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Vegetative substrates used by larval northern pike in Rainy and Kabetogama Lakes, Minnesota

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Abstract – Our objective was to identify characteristics of aquatic vegetative communities used as larval northern pike nursery habitat in Rainy and Kabetogama lakes, glacial shield reservoirs in northern Minnesota. Quatrefoil light traps fished at night were used to sample larval northern pike in 11 potential nursery areas. Larval northern pike were most commonly sampled among floating-leaf burreed *Sparganium fluctuans*, common burreed *Sparganium eurycarpum*, sedges *Carex* spp., hybrid cattail *Typha* × *glauca* and wild rice *Zizania palustris*. A negative binomial model of light-trap catches using the presence/absence data for 2012 from all 11 bays included water elevation and the presence of cattail as significant variables. Ultimately, the species of vegetation may not be as important as the physical quality or form of the vegetation in supplying feeding and hiding cover. The aquatic plant species and structural forms encountered by larval northern pike suggest they use nearly any vegetated cover available in early spring. Water-level regulations that change availability of aquatic vegetation are likely to influence recruitment of northern pike to larger sizes.

Key words: northern pike; water level; light trap; larval; aquatic vegetation

Introduction

Nursery habitats for northern pike *Esox lucius* are much less thoroughly studied than spawning habitats even though the larval stage may be a critical period for survival (Franklin & Smith 1963; Casselman & Lewis 1996). Forney (1968) concluded that maintenance of northern pike populations in many lakes may depend primarily on the production of juvenile fish in their nursery habitat. However, the nursery habitat used by northern pike is susceptible to human perturbations such as shoreline development, water-level manipulation, and forestry and other land-use practices that disrupt, disconnect or drain wetlands and nearshore shallow-water habitats that are considered important for larval fish production.

Nursery habitat of northern pike is difficult to sample because it consists primarily of marshes or shallow water with submerged and emergent vegetation (Bry 1996; Casselman 1996). Lighted quatrefoil plexiglass traps can be used for sampling in vegetation and have been an effective method of collecting larval fish because fish that are positively phototactic are drawn into the four columns of the traps by artificial light during nocturnal sampling (Kelso & Rutherford 1996; Pierce et al. 2007). Light traps offer the advantage of minimally disrupting fish nursery habitat compared with other sampling techniques such as seining. Two previous studies evaluated the potential of light traps for sampling young northern pike. Zigler & Dewey (1995) used a series of raceway and pond experiments to test for phototaxis in larval and juvenile northern pike. They compared catches in lighted (using chemical light sticks) versus unlighted quatrefoil traps, and their results showed that catches of northern pike were 3–35 times greater in lighted traps. Pierce et al. (2006) reported that light-trap catch rates discriminated between different densities of larval northern pike stocked into hatchery raceways and that light traps were capable of detecting patchy fish distributions. This study also illustrated growth rates and differential survival among managed wetlands. Light trapping can

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effectively sample larval northern pike from the time their mouths form and they begin exogenous feeding (10–12 mm) through the sizes when they complete the larval stage and attain the general form of the adults (about 35–40 mm; Franklin & Smith 1960; Pierce et al. 2006).

Rule curves have been implemented by the U.S.-Canadian International Joint Commission (IJC) to regulate water levels in important Minnesota–Ontario border-water reservoirs including Rainy and Namakan Lakes (Cohen & Radomski 1993). Both reservoirs are located on the Canadian glacial shield, which is a geological region of Precambrian rock and thin layers of soil that covers large portions of Canada and extends south into northeastern Minnesota. A result of this geological formation is that lakes in northeastern Minnesota are different than southern and even central Minnesota lakes and can have different water chemistries and flora than lakes farther south and west (Moyle 1956). The rule curves for the two reservoirs are ranges of water levels that vary seasonally, allowing for declining water levels through late fall and winter followed by increasing water levels during spring and early summer. Cohen & Radomski (1993) considered that the northern pike might be a species sensitive to the frequency and amplitude of managed water-level fluctuations in these lakes.

Such manipulation of water levels has the potential to affect shallow-water habitats in spring and early summer when northern pike need nursery areas with protective cover and an abundant supply of food (Franklin & Smith 1963; Craig 1996). Evaluation of the ecological appropriateness of the IJC rule curves for managing water levels will require an understanding of how aquatic plants are used as cover by larval northern pike in their nursery areas and a further understanding of how water-level regulations affect the availability of aquatic plants. Identification of specific forms of aquatic plants that are used as nursery habitat by northern pike will be important for other environmental reviews aimed at predicting the environmental consequences of lakeshore development and other human perturbations in northeastern Minnesota. Loss of critical habitat has been an important issue for maintaining northern pike populations (Casselman & Lewis 1996; Margenau et al. 2008), and yet, information about the forms of aquatic plants used as nursery habitat across a variety of aquatic systems is nearly nonexistent, especially for glacial shield lakes. In this study, our goal was to document the types of aquatic plants present in microhabitat of nursery areas where larval northern pike were sampled in two glacial shield lakes. Our objective was to identify characteristics of the aquatic habitat that result in the production of larval northern pike.

Methods

Study area

The use of vegetative substrates as nursery habitat by larval northern pike was documented by light trapping in 11 potential nursery areas located in the South Arm of Rainy Lake and in Kabetogama Lake; both lakes are reservoirs located on or near the border between Minnesota and Ontario. Rainy Lake covers 92,110 ha and has three basins. The North Arm and Redgut Bay are located on the Canadian side of the border, while the South Arm is divided between Minnesota and Ontario. Kabetogama Lake, with a surface area of 10,425 ha, is on the Minnesota side of the border and is the largest of three basins in the Namakan Reservoir. Specific locations sampled in Rainy Lake were Cranberry Bay, Dove Bay, Jackfish Bay and Reuter's Creek of Black Bay (Fig. 1). Specific locations sampled in Kabetogama Lake were Blind Ash Bay, Bowman Bay, Daley Bay, Irwin Bay, Peterson Bay, Sullivan Bay and Tom Cod Bay (Fig. 1). Our sampling was stratified randomly throughout depths where aquatic macrophytes were available for spawning, in depths ranging from 15–65 cm. We chose this sampling strategy because proximity to spawning areas has been identified as important for ranking the quality of northern pike nursery habitat, along with the presence of relatively dense submergent and emergent aquatic plants (Casselman & Lewis 1996). Water levels affecting spring habitat for fish, particularly in the shallow waters we sampled, are regulated by IJC rule curves and controlled by dams at outlets from each of the reservoir systems.

Timing of sampling

Due to a warm spring and early ice-out, light-trap sampling began on 23 April, but larval northern pike were not caught until 8 to 16 May 2012. From previous sampling in Dove Bay, Rainy Lake and Sullivan Bay, Kabetogama Lake, 2008–2011, the earliest period in which larval northern pike were sampled was 27 April to 3 May 2010, and the latest samples were obtained during 27 May to 3 June 2008.

Light-trap methods

The quatrefoil light traps featured a 6-mm entrance slot and light-emitting diodes (LED lights) powered by dry-cell batteries. This light-trap design was modified from the Killgore (1991) design to a 6-mm entrance width, which was larger than the 5-mm entrance used by Zigler & Dewey (1995) in testing for phototaxis of larval pike. The LED lights were chosen over chemical light sticks because they emit a

