

Habitat Utilization and Early Life History Characteristics of Larval, Young-of-Year, and Juvenile Lake Sturgeon (*Acipenser fulvescens*) in the Great Lakes Connecting Channels

By

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DEDICATION

To my parents

Scott and LaDonna

For their love, support, and encouragement

To my brothers

Scottie and Steven

Our experiences together have shaped my path in ways they will never know

To my grandparents, uncle and aunt

Ron and Corlene, Tim and Jen

For inspiring me to pursue my ambitions and sharing with me their “wisdom” on all manners of
life

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ABSTRACT

I used field surveys, geospatial modeling, and cross-system comparisons to determine if dispersal of larval Lake Sturgeon (*Acipenser fulvescens*) differed in small and large river systems and resulted in a corresponding difference in habitat use for age 0 – 2 individuals. Most species – environmental relationships have been described based on interactions observed during an animal’s most dominant life history stage, or extrapolated from systems where animal behavior is better understood. As a result, knowledge of habitat use during early development of a species is often poorly understood, or assumed to be consistent throughout the animal’s range. Using field surveys in North Channel (NC) and Middle Channel (MC) of the St. Clair River, Michigan, I assessed movement patterns of larval Lake Sturgeon and found significantly higher catch per unit effort (CPUE; No. larvae / hour) in 3 locations 0.5 – 5 km downstream from their natal reefs. Further, I found variation in larval lengths and yolk sac stages from individuals collected in single nets at each of these sites. This suggests larvae of variable ages remained in the river and that suitable nursery habitat existed there and was being utilized by young sturgeon. I then developed a novel habitat suitability model (HSM) to evaluate the quantity, quality, and spatial distribution of riverine nursery habitat for larval, young-of-year (YOY), and juvenile (< 500 mm) Lake Sturgeon in NC. This HSM was developed using georeferenced information on substrate, invertebrate densities, benthic current velocities, and depth. Of the 283 larval Lake Sturgeon collected, the majority were found in high quality habitat (81%) and clustered in three locations (91.2% of total catch). Nine out of 11 YOY and juveniles collected in NC were also in high quality habitat, suggesting suitable habitat also exists for young Lake Sturgeon in NC. Cross-

system comparisons of the HSM developed for NC were undertaken for MC and Fighting Island Channel (FIC) of the Detroit River. Model outputs indicated a significantly higher abundance of high quality habitat present in NC (29.1%) than MC and FIC (16.9% and 15.7%, respectively). HSM modeled output for NC indicated an abundance of suitable habitat first occurred < 0.5 km downstream from a known spawning location. Larval, YOY, and juvenile Lake Sturgeon were found in high densities at three distinct locations of high quality habitat and appeared to utilize similar riverine habitat throughout early development. In MC, larvae also concentrated in three distinct locations of high quality habitat. However, this habitat was less abundant and did not occur until 4.5 km downstream from MC reef. Larval collections in MC decreased as sampling progressed downstream, suggesting increased drift distance to suitable habitat resulted in increased larval mortality or alternative dispersal behavior. In FIC, high quality habitat was less common, larval Lake Sturgeon abundance was low, and larvae were not observed in high concentrations. This suggests that newly emerged larvae did not utilize available habitat in FIC, but instead drifted into the main channel of the Detroit River. My dissertation showed that dispersal of larval Lake Sturgeon in the GLCCs is strongly associated with location and abundance of suitable nursery habitat downstream from natal spawning reefs. Further, results indicated variation in habitat conditions downstream of natal reefs resulted in variable dispersal patterns of young Lake Sturgeon and should be taken into account for the planning of future restoration efforts.

CHAPTER 1

Introduction

Understanding physical and ecological attributes that dictate the physiological and behavioral responses of organisms is fundamental to understanding ecological systems (Begon et al. 1986, Odum 1997). The ability to comprehend or predict how an organism can utilize, manipulate, or adapt to its surrounding environment is not only vital in advancing ecological theory, but is also of tremendous practical value in terms of management. However, knowledge of both the details of the surrounding environment, and the flexibility in potential response is often incomplