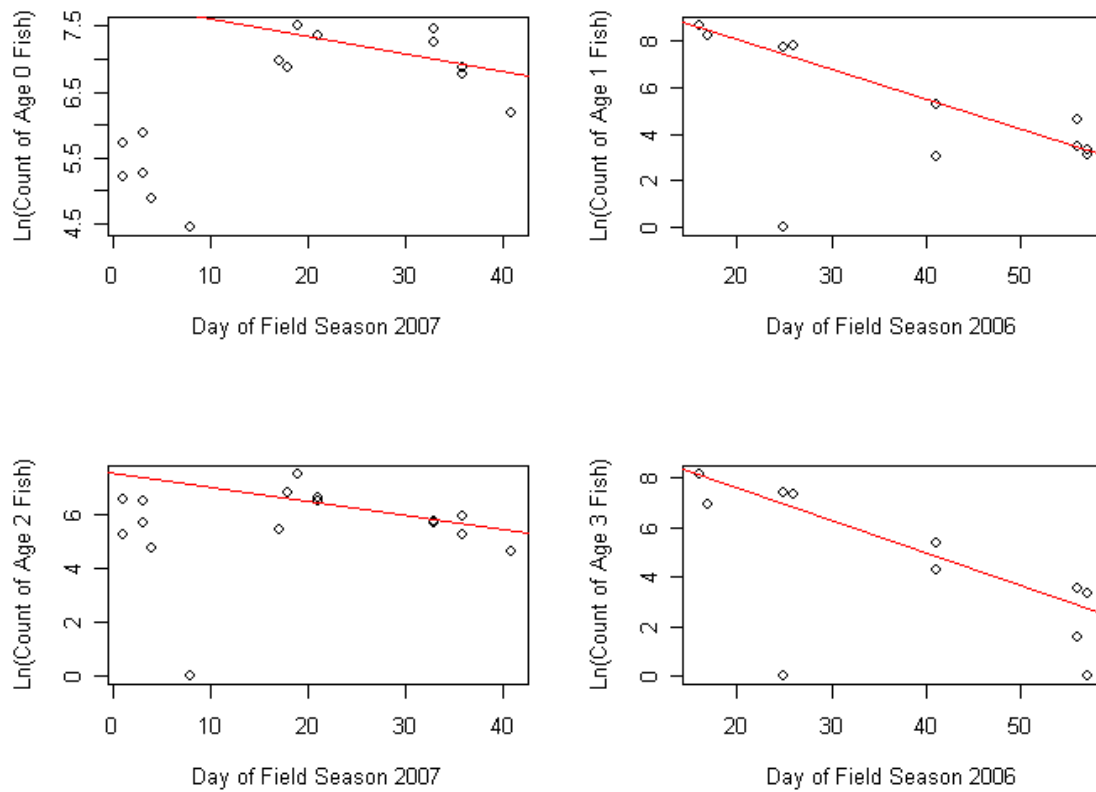


Figure 4.19 Natural logarithms of counts of juvenile northern pikeminnow in Dads Lake for 2006 and 2007 with fitted lines whose slope corresponds to the instantaneous natural mortality rate. Note the age 0 counts start low then reach a peak and eventually decline. When fitting lines to age 0 counts, only the declining (day 10+) portion of the data was used in order to account for delayed entrance on age 0 fish to the study area.

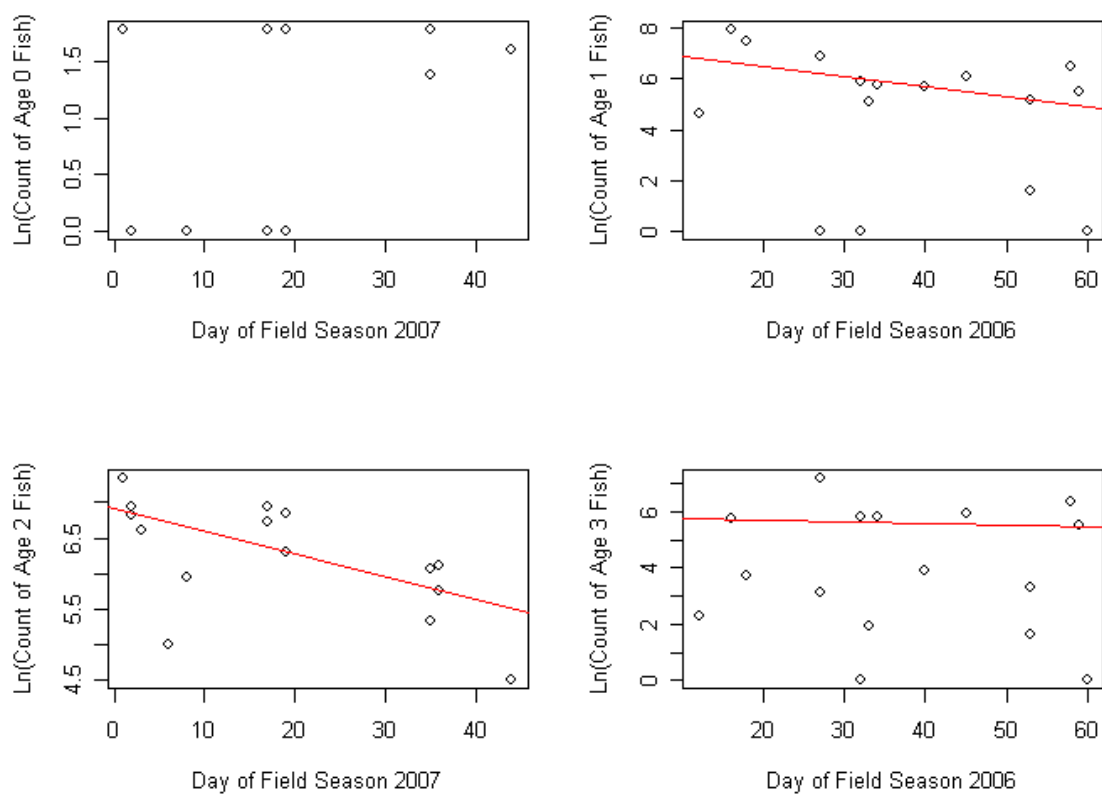


Figure 4.20 Natural logarithms of counts of juvenile northern pikeminnow in Cath Lake for 2006 and 2007 with fitted lines whose slope corresponds to the instantaneous natural mortality rate. Notice there was no line fit to the 2007 Age 0 fish data as the very low counts of fish did not show a pattern of declining count.

Table 4.1 Summary of instantaneous mortality rates estimated by visual census 2006 and 2007. These are daily instantaneous mortality rates over the portion of the summer where abundances were observed to decline.

Age	Moose	Dads	Cath
0	0.02877	0.06364	-
1	0.03192	0.1446	0.04302
2	0.03485	0.008426	0.03194
3	0.09857	0.2037	0.04887

The natural mortality estimates from the regression method are summarised in Table 4.1. Estimated instantaneous natural mortality rates varied from 0.008426 to 0.2037 per day. Even the lowest of these estimates represent annual mortality rates of order 3.0 or higher, far too high to permit sustainable natural populations. Evidently they either represent short seasonal periods of high mortality, or bias due to decreasing activity and shoreline use by juveniles late in each season. However, note from the observed patterns in Figs. 4.18-4.20 that even removing the last sampling period or two from the data would not result in substantially lower rate estimates, suggesting that the rates do in fact represent seasonally high loss rates that very likely are much higher than overwinter rates. Apparent annual survival rates, which include overwinter survival, can be calculated by comparing annual mean indices of abundance (corrected for effort, i.e. total count divided by effort, averaged over all survey dates within each year) between years for each cohort. The ratio of the count over all censuses of fish observed in an age category this year to the number of fish observed in the earlier age category last year provides an estimate of the annual survival for that earlier age cohort.

$$N_{a,t}/N_{a-1,t-1} = S_{a-1 \text{ to } a} \quad (4.5)$$

This interannual survival rate was calculated for each age category for fish in Moose Pasture Lake and Dads Lake (Table 4.2).

Table 4.2 Summary of annual survival rates and the corresponding natural mortality rates estimated by comparing visual census 2006 and 2007.