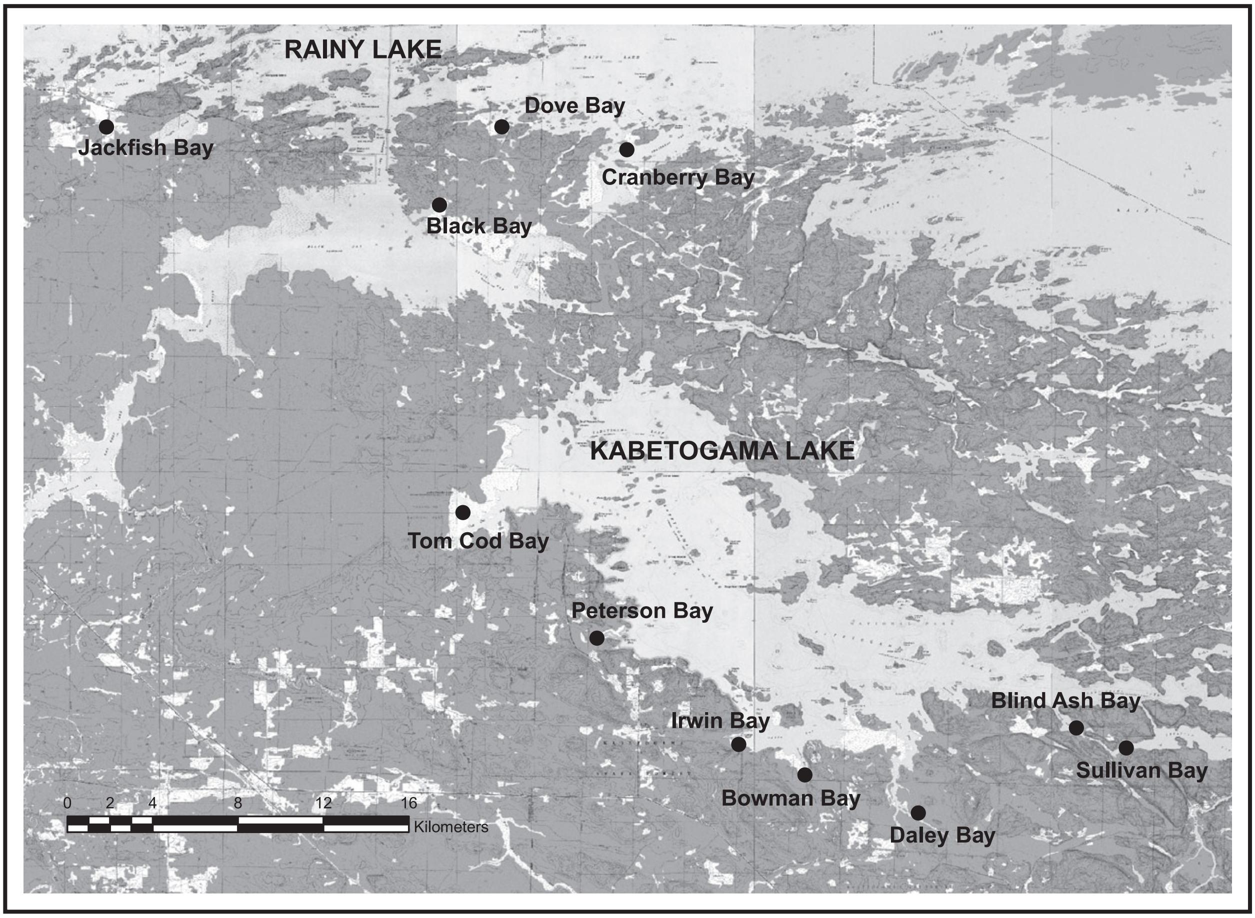

Fig. 1. Rainy and Kabetogama Lake sample locations from 11 potential northern pike nursery areas. Both lakes are reservoirs located near the border between Minnesota and Ontario. Rainy Lake has a surface area of 92,110 hectares, and Kabetogama Lake has a surface area of 10,425 hectares.

very consistent light intensity for the duration of each sampling period.

A night of sampling in each location during spring 2012 consisted of setting 18–20 light traps for two hours beginning at sunset. Light traps were floated from 1.2-m-long fibreglass stakes driven into bottom substrates in water 15–65 cm deep. We applied a stratified random sampling approach by setting light traps randomly throughout the 15–65 cm depths where aquatic macrophytes were available for northern pike spawning. Samples were stratified by these depths where aquatic plant growth occurred because we were investigating characteristics of the aquatic macrophyte community that resulted in larval pike production. During April to May 2012, aquatic vegetation was accessible at depths up to 65 cm. The light trap must be suspended above the bottom to effectively sample larval northern pike, so 15 cm was the minimum for keeping the light trap above the sediment. Vegetation types at each light trap were classified according to the most abundant one or two species within 0.5 m of the trap. Water temperature was recorded for each sampled bay, and water depth was recorded at each light-trap location. Pike larvae total counts and lengths (mm) for each light trap were recorded and compiled for each sampled bay (Pierce et al. 2007).