Survival Rate			Natural Mortality Rate		
Age	Moose	Dads	Age	Moose	Dads
0-1	-	0.190121	0-1	-	1.660092
1-2	0.280519	0.398452	1-2	1.271112	0.920169
2-3	0.665171	0.908451	2-3	0.407712	0.096015

Applying Lorenzen's (1996, 2006) model of survival based upon length (which assumes that natural mortality is a power function of length) to northern pikeminnow predicts survival rates that are close to the survival rates observed by the visual surveys. In Lorenzen's method, survival rate is predicted by combining the vonBertalanffy growth model with length-dependent mortality rate, with length expressed in terms of the ratio of current length (L_t) to the maximum length (L_{∞}) from the vonBertalanffy growth equation and mortality rate expressed relative to the rate felt by adult fish that have approached L_{∞} :

$$M_t = M_{\text{adult}} / (L_t / L_{\text{inf}}) \quad (4.5)$$

The average mortality over the year is then used to estimate the annual survival rate for northern pikeminnow.

Table 4.3 Comparing Lorenzen estimates of annual survival to estimates of annual survival based on observed changes in visual counts of age categories between 2006 and 2007.

Survival Rate			
Age	Moose	Dads	Lorenzen
0-1	-	0.190121	0.190836
1-2	0.280519	0.398452	0.522251
2-3	0.66517	0.908451	0.642318

The Lorenzen survival rates of the northern pikeminnow (Table 4.3) were calculated using the estimates for the vonBertalanffy growth parameters and mortality rates (M_{adult}) of older fish estimated to be 0.2 by Dr Taylor (Taylor 2005). Table 4.3 shows that the survival observed in Dads Lake for age 0 to age 1 northern pikeminnow is very similar to that predicted while the survival observed for age 1 to age 2 northern pikeminnow is lower than predicted by the Lorenzen model. The survival of age 2 to age 3 fish is accurately predicted by the Lorenzen model for Moose Pasture Lake, but is underestimated for Dads Lake. The high survival of age 2 to age 3 northern pikeminnow observed in Dads Lake might be a result of misidentifying small age 4 northern pikeminnow as age 3 fish; this would be very easy to do especially towards the end of the summer when age 3 fish become morphologically very similar to age 4 fish.

4.3.3 Preliminary Evidence for Cyclic Recruitment

The patterns of abundance of pikeminnow observed in the three study lakes do not show simple age distributions of the sort expected from stable or even randomly varying recruitment rates. In a population with constant recruitment, we expect to see a regular decline in numbers over age. Assuming that the number of fish in any age category at any time ($N_{a,t}$) are the fish that have survived from the previous year and age category

$(S_a * N_{a-1,t-1})$ then a simple model representing the expected proportion of numbers of fish in each age category can be expressed in the form:

$$N_{a,t} = S_a * N_{a-1,t-1} \quad (4.6)$$

This model predicts an age distribution pattern as shown in Fig. 4.21

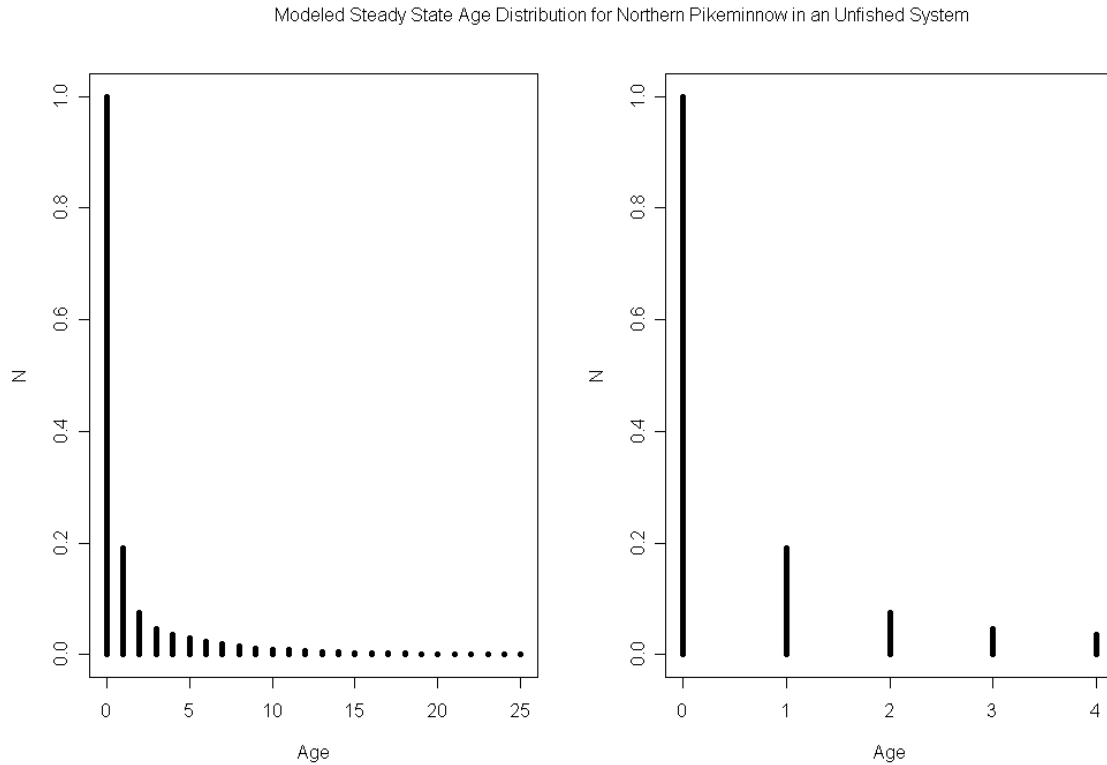


Figure 4.21 Predicted Pattern of Age Distribution in an Equilibrium System: A constant recruitment is assumed and survival rates are assumed as per the Lorenzen estimate presented in Table 4.3 (S_{0-1} was 0.19, S_{1-2} was 0.52, and S_{2-3} was 0.64) while in older fish a fixed survival rate of 0.8 is assumed. Note the first 5 years of life are highlighted in the right-most graph.

4.3.3.1 Moose Pasture Lake

Moose Pasture Lake is a system with extremely low fishing effort, and deliberate culling of pike minnow by trapping them in spawning areas upstream from Moose Pasture has not been practiced since 2000 (Terry Benesh pers comm.) except for a depletion removal of adult fish by Taylor in 2002. Despite lack of such fishing disturbance, the observed pattern of distribution of fish in age cohorts did not match that of a system with constant recruitment and low fishing mortality. A system with constant recruitment should show decreasing numbers of fish in each age category, as demonstrated above. In Moose Pasture Lake in 2006 and 2007 this pattern was not present. In 2005 there were few age 0 pikeminnow observed, while in 2002 and 2003 surveys carried out by Nathan Taylor showed large numbers of age 0 northern pikeminnow. Unfortunately there were only 3 2005 surveys carried out as part of this study and Dr Taylor was only able to carry out two surveys in 2002 and one survey in 2003. Given the variability shown by visual survey results it is hard to compare these data to the data collected in 2006 and 2007. What it can show is that age 0 fish were present in Moose Pasture Lake in 2002 and 2003 and 2005, and there is some indication that 2005 could have been a year with weak recruitment as expected from the impact of Taylor's removal experiment on potential fry production.

4.3.3.1.1 Moose Pasture Lake 2006

Moose Pasture Lake in 2006 showed a markedly different pattern than expected (Fig. 4.22). As expected the age 0 cohort is larger than the age 1 cohort. The age 1 cohort is orders of magnitude smaller than the age 0 cohort, but the age 2 cohort is orders of

magnitude larger than the age 1 cohort. Examining the age 3 cohort we see that it is smaller than the age 2 cohort as expected. The age 1 and age 3 cohorts are much smaller than the age 0 and age 2 cohorts. Both age 1 and age 3 cohorts show a much greater decrease in numbers than predicted by natural mortality rates.

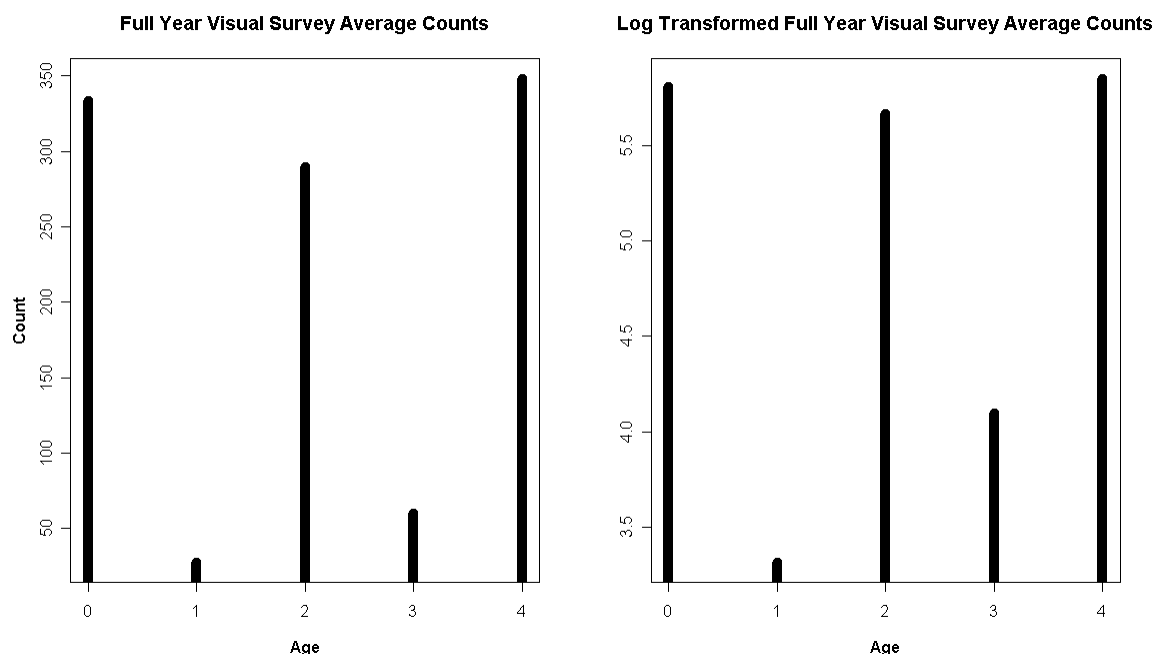


Figure 4.22 Observed age distribution of juvenile pikeminnow in Moose Pasture Lake 2006: Notice that the right-most graph shows the log transformed average counts and clearly shows orders of magnitude difference between observations of fish in separate age cohorts.

4.3.3.1.2 Moose Pasture Lake 2007

Moose Pasture Lake in 2007 showed the opposite age composition pattern from 2006 (Fig. 4.23). In 2007 the age 0 cohort was smaller than the age 1 cohort. The age 1 cohort was orders of magnitude larger than the age 0 cohort, but the age 2 cohort was orders of magnitude smaller than the 1 cohort. This pattern is expected based on the 2006 observations, assuming stable survival rates of the 2006 fish. Examining the age 3 cohort we see that it is larger than the age 2 cohort as expected. The age 0 and age 2 cohorts are much smaller than the age 1 and age 3 cohorts.

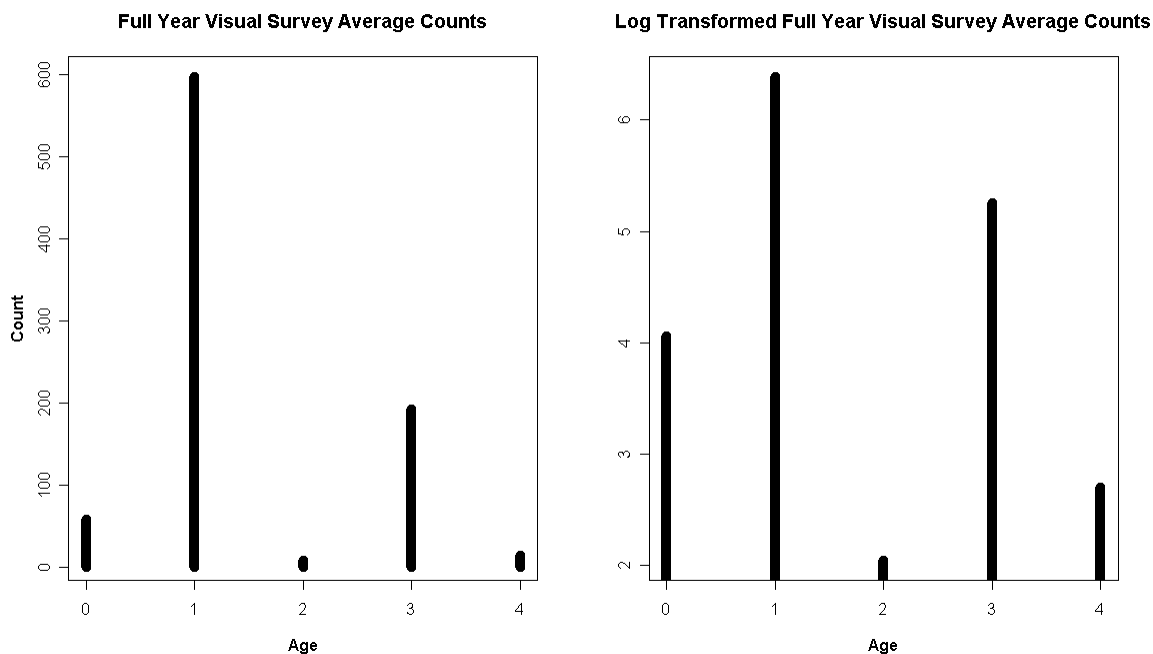


Figure 4.23 Observed age distribution of juvenile pikeminnow in Moose Pasture Lake 2007: Notice that the right-most graph shows the log transformed average counts and clearly shows orders of magnitude difference between observations of fish in separate age cohorts.

4.3.3.2 Dads Lake

Like Moose Pasture, Dads Lake is a system with extremely low fishing (Terry Benesh pers. comm.), and no significant history of culling or experimental removals. Again when examining the pattern of abundance, the expected distribution of fish by age cohorts does not match that of a system with constant recruitment and low fishing effort. The 2006 and 2007 visual survey data for Dads Lake show a pattern that suggests a cyclic recruitment phenomenon as in Moose Pasture. Dad's Lake shares most environmental variability with Moose Pasture Lake, though they are in different watersheds. Dads Lake shows an opposite pattern of high and low abundance than Moose Pasture Lake, i.e. Dads Lake appears to be cycling out of phase with Moose Pasture Lake. In 2005 there were

few age 0 pikeminnow observed, while in 2002 and 2003 surveys carried out by Nathan Taylor showed large numbers of age 0 northern pikeminnow. Unfortunately there were only 2 surveys carried out as part of this study in 2005 and Dr Taylor was only able to carry out two surveys in 2002 and one survey in 2003. Given the variability shown by visual survey results it is hard to compare these data to the data collected in 2006 and 2007. What it can show is that some age 0 fish were present in Dads Lake in 2002 and 2003 and 2005.

4.3.3.2.1 Dads Lake 2006

The age 0 cohort was much larger than the age 1 cohort (Fig. 4.24). In a normal population the age 1 cohort should be smaller than the age 0 cohort. Examining the age 2 cohort, we see that it is many orders of magnitude smaller than the age 1 cohort, and while this fits expectations of a decline from age 1 to age 2 cohort, it is a much greater decline than can be attributed to normal natural mortality rates. The age 3 cohort is orders of magnitude larger than the age 2 cohort; this is again against all expectations and reinforces the idea that there is a cyclic recruitment pattern.