Modelling larval northern habitat

We developed a mixed-effects multivariate regression model of larval northern pike count data among the 11 bays sampled during 23 April to 16 May 2012. Patchy fish distribution data, such as our counts of larval fish abundance, often have large proportions of zeros that cause skewed distributions that are non-normal and do not fit standard models such as the Poisson distribution for count data (Heilbron 1994; Martin et al. 2005). Alternatively, models such as the zero-inflated Poisson (ZIP), negative binomial Poisson, zero-inflated negative binomial (ZINB) and the negative binomial hurdle model have been developed to accommodate data sets with large proportions of zeros (Hall 2000; Martin et al. 2005; Warton

2005; Miller 2007). All of these models can accommodate both random and fixed effects, and negative binomial distributions are probability based, with zero-inflation referring to the probability of generating a zero (Hall 2000). Mullahy (1986) and King (1989) developed the hurdle probability model where a certain probability of a nonzero count allows the 'hurdle' to be crossed (Cameron & Trivedi 1998). Zero-inflated Poisson distributions are best for data sets with lower proportions of zeros (0.10–0.25); negative binomial Poisson models can be used for data sets where variance is greater than the mean and the proportion of zeros is 0.50–0.75; and negative binomial hurdle models work best for data sets where variance is greater than the mean and where the proportion of zeros is 0.75–0.90 (Hall 2000; Miller 2007).

Our study fits negative binomial Poisson, zero-inflated Poisson (ZIP), zero-inflated negative binomial (ZINB) and negative binomial hurdle models using the FMM procedure for finite mixture models in SAS 9.3 (Kessler & McDowell 2012) to determine significant variables related to larval pike counts. Model selection was determined using Akaike's information criterion (AIC) for each model run (Burnham & Anderson 2002). The following variables were included in models for the 2012 data set of 11 bays: water temperature, water elevation, bay, the presence of hybrid cattail *Typha* × *glauca*, the presence of sedge *Carex* spp., the presence of wild rice *Zizania palustris* and the presence of burreed *Sparganium* spp. *Typha* × *glauca* is a combination of hybrids between *Typha latifolia* and *Typha augustifolia*, and previous research in Voyageurs National Park documents the hybrid as the dominant species at sites in Rainy and Kabetogama Lakes (Travis et al. 2010). Therefore, for the purpose of this study, we will refer to the hybrid cattail throughout. These four plant classifications were the most abundant among light-trap sampling locations. In these models, the vegetation variables (the presence of hybrid cattail, the presence of sedge, the presence of wild rice and the presence of burreed) were considered fixed effects, and water elevation was considered a covariate.

Results

Species of aquatic plants present

A total of 164 larval northern pike were caught in 210 light-trap sets among common forms of submerged and emergent aquatic vegetation growing in 11 shallow bays of the two border-water reservoirs during the 2012 field season. The aquatic plants present most often were hybrid cattail (83 light traps); floating-leaf burreed *Sparganium fluctuans* and common burreed *Sparganium eurycarpum* (37 light traps); sedges (19 light traps); and wild rice (12 light traps) (Table 1). Other important aquatic plant habitat for larval northern pike included common waterweed *Elodea canadensis* in Blind Ash Bay, Kabetogama Lake and northern watermilfoil *Myriophyllum sibiricum* in Jackfish Bay, Rainy Lake. (Table 1). Light traps with the greatest numbers of sampled larval pike were found in microhabitats with hybrid cattail (48%), burreed spp. (16%), burreed/hybrid cattail (11%), common waterweed (11%), sedge (4%) and cattail/common waterweed (4%). The other category included plant categories with <3 light-trap samples: common bladderwort *Utricularia macrorhiza*, common bladderwort/northern watermilfoil, common

Table 1. Number of light-trap sets, total larval count, mean light-trap catch rate and overall mean catch rate for all 15 plant categories in Rainy Lake and Namakan Reservoir, spring 2012. The other category includes plant categories with <3 light traps.

Plant category	Total light traps	Total count	Mean catch rate per light trap
Typha × *glauca*	83	79	0.95 ± 1.61
Sparganium spp.	37	26	0.70 ± 1.22
Carex spp.	19	6	0.32 ± 0.48
Zizania palustris	12	3	0.25 ± 0.45
Sparganium spp./*Typha* × *glauca*	9	18	2.00 ± 3.28
Myriophyllum sibiricum	9	1	0.11 ± 0.33
Potamogeton sp.	7	0	0.00 ± 0.00
Sparganium spp./*Carex* spp.	4	1	0.25 ± 0.50
Typha × *glauca*/*Carex* spp.	4	3	0.75 ± 1.50
Schoenoplectus spp.	3	0	0.00 ± 0.00
Sparganium spp./*Myriophyllum sibiricum*	3	1	0.33 ± 0.58
Sparganium spp./*Zizania palustris*	3	1	0.33 ± 0.58
Typha × *glauca*/*Elodea canadensis*	3	6	2.00 ± 1.00
Elodea canadensis	3	18	6.00 ± 4.36
Other (plant categories with <3 light traps)	11	1	0.17 ± 0.41
Mean ± SD	14 ± 21	11 ± 21	0.94 ± 1.54

waterweed/northern watermilfoil, horsetail *Equisetum* sp., northern watermilfoil/sedge and sedge/wild rice (Table 1). During April and May, these plant types were available in different growth stages, although most were in the form of newly emerging green shoots such as those of burreed, wild rice and sedges. In contrast to newly emerging plant materials, hybrid cattails were available mainly as dried-up stalks from the previous summer and wild rice was also often evident as remnants from the previous year. Of interest was the observation that while emergent forms of vegetation had the highest overall counts of larval northern pike (hybrid cattail, 79; burreed, 26; and burreed/hybrid cattail, 18), the highest mean catch rate (count/# light traps per plant category) was found in submerged common waterweed (mean catch rate of six per light trap; Table 1).

Catches of zero larval northern pike were common for light trapping in the various plant categories. Frequent occurrences of catch rates of zero indicate patchy distributions of the larval northern pike and illustrate the difficulty of sampling larval fish that were only 10–35 mm total length in such large aquatic systems. More zero values in one year compared with other years may also indicate lower recruitment of larval northern pike in that year. The percentage of zero catches of larval northern pike for all 11 bays sampled in 2012 was 68% (143 out of 210 records). The percentage of zero catches for the top four aquatic plant categories was 63% for hybrid cattail, 68% for burreed spp., 68% for sedge spp. and 75% for wild rice (Table 2).

Models of light-trap catches

Preliminary analysis of the 2012 larval northern pike data set using the FMM procedure for finite mixture models in SAS 9.3 (Kessler & McDowell 2012) eliminated bay and water temperature as significant variables ($P = 0.50$ for bay and $P = 0.31$ for water temperature). Across all of the 11 (2012) sample sites, water elevation and the presence of hybrid cattail seemed to have important influences on catches of larval northern pike. Final models for the compiled 2012 data set (with all 11 bays) included the following parameters: water elevation, the presence of hybrid cattail, the presence of sedge, the presence of wild rice and the presence of burreed. The model with the lowest AIC was the negative binomial with water elevation and hybrid cattail as significant variables (Table 3), and estimated model parameters were as follows:

Table 2. Frequency (and percentage) of northern pike larvae present or absent among four of the most frequently sampled plant types in Rainy Lake and Namakan Reservoir, spring 2012. The frequency of larva present/absent represents the number of times out of the total samples for each aquatic plant that a larva is present or absent. The percentage of larva present/absent represents the percentage of times that a larva was present or absent.