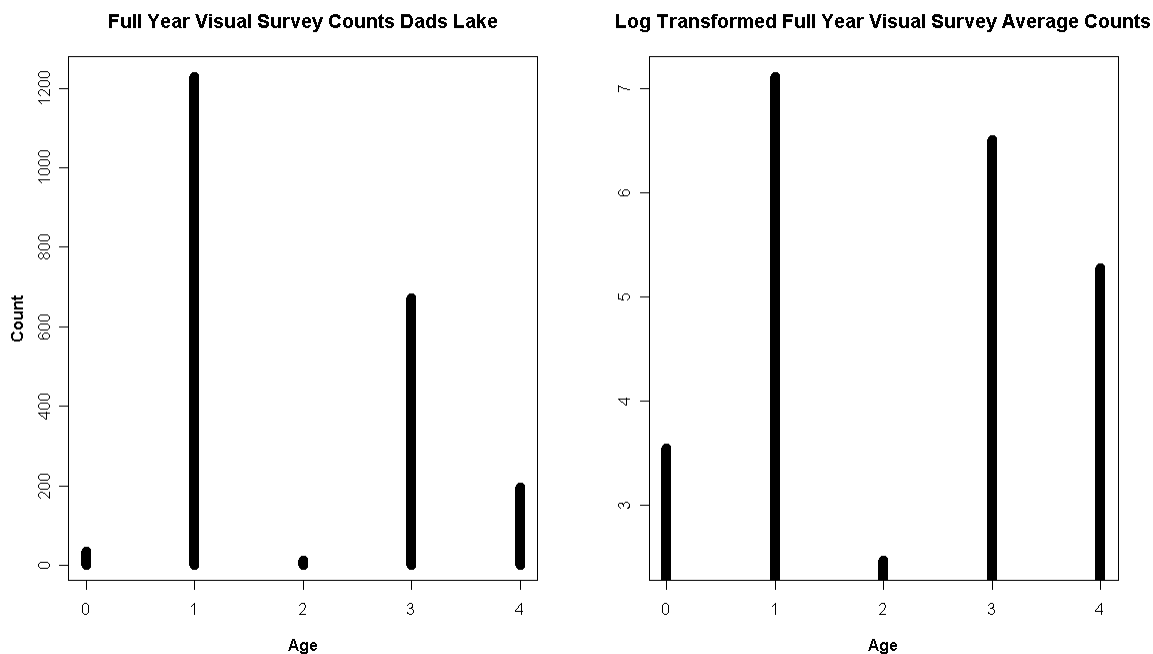


Figure 4.24 Observed age distribution of juvenile pikeminnow in Dads Lake 2006: Notice that the right-most graph shows the log transformed average counts and clearly shows orders of magnitude difference between observations of fish in separate age cohorts.

4.3.3.2.2 Dads Lake 2007

Dads Lake in 2007 showed a high abundance of age 0 fish and a continuation of the cohort size ratios observed in 2006 (Fig. 4.25). In 2007 the age 0 cohort was orders of magnitude larger than the age 1 cohort. The age 1 cohort was orders of magnitude smaller than the age 2 cohort, and the age 3 cohort was orders of magnitude smaller than the age 2 cohort. The pattern from 2006 was carried on into 2007 as the fish aged. It appears that 2007 was a high age 0 year, further supporting the idea that Dads Lake is on an “odd year” high recruitment cycle. Examination of Fig. 4.25 shows that if there is indeed a cyclic recruitment phenomenon at work, the odd years are the ones with a much higher proportion of age zero fish entering the lake and surviving.

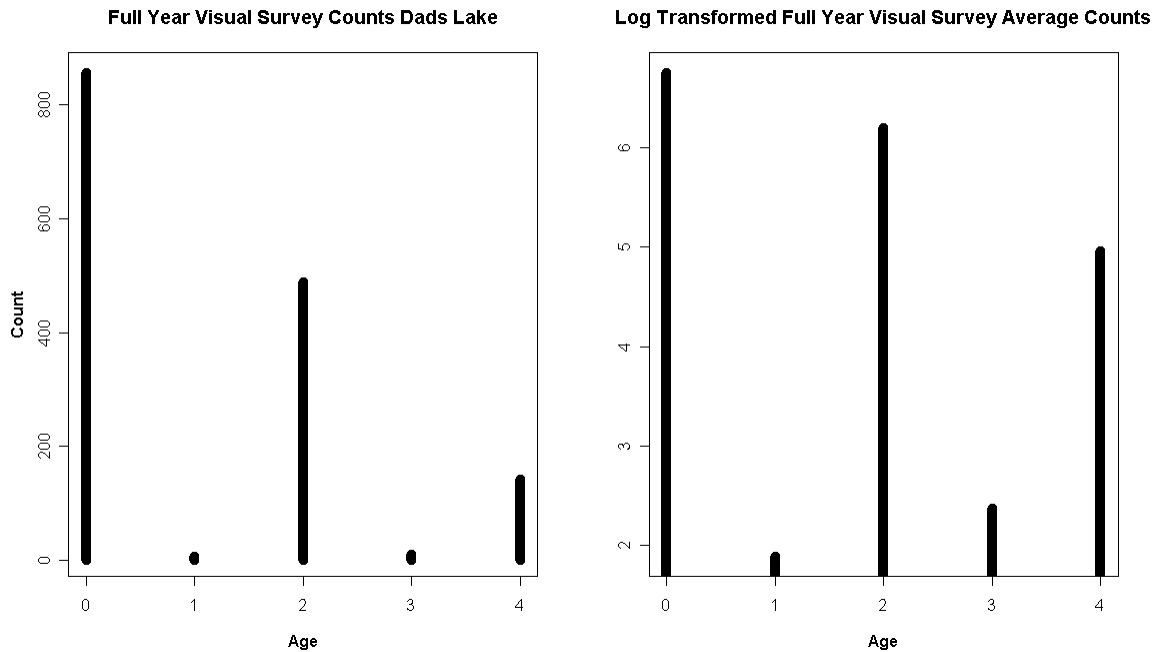


Figure 4.25 Observed age distributions in Dads Lake 2007: Notice that the right-most graph shows the log transformed counts and clearly shows orders of magnitude difference between observations of fish in separate age cohorts.

4.3.3.3 Cath Lake

Cath Lake is immediately downstream from Moose Pasture Lake in the same drainage system, and until 2006 was an unfished system. Like Dads and Moose Pasture Lakes this lake does not show the expected pattern of declining numbers of fish over ages. Cath Lake in 2006 showed a pattern of high and low abundance that is suggestive of a cyclic recruitment phenomenon (Fig. 4.26), but in 2007 there is an absence of the expected high abundance age 0 cohort. This is interesting because it could be a recruitment failure caused by intensive fish removals (depletion experiment) conducted in a related study at the end of 2006, and at the very least it will provide information on the stock recruitment relationship at low spawner abundance.

4.3.3.3.1 Cath Lake 2006

The patterns of abundance of fish observed in Cath Lake in 2006 show a similar saw-toothed pattern as the abundances observed in Moose Pasture Lake and Dads Lake. The age 1 cohort is orders of magnitude larger than the age 0 cohort. Examining the age 2 cohort we see that it is much smaller than the age 1 cohort, and while this fits expectations the decline from age 1 to age 2 is much greater than can be explained by natural mortality rates. The age 3 cohort is again orders of magnitude larger than the age 2 cohort. This all supports the idea that a cyclic recruitment pattern was occurring in Cath Lake prior to the 2006 depletion removal.

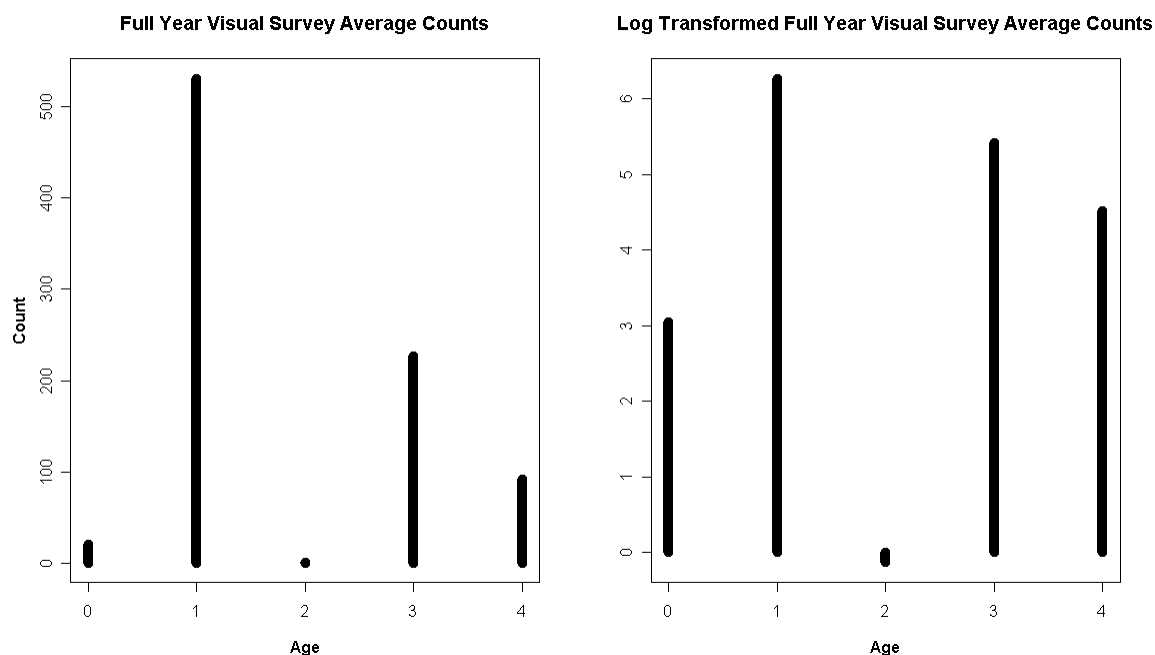


Figure 4.26 Observed Pattern of Age Distribution in Cath Lake 2006: Notice that the right-most graph shows the log transformed counts and clearly shows orders of magnitude difference between observations of fish in separate age cohorts.

4.3.3.3.2 Cath Lake 2007

In 2007 an interesting phenomenon was observed. A very severe five-day netting depletion was conducted at the end of 2006, imposing a very high mortality on the previously unfished system. The depletion on Cath Lake collected 2585 pikeminnow from an estimated population of 10,506 this represents a 25 % depletion of the pikeminnow population. The selectivity of the gear used for the depletion caused this mortality to be heavily concentrated in the larger age classes. This loss of the most fecund individuals is suggested to have so depleted the spawning stock that there was no successful recruitment in 2007. The expected high abundance of age 0 juveniles was not observed; instead there was a second year with a very small age 0 cohort (Fig. 4.27). The rest of the pattern was as expected from 2006. The age 1 and 3 cohorts were small as expected from the age 0 and 2 cohorts observed in 2006. As expected the age 2 cohort was orders of magnitude larger than the age 0, 1, and 3 cohorts.

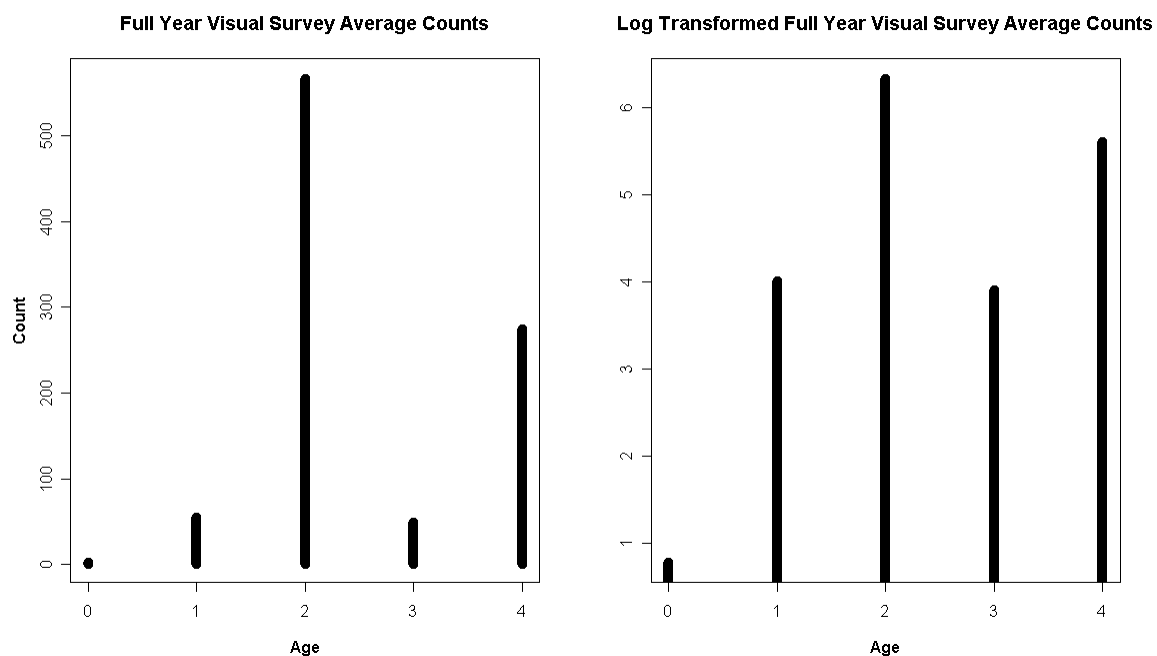


Figure 4.27 Observed age distribution of juvenile pikeminnow in Cath Lake 2007: Notice that the right-most graph shows the log transformed counts and clearly shows orders of magnitude difference between observations of fish in separate age cohorts.

Chapter Five: Discussion

This thesis evaluates the use of shore based visual surveys to gather an index of abundance of juvenile northern pikeminnow, and reviews spatial and temporal patterns that have been found in these surveys. There are some biases and problems associated with the use of visual surveys in this study, but because the juvenile pikeminnow are invulnerable to normal sampling techniques it is the method of choice. Strong interannual variation in age 0 recruitment was observed over two years in the study lakes by the visual surveys method, suggesting that a cyclic recruitment phenomenon is occurring in the northern pikeminnow populations of the study area. This cyclic recruitment phenomenon is worth further study, because it is likely associated with strong density-dependent competition or predation effects, and such effects are key determinants of the stock recruitment relationship, which in turn is at the heart of most modern fisheries problems.

5.1 Visual Survey Methods

5.1.1 Visual Surveys Provide a Reasonable Index of Abundance

Given that the visual survey method is the central sampling technique used to examine the abundance of juvenile northern pikeminnow in this study, a careful examination of the limitations and biases of this method must be made in order to draw credible conclusions from the data. The critical requirement for the visual survey technique used in this study is not that it provides an estimate of absolute or total abundance, but that it instead provides an index of abundance that can be assumed proportional to population size. A properly conducted visual survey should be capable of detecting patterns of

recruitment variation and differences among lakes even if the absolute numbers of fish counted are not an accurate count of abundance.

An overall minimum estimate of the proportion of age 0 juveniles seen in the surveys can be obtained for each of the two watersheds by summing estimates of adult (age 4+) abundance over the nursery and upstream lakes for each watershed, estimating average annual mortality loss from those adult populations, and comparing that loss to the number of age 0 recruits. Taylor's (2005) age composition data suggest that the overall watershed adult populations were relatively stable before the experiment began, i.e. had age compositions indicative of populations with relatively stable average recruitment and natural mortality loss of around 20-30% per year. The total estimated adult (age 4 and older) northern pikeminnow populations for the two watersheds for the 2006-2007 periods averaged 17,863, adult northern pikeminnow for the lakes around and including Dads, and 45,598 adult northern pikeminnow for the lakes around and including Moose Pasture and Cath. Looking at Dads and Moose Pasture lakes in particular, Dads is estimated to have had an average adult northern pikeminnow population (age 4+) in 2006 and 2007 of 14,711 and Moose Pasture is estimated to have had an average adult northern pikeminnow population of 9425 age 4+ individuals in 2006 and 2007. Both of these population estimates were made using a mark recapture technique (van Poorten unpublished data) that is likely biased upward by a factor of at least 1.5-2.0 due to tag loss. These populations likely have had annual recruitment rates averaging approximately 2942 and 1885 age 4 individuals respectively.