Aquatic plant	Total samples	Frequency larva present	Frequency larva absent
Typha × *glauca*	83	31 (37%)	52 (63%)
Sparganium spp.	37	12 (32%)	25 (68%)
Carex spp.	19	6 (32%)	13 (68%)
Zizania palustris	12	3 (27%)	9 (75%)
Mean ± SD	38 ± 32	13 ± 13	25 ± 19

Catch rate (number of fish/light trap) if hybrid cattail present = −88.1260 + 0.2602 water elevation−0.6350 hybrid cattail

Catch rate (number of fish/light trap) if hybrid cattail absent = −88.1260 + 0.2602 water elevation + 0 hybrid cattail

An alternate model using the presence of sedge and wild rice was nearly as good (Table 3).

We applied known water elevations for our light-trap sample sites to the estimated model and produced predicted catch rate results. Predicted catch rates (number of fish per light trap) from the above models were higher for all combined sample sites with hybrid cattail absent (mean catch rate of 0.97) when compared to sample sites with hybrid cattail present (mean catch rate of 0.60) (Fig. 2).

Discussion

This study contributes to the very limited amount of information available on types of aquatic vegetation used as nursery habitat in natural systems by larval

Table 3. Model comparisons for all 2012 sampled bays for the zero-inflated Poisson, negative binomial Poisson, zero-inflated negative binomial and negative binomial hurdle models. Final models for the compiled 2012 data set (with all 11 bays) included the following parameters: water elevation, the presence of hybrid cattail, the presence of sedge, the presence of wild rice and the presence of burreed. The model with the lowest AIC was the negative binomial with water elevation and hybrid cattail as significant variables.

Model	AIC	Significant parameters
Zero-inflated Poisson	598.1	Water elevation ($z = 3.74$, $P = 0.0002$); hybrid cattail ($z = -3.40$, $P = 0.0007$)
Negative binomial	484.0	Water elevation ($z = 2.19$, $P = 0.0284$); hybrid cattail ($z = -2.06$, $P = 0.0398$)
Zero-inflated negative binomial	485.2	Sedge ($z = 3.24$, $P = 0.0012$); wild rice ($z = 2.66$, $P = 0.0077$)
Negative binomial hurdle	486.3	None

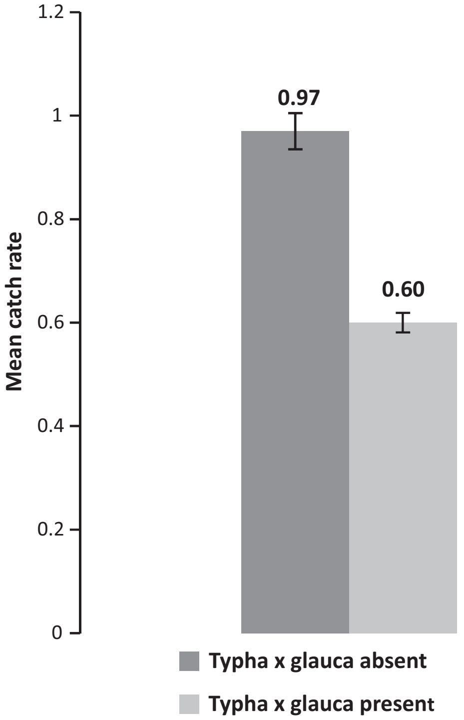

Fig. 2. Predicted mean larval pike catch rates for all light traps in Rainy and Kabetogama Lakes with hybrid cattail absent (0.97) and hybrid cattail present (0.60). The mean larval pike catch rates (number of fish per light trap) presented here are based on the predictive negative binominal model that we applied using known water elevations for our light-trap sample sites.

northern pike. The aquatic plant types observed during our study are commonly found in glacial shield lakes of northeastern Minnesota, and therefore, our records of plant forms used as nursery habitat are most applicable for glacial shield lakes. Results from this study showed that larval northern pike used habitat associated with several different aquatic plant forms, including hybrid cattail stands, which were present in many of our study sites. Light traps were set more often along edges of hybrid cattail stands (83 light traps; Table 1) because this aquatic macrophyte was the dominant available habitat compared to other aquatic vegetation types. Larval northern pike catch numbers were the highest for hybrid cattail (79 larvae) as a reflection of the dominance of hybrid cattail as available spawning habitat. This hybrid cattail dominance is most likely why it was a significant explanatory variable for modelling larval catches. However, hybrid cattail did not have the highest mean catch rate overall, and the predictive models with hybrid cattail present had lower counts overall (Fig. 2). For example, light traps were set 83 times in hybrid cattail with an average catch rate of 0.95 larva per light trap, whereas light traps were set three times in common waterweed with an average catch rate of six larvae per light trap.