Assuming the annual survival rates estimated in the results section (Chapter 4, Table 4.3), the expected age 0 fish produced each year given stable average recruitment to age 4 can

be back-calculated to have been 49,542 individuals for the Dads Lake watershed and 31,181 individuals for the Moose Pasture watershed. This means that if all of the recruitment for Dads Lake and Moose Pasture Lake and surrounding upstream lakes were age 0 fish produced in Dads and Moose Pasture Lake, 2006 peak visual surveys were seeing only 0.35 % of the age 0 fish expected in Dads lake and 2.92% of the age 0 fish expected in Moose Pasture Lake, while 2007 peak visual surveys were seeing only 3.73% of the age 0 fish expected in Dads lake and 0.37 % of the age 0 fish expected in Moose Pasture Lake. The efficiency varies by lake and by year (Table 5.1) the efficiency is higher in Moose Pasture Lake in 2006 than 2007, but in Dads Lake the efficiency is higher in 2007 than 2006, this result suggests that there has been a recruitment failure in Moose Pasture Lake in 2007 and Dads lake in 2006.

Table 5.1 Summary of annual peak counts, expected age 0 northern pikeminnow abundance (from mark recapture) and the corresponding efficiency of visual surveys in Dads and Moose Pasture Lakes in 2006 and 2007 (assuming fixed recruitment).

Lake	Year	Peak Count	Expected R_0	Efficiency
Dads	2006	173	49,542.38	0.35%
	2007	1849	49,542.38	3.73%
Moose Pasture	2006	910	31,181.63	2.92%
	2007	116	31,181.63	0.37%

Given that Moose Pasture and Dads Lake both have small shallow lakes nearby and upstream that are excellent juvenile pikeminnow habitat (Little Moose Pasture Lake, Tasha Lake) it is reasonable to assume that a high proportion of the recruitment to the watersheds including Dads and Moose Pasture Lake is a result of the age 0 juveniles that reared in those nearby lakes.

It is also possible that a time-recruitment mechanism from the nursery streams and small upstream lakes is gradually feeding age 0 fish into Moose Pasture and Dads Lake so as to cause peak age 0 counts to be much lower than total age 0 recruitment.

Assuming recruitment of age 0 northern pikeminnow from nursery streams and upstream nursery lakes like Tasha and Little Moose Pasture Lakes to be a normal distribution over time, the expected age 0 counts should start low then reach a peak and eventually decline exponentially. This pattern is seen in the counts of age 0 fish in Figures 4.18-4.20. The implication of this pattern is that the peak numbers counted at any point during the summer can be a drastic underestimate (by 50% or more) of the total number of recruits, unless mortality is very low (which is not the case here) or entry timing is very tight.

Taken together, the time-recruitment mechanism and the occurrence of considerable rearing in nearby lakes imply that survey efficiency is not nearly as low as indicated by the initial calculations above. Still, these calculations indicate that either (1) a very high proportion (perhaps > 90%) of the age 0 fish are not being seen even in the surveyed lakes, or (2) survival rates from age 0 to age 4 are considerably higher than estimated from the visual survey over-year declines, or (3) the stock assessment procedures (depletion and mark-recapture) used to estimate age 4 and older abundance are badly biased upward. Possibilities (1)-(2) are reasonable, and are supported by observations of peak seasonal visual counts for older ages that are often as high or higher than for age 0 fish (see peak counts in Fig. 4.18-4.20, indicating either increasing survey vulnerability or higher survival than estimated from ratios of mean seasonal counts. Possibility (3) is also reasonable, especially in view of possible upward bias in mark-recapture estimates due to tag loss.

5.1.1.1 Habitat

At the core of the visual technique is the assumption that either the whole of the juvenile northern pikeminnow population or a density-independent, fixed fraction of the population is concentrated in the shore habitat accessed by the visual surveys even if that fraction is small. If this assumption is violated then the visual surveys cannot be used as an index of abundance. This study found no evidence of density dependence in the fraction of fish observed. Three important pieces of evidence support the idea that juvenile northern pikeminnow are restricted to shoreline habitat, i.e. they do not show density-related proportional use of habitats not accessible to visual surveys. First, the habitat preferences exhibited by juvenile northern pikeminnow in the point observations and the transect surveys show a distinct preference for shallow water habitat. Second, in addition to the shore surveys 8 transect surveys were conducted by boat in 2005 and 2006 across the three lakes. The boat transects were carried out in the same manner as the walking transects, but the boat was able to explore both the shallow shoreline habitat accessed by the shore based visual surveys and deeper water habitat out of the range of the shore surveys, to water depths of around 1.0 m. The boat surveys showed no age 0 or age 1 northern pikeminnow in deeper water, while at the same time observing these fish in the shoreline habitat. These paired observations suggest that the juvenile northern pikeminnow population, especially the critical age 0 and age 1 cohorts, are concentrated in the shoreline habitat and as a result a consistent (albeit low) fraction of the juvenile northern pikeminnow population should be vulnerable to detection by the visual survey technique used in this study. If small juveniles were using deeper habitats, these individuals were consistently cryptic in behaviour, i.e. did not move up from the bottom

and form actively moving shoals during periods of bright sunlight, and did not move onshore to take advantage of warmer shoreline conditions. Third, there was no evidence of extensive use of shallow areas where visual surveys might miss a high proportion of the fish (densely vegetated areas), or that proportional use of such areas either increased or decreased with differences in juvenile density and age. In general, habitat use patterns were similar for both strong and weak cohorts in terms of general shoreline positions, avoidance of vegetated and woody debris areas, and avoidance of deeper waters.

5.1.1.2 Design Bias

The design of the surveys was chosen in order to minimize bias. Four major methodological decisions can be shown to reduce bias in the surveys. Many surveys suffer because transects do not cover the full range of habitat types. Most fish display strong habitat-related spatial heterogeneity and as a result unless the transect covers a range of habitat types and is large enough to capture an accurate index even in the face of patchy distribution, the visual surveys do not provide an accurate index of abundance (Eberhardt 1978, Sale 1997). The visual survey design used in this study avoids these two problems by using transects that are the full circumference of the lake.

Studies of visual surveys have identified variability between observers as a cause of bias (Sale 1997). The same observer was used in every visual survey except for two surveys conducted to test repeatability in which two observers were used. That test with two observers showed high repeatability of the method, despite the second observer being considerably less experienced.

Double counting of fish is another methodological source of bias (Sale 1997). This was addressed by the observer only counting fish in front of and offshore of his position.

Visual surveys count a proportion of fish in the transect area, however some studies (Sale 1997) show that an observer has a higher chance of spotting fish the more effort he puts into any one portion of the transect. It is important therefore to maintain a constant rate of forward travel while conducting the survey so that equal effort is made across all transects. The walking speed of the observer was constant across all visual surveys and monitored by recording the start and stop times of transects.

5.1.1.3 Reproducibility of Observations

To use the visual surveys to compare between observations, there has to be an expectation of reproducibility by different observers, i.e. there has to be an expectation that using the same techniques under a normal range of conditions, the results achieved are independent of which scientist happens to make the observations. If this condition holds, it is expected that the results obtained by one visual survey can be meaningfully compared to the results of other visual surveys at other times and/or places.

Reproducibility was tested by using a more than one observer on the same survey. In 2007 two tests of repeatability were carried out. In the first, two observers conducted a visual survey transect and compared their counts of age 0 pikeminnow. There was good agreement in count and location observed for the age 0 pikeminnow, the counts seen by each observer were not significantly different when tested using a Pearson's chi-square test. The same test was used to examine the numbers of shoals of age 0 pikeminnow observed in a visual survey transect and this data set also showed good agreement in count and location. The chi-squared test indicated that the number of shoals counted by the two observers was not statistically different. This indicates that the results of the visual survey observations can be compared against one another.

Another basic test of reproducibility is whether visual surveys taken on different dates give similar estimates of relative year-class strengths for the various lakes. The data in Figs. 4.21-4.27 indicate that this is the case for most lake-year combinations, with a few exceptions like age 3 northern pikeminnow in Cath Lake in 2006 (where the counts were highly variable). However, those figures also show that any single count does not provide a reliable index, as indicated by the substantial number of very low counts scattered over lakes, years, and ages; these scattered low counts generally represent days when sunlight/temperature conditions were marginal for seeing small juveniles, and simply emphasize the need to do repeated surveys in each lake every year so as to reduce variance due to factors like sunlight.

5.1.1.4 Precise Estimation of Numbers and Length of Pikeminnow

The problem of precisely and accurately measuring length of fish in the water has been addressed by many authors (Williams et al. 2006, Edgar et al. 2004) and they conclude that an experienced observer can accurately estimate the lengths of fish in a visual survey. The observer who conducted the visual surveys in this study was experienced and the few net captures of juvenile northern pikeminnow confirm the ability to estimate length.

Studies (Williams et al. 2006, Edgar et al. 2004) also show that estimating numbers of fish in a shoal can be precisely done by a practiced observer, though this ability does not imply accuracy in obtaining overall population counts. These studies show as long as the observer is experienced and visibility conditions are similar between surveys, then visual surveys can provide a usable and consistent index of abundance. In this study the observer is experienced, the methods have been chosen to reduce as much bias as

possible, and the estimates of numbers and lengths of juvenile pikeminnow in the visual surveys have been tested and found accurate though not highly precise; in particular, separation of older ages (1's late in the season from 2's, 2's from older juveniles) was certainly not accurate and probably could never be made so due to size overlap among these older ages of juveniles.

5.1.1.5 Visibility

The visibility of fish in a visual survey is an important concern of this study. It is not important that every fish be visible and thus counted, but it is important that the same proportion of fish are seen (at least on average over multiple surveys for each lake), i.e. that the counts represent the same fraction of the fish present, on average. Weather conditions, light levels, and water clarity are the most important (Sale 1997) factors that affect fish visibility. The water clarity in this system is good (Secchi depths were consistently measured in excess of two meters across all the study lakes). In the habitat surveyed the depth of the water usually varied from 0.0 to 1.0 meter, and water clarity only became an issue when heavy winds or storms stirred up sediments. Since weather conditions were such an important factor for these studies the surveys were only conducted on days with light breezes and no rain. If there was any wind or rain that disturbed the surface of the water then the survey was halted, and in the event that there was continuing rain or wind the survey was abandoned for the day. Light levels were observed to have strong impact on surveys, so in most cases they were conducted only on days with little or no cloud cover and between 0945 and 1700 hours.

5.1.2 Visual Survey Failure

The tested method for visual surveys will produce counts that are a representative index of the abundance of juvenile northern pikeminnow in the study lakes. However, there are dangers in relying solely upon this method, because the seasonal window when the survey method works is dangerously short. Two conditions could make the surveys fail given such a short observation period: (1) consistently cloudy weather so that the observer cannot make counts during August, or (2) inability to do the counts during August for some logistic reason (like being kept out of the study area by forest fires as occurred in 2003). Either of these two conditions could cause loss of a whole year of data.

A wide variety of methods have been tested by Nathan Taylor and this investigator for providing alternative indices of juvenile pikeminnow abundance, including seine netting minnow trapping, electrofishing, explosive shocking (shotgun) and small-scale poisoning of sample areas. None of these alternative sampling methods has been consistently successful at catching particularly age 0 and age 1 juvenile pikeminnow.

The low estimates of proportions of age 0 juveniles seen when counts are compared to back-calculated recruitments from adult population estimates are a warning that high proportions of the juveniles may routinely exhibit cryptic behaviour (laying on the bottom, not forming shoals). This study cannot rule out the possibility of density-dependent variation in the proportions of fish that adopt such cryptic behaviours. There is a key need to continue testing alternative methods for exposing such cryptic individuals to counting, for example through use of chemicals that reduce oxygen concentration and drive such individuals away from the bottom.

5.2 Cyclic Recruitment

The pattern of alternating strong and weak year classes of juvenile northern pikeminnow observed in the visual surveys is very likely the result of cyclic recruitment. This pattern is worth examining in more detail, using further monitoring and manipulative experiments to help determine causes of the cyclic pattern. Behavioral data (agonistic interactions between age 0 and age 1 northern pikeminnow) suggest that direct contest competition may be the main cause of very low age 0 survival in the weak years of the cycle.

Assuming stable production of potential age 0 recruits from year to year, the period of low age 0 survival when age 1 juveniles are present must be occurring very soon after newly hatched juveniles enter the nursery lakes, before they first become vulnerable to visual surveys. That period of low survival must last only a few weeks long at most. Information needs to be gathered on spawn timing and the early life history of age 0 pikeminnow. There is a need in future studies to begin focussed surveys at stream mouths just as fry are entering the nursery lakes, and to track the early dispersal and mortality of these fry; it is not yet clear whether the survey methods described in this thesis will be adequate to that task.

5.2.1 Patterns

Examining the visual survey results it is obvious that there is a strong variation in recruitment. The three different nursery lakes show unusual patterns where older age cohorts are more numerous than younger age cohorts. In order to have an older age cohort at higher abundance than an earlier age cohort the more abundant older age cohort must have had greater recruitment than the younger less abundant age cohort; since

annual egg productions have likely been stable in at least Moose Pasture and Dads over recent years (based on adult age compositions and abundance estimates, Taylor 2005), the variable recruitment has most likely been due to variable survival rather than variable egg production or spawner abundance.

A concern when apparent cyclic patterns were first observed was that these might be simply a result of inter-cohort suppression of activity, i.e. age 0s might be present but cryptic in behaviour when age 1s are present (Walters, pers. Comm.) so as to cause systematic changes in survey visibility. The observations of persistent differences in cohort strength across study years allow us to rule out this possibility, since low counts of 0s when 1s are present would not prevent those 0s from being visible to surveys the following year.

Further, the lakes appear to be out of phase in production of strong cohorts. The following subsections review the findings from Chapter 4 about phase patterns, and about the probable mechanism for apparent disruption of the pattern in Cath Lake (and possibly Moose Pasture) by depletion experiments.

The otoliths collected by Taylor in 2002 (Figure 4.3) do not show a pattern of alternating abundance in year categories. They do not appear to show a population with cyclic recruitment. There are several possible reasons why this data does not show a pattern of repeating high and low abundance, three of these reasons are (1) errors in aging otoliths, (2) migration in and out of this population, and (3) the pattern of cyclic recruitment is a new phenomenon, occurring only in the last several years. Otoliths are difficult to accurately and precisely age, and with the pygmy northern pikeminnow in particular because of its extremely slow juvenile growth it is hard to differentiate the first year of

growth rings (Hillary Ward pers comm.). Errors in aging otoliths would tend to obscure the expected pattern of alternating high and low years expected in a population with cyclic recruitment. Taylor (2005) establishes that the lakes upstream of Moose Pasture Lake only recruit adult migrants from Moose Pasture Lake; this migration of adult pikeminnow from Moose Pasture Lake would tend to reduce any pattern resulting from cyclic recruitment by reducing the numbers of abundant year class fish. If the cyclic recruitment suggested by observations in 2006 and 2007 is a response to a disturbance it might not have begun until after the depletion fishing of Moose Pasture Lake in 2002, if this is the case then there should be no evidence of cyclic recruitment in the otoliths collected.

5.2.1.1 Moose Pasture

In Moose Pasture Lake in 2006 the age 0 and age 2 northern pikeminnow cohorts are orders of magnitude larger than the age 1 cohort. In 2007 Moose Pasture Lake had orders of magnitude higher abundances of age 1 and age 3 northern pikeminnow than age 0 or age 2 northern pikeminnow. Moose Pasture Lake had strong age 0 northern pikeminnow recruitment in 2004 and 2006, but weak age 0 northern pikeminnow recruitment in 2005 and 2007. Moose Pasture Lake is apparently on an even-year cycle, every even year has a strong age 0 northern pikeminnow cohort and every odd year has a weak age 0 cohort.

5.2.1.2 Dads Lake

In Dads Lake in 2006 the age 1 and age 3 northern pikeminnow cohorts are orders of magnitude larger than the age 0 and age 2 northern pikeminnow cohorts. In 2007 Dads Lake had orders of magnitude higher abundances of age 0 and age 2 northern pikeminnow than age 1 or age 3 northern pikeminnow. This suggest that the 2007 and

2005 age 0 northern pikeminnow cohort were orders of magnitude larger than the 2004 or 2006 age 0 pikeminnow. Thus Dads Lake is apparently on an odd-year cycle.