One of the few other studies to sample larval northern pike in natural wetlands was conducted by Morrow et al. (1997), who compared catches of larvae between natural and constructed wetlands connected to Conesus Lake, New York. The natural wetlands had grasses, cattails, willows *Salix* spp. and buttonbush *Cephalanthus occidentalis*. Vegetation in the constructed wetlands was predominantly grasses (they had been planted with reed canary grass *Phalaris arundinacea* but had cattail in the deepest areas). Larval northern pike used both the natural and constructed wetlands, but they seemed to have migrated out towards the lake or died by 26 May. A study by Holland & Huston (1984) sampled various habitats in Pool 7 of the Upper Mississippi River throughout the summer by seining. The seines sampled larger juvenile northern pike that were 38–190 mm long, and although some of the juvenile northern pike were seined in emergent vegetation, many more were collected in areas with beds of submersed vegetation. Emergent species in that study included arrowhead *Sagittaria* sp. and wild rice. Submerged plants included curly leaf pondweed *Potamogeton crispus*, common waterweed, northern watermilfoil and water celery *Vallisneria americana*. Bry (1996) diagrammed an example of nursery habitat for northern pike in northern France during mid-April. Emergent vegetation included *Glyceria maxima* and *Rumex hydrolapathum*; floating-leaved plants were *Glyceria fluitans*; submerged plants were *Callitriche* sp. and *Mentha aquatica*.

Other studies have documented aquatic plant types used by larval and juvenile northern pike in constructed wetlands that were managed as spawning and rearing areas in Minnesota. Franklin & Smith (1963) identified vegetation in a slough adjacent to Lake George, in southern Minnesota, where survival of larval northern pike was monitored. Shallowest habitat in the slough consisted of common cattails, sedges, reed canary grass, *Persicaria hydropiper*, arrowhead and sterile culms of *Eleocharis ovata*. In a bit deeper and more open water (maximum depth of the slough was only 1.2 m), were wild rice, *Nuphar variegatum*, *Ceratophyllum demersum and Myriophyllum* spp. Bryan (1967) observed larval northern pike using a dense mat of filamentous algae as hiding cover in a 1.2-ha urban rearing pond in southern Minnesota. Previous light trapping in three southern Minnesota ponds that were also managed as northern pike rearing areas showed best survival of larval northern pike in dense beds of flooded reed canary grass (Pierce et al. 2006). Southern Minnesota has much heavier agricultural and urban land-use than the northern reservoirs we studied.

Elsewhere, Carbine (1941) studied the growth of larval and juvenile northern pike in marsh drainage ditches connected to Houghton Lake, Michigan. The predominant plant used by spawning and larval northern pike was Canada bluejoint grass *Calamagrostis canadensis*. Forney (1968) documented northern water plantain *Alisma triviale*, spike rushes *Eleocharis calva* and *Eleocharis obtusa*, sedges, cattail and reed canary grass as plants in a constructed marsh connected to Oneida Lake, New York, where numbers and growth rates of young-of-the-year northern pike were monitored. Emigration of northern pike out of the constructed marsh peaked in early May when the larvae approached 30 mm total length. Habitat for larval northern pike was also described in two rearing areas in southeastern Wisconsin that had a history of good fingerling production (Fago 1977). One of the rearing areas was a monotypic marsh of reed canary grass. The other rearing area had a dense stand of leatherleaf *Chamaedaphne calyculata*, cattail, and a few patches of sedges.

Our sampling with light traps was directed towards aquatic plant species that were available in late April and May when larval northern pike were developing and when most aquatic plants species were only beginning to sprout or emerge. The aquatic plant species and structural forms encountered by larval northern pike suggest they use nearly any vegetated cover available in early spring. Ultimately, the species of vegetation may not be as important as the physical quality or form of the vegetation in supplying feeding and hiding cover for larval northern pike.

Our results contradicted previous research by Franklin & Smith (1963) that documented northern pike avoidance of cattail for spawning. It also contradicted research by Farrell (2001) that documented a decrease in northern pike spawning success as a result of less access to submerged aquatic macrophytes as a result of an increase in the presence of cattail. Cooper et al. (2008) documented a 155–241% increase in coverage of cattail and a resulting 46–96% reduction in shallow emergent coverage using 1948–2003 aerial photos. As a result of this reduced access to submerged aquatic macrophytes in both of these studies, northern pike spawned in deeper, colder water, where spawning success was reduced. Although we did not sample in deeper habitats to verify that northern pike chose spawning sites in deeper areas of Rainy Lake and Kabetogama Lake, we did document spawning success in cattail in ten of the 11 sampled bays. The cattail dominated the habitat and reduced available areas for other submerged macrophytes to grow, but the cattail was exposed to water and was accessible for spawning throughout the system. The submerged macrophytes grew in the same depths as the cattail inside the outer ring of cattail that was the outer boundary of the littoral zone in our case, which was not the case in the Farrell (2001) and Cooper et al. (2008) studies.

Our results can also be used for projecting the influences of reservoir water-level regulations on nursery habitats of northern pike by overlaying maps of shallow aquatic vegetation on contour maps of elevation for individual water bodies. Water-level changes have caused increases in percentage coverage of cattail over time, as documented by the 155–241% increase in cattail Cooper et al. (2008) study. Our predictive model results showed a reduced catch rate of larval pike where hybrid cattail was present. Water-level regulations may have their greatest influence on larval northern pike through the quality of vegetation available in shallow water during nursery periods. An important remaining question is the extent to which water-level regulations eventually influence plant succession, density and types of aquatic plants in shallow-water habitats of reservoirs. Future work can address this question with the development of a bathymetric LiDAR-based digital elevation model that can predict total available areas of emergent and submerged vegetation throughout Rainy Lake and Namakan Reservoir according to different water levels.

In addition to water-level change, lakeshore development can affect nearshore vegetation development by changing the availability of different plant forms, densities and cover at different depths in relation to the lakeshore (Wilcox & Meeker 1992; Casselman & Lewis 1996). Removal of nearshore aquatic plants is associated with destruction of habitat for various life stages of northern pike (Bryan & Scarnecchia 1992; Radomski & Goeman 2001) and occurs where shorelines are disturbed by construction of homes, boat docks and swimming beaches. In glacial shield lakes, where bedrock shorelines are common, shallow, vegetated habitat potentially has more limited availability to larval northern pike. The practical implication from our study is that these results can be used during environmental reviews of lakeshore development projects to provide justification for protecting species of aquatic plants that comprise nursery habitat.

One of the principal challenges for light-trap sampling of larval northern pike during spring is variable weather patterns that make it difficult to achieve a consistent sampling scheme. Year-to-year differences in precipitation affect the rate at which water levels increase and, therefore, affect the nearshore aquatic macrophyte habitat available for larval northern pike. Spring weather patterns also affect ice-out dates and subsequent water temperatures, which in turn seem to influence survival and growth of northern pike eggs and fry (Pierce et al. 2007; Pierce 2012). Sampling larval fish in highly variable habitats typically results in data sets with high percentages of catches of zero fish, which our modelling of light-trap catches attempted to address. Despite the occurrence of low catch rates in some samples, light trapping was appropriate for our sampling because our efforts were focused on some of the shallowest and most vegetated locations in each bay. Casselman & Lewis (1996) found that water depths occupied by northern pike throughout their first summer were highly correlated with the age and size of the fish, with the smallest fish found in the shallowest habitats.

Our literature review exposed a general lack of knowledge about nursery habitat and the behaviour of larval northern pike in systems where they occur naturally. Using lighted traps to attract larval northern pike at night, we identified nursery habitat in 11 bays of two very large glacial shield lakes and linked catches of larval northern pike to the presence of specific types of aquatic plants. These data and subsequent investigations will be used to project the effects of water-level regulations on aquatic macrophyte habitat quality and the productivity of northern pike nursery habitat.

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