4.2.1.2 Cath Lake

Cath Lake in 2006 shows two older cohorts where the recruitment must have been orders of magnitude higher than the recruitment to a later cohort; the age 2 cohort is much larger than the age 1 cohort, this means that the age 2 cohort must have had higher recruitment than the age 1 cohort had. In 2007 Cath Lake had a second weak age 0 northern pikeminnow cohort. This is different from the patterns observed in the other two study lakes. In August and September of 2006 Cath Lake was subject to a heavy fishing effort that removed at least 25% of the adult northern pikeminnow in the lake and concentrated effort in the largest size northern pikeminnow. It is possible that the heavy fishing mortality caused a recruitment failure if there were markedly fewer mature fish available to spawn in 2007. A similar shift in cycle pattern may have occurred in Moose Pasture following a depletion experiment there in 2002; before that experiment, visual surveys by Taylor (2002-2003) suggested that Moose Pasture and Dads both had substantial numbers of age 0 fish in 2002 and 2003 though Moose Pasture Lake showed fewer age 0 fish in 2003 than 2002 (Taylor, unpublished data).

5.2.2 Examining Potential Causes

Cyclic recruitment variation is a type of pattern that is seen in other fish populations; there are two case studies of brown trout and vendace populations that have similar recruitment patterns. These two populations have been studied in depth (Helmnen et al. 1997, Borgstrom et al 1993). The brown trout population cycle has been explained by competition for limited favourable habitat by juvenile fish, which causes disproportionate

juvenile survival across age cohorts. The brown trout population has a three year cycle where the dominant age class holds the best habitat for three years, greatly reducing survival in other juvenile age classes for those three years (Borgstrom et al 1993).

Vendace also show a population cycle, in this case however it has been argued that competition for food resource between larger age 2 and smaller age 1 fish drastically reduces the fecundity of age 1 fish every other year. This is argued to have produced a two year cycle driven by reproductive success of the age 1 cohort (Helmnen et al. 1997).

In either case there is a clear pattern of low and high abundance across year classes.

However, as noted in the literature review (Chapter 2), it is unclear whether strong year classes could in fact be produced by the much less abundant age 1 fish that supposedly are the main spawners, suggesting that a better hypothesis would be that ages 1 fish suppress age 0 survival through competition or predation.

These and other studies have identified three potential causes of recruitment variation; (1) competition for habitat causing a density dependent survival of juveniles perhaps due to an increase in inter-cohort predation of juveniles by adults or larger juveniles or increased predation by other predators. (2) A bioenergetic factor such as intense competition for resources could be forcing the mature fish to take 2 or more years to develop their gonads. (3) The third possibility is an environmental effect such as cyclic variation in temperature or spring runoff that could affect the spawning success or the survival of northern pikeminnow eggs or larvae.

5.2.2.1 Competition

Competition for habitat between age 0 and age 1 northern pikeminnow is likely to be very strong in the study area. Age 0 and age 1 juveniles evidence strong habitat

preference for shallow, debris free shoreline habitat with low plant density. This specific habitat type is limited in the lakes of the study area. Much of the shoreline of the studied lakes is steep, muddy, or rocky. Restriction in habitat use is clearly demonstrated by the spatial distribution maps (Figs. 4.12-4.17) of the juvenile northern pikeminnow in the three study lakes.

The aggressive behaviour of age 1 fish towards age 0 northern pikeminnow combined with this limited habitat area, suggest that the age 1 fish exclude age 0 fish from their preferred habitat. It seems likely that survival of the age 0 northern pikeminnow is negatively affected by this competition with age one northern pikeminnow. Competition for habitat could be driving the recruitment cycle. A key point is that the competitive exclusion apparently takes place very early in the lake rearing period, before the age 0 juveniles first become vulnerable to the visual survey methods used in this study.

5.2.2.2 Bioenergetics

The spawning stocks remained relatively stable over the four years of interest except in the case of the 2007 spawning stock for Cath Lake, which was heavily fished in two depletions at the end of 2006 (Van Poorten, in press), and there may have been some recovery in annual egg production in Moose Pasture following the 2003 depletion of larger fish. Since spawner numbers were likely stable over the last four years, the recruitment variation and the population cycle it leads to must be coming from something other than radical changes in spawning stock size. Systematic spawning observations have not been made, though casual examination of spawning streams indicates that spawning occurs every year. Early season netting trips (capturing fish for a mark recapture population estimate) conducted every year of the study period have captured

ripe male and female pikeminnow, with no indication of substantial numbers of larger (older) fish with undeveloped gonads.

5.2.2.3 Environmental Variation

An external environmental variable is unlikely to be causing the cycles. Moose Pasture and Cath Lakes are in a different watershed than Dads Lake. The three study lakes are however within three kilometres of each other. These lakes being in such close proximity should be experiencing broadly similar environmental effects. Temperature, rain and snowfall (snow melt is a key determinant of water flow in the spawning streams during the spawning period) should be very similar across these three lakes. If there were an environmental factor acting to force the recruitment cycle in the northern pikeminnow populations of these lakes, it would be reasonable to assume that the forcing effect would be acting equally on all three lakes. If all three lakes are subject to the same environmental forcing effect they should display the same patterns of high and low recruitment. But the study lakes are on separate cycles, with both even-year and odd-year dominance. In addition, lakes on the same watershed have different cycles (Cath vs. Moose Pasture). Any changes in spring runoff, thermal regime, or whatever that varied across the two watersheds should be felt in a similar fashion by the lakes on the same watershed, while any temperature and large-scale snowpack/stream flow variations would be experienced by all three lakes. As the three lakes are not on the same cycle, and the lakes on the same watershed are not even on the same cycle, it seems very likely that cyclic patterns are driven by dynamical interactions within each of the study lakes.

5.3 Future Studies

The cause of the recruitment variation in juvenile northern pikeminnow is not yet clear. Several next steps could be carried out to establish that there is a regular cycle in these populations, and to determine the most likely cause of the cycles. Ongoing visual surveys particularly focussing on the period immediately after fry enter the lake, increased capture of juvenile fish, a new study of spawning, and re-examination of previous catch records should provide a full picture of the early life history of the northern pikeminnow, and might uncover alternative explanations for the cyclic pattern. There is a good opportunity at this time for such a study, since further manipulations of spawner abundance have occurred in 2007 that will lead to the possibility of changes in dominant cycle line like those already seen in Moose Pasture and Cath, and will help sort out the effect of adult and hence fry abundance on age 0 survival versus the effect of competition or predation by older juveniles. To date there have been two experimental manipulations of the density of northern pikeminnow in the study lakes. The Moose Pasture Lake northern pikeminnow population was experimentally reduced in 2003 and the Cath Lake population was reduced in 2006. Moose Pasture Lake appears to have recovered from the reduction in 2003 and to have established a new dominant cycle line started by the first large age 0 cohort. Though Cath Lake was again heavily fished in 2007 as part of the population monitoring conducted by Brett van Poorten (removing approximately 40% of the adult fish) in the absence of further depletions it is expected to recover from these reductions in 2 years, and it is expected that the next strong age 0 cohort will establish a new dominant cycle line. Continuing to monitor the population abundance and growth of northern pikeminnow in Cath Lake as well as continued visual

surveys should be able to identify at what population level there is successful reproduction and hopefully identify and track the establishment of the new dominant line in Cath Lake. This should provide information about the spawner recruit relationship in this system.

In addition to continuing to monitor the Cath Lake recovery and the existing cycles in Dads and Moose Pasture Lake the effect of temperature on activity and growth can be examined in more detail. Simple penning experiments where large pens with age 0 northern pikeminnow are fixed in shallow or deep water, when combined with temperature monitoring, should be able to establish whether there is a growth advantage to fish that stay in shallow water and whether cooler temperatures in general are a driver for cryptic behaviour and low survey efficiency at cooler times and in deeper waters. Point observations combined with temperature readings should be able to demonstrate whether there is a simple, repeatable correlation between water temperature and activity levels of juvenile northern pikeminnow.

The question of whether predation or competition between age 0 and age 1 northern pikeminnow is driving the recruitment cycles should be investigated further. Carefully designed tethering experiments should be able to show whether or not shallow water reduces the predation risk faced by juvenile northern pikeminnow as well as whether or not age 1 northern pikeminnow prey upon age 0 northern pikeminnow. Penning experiments that confine age 0 and age 1 northern pikeminnow both together and separately should help to establish how competition from age 1 northern pikeminnow affects the growth of age 0 northern pikeminnow.

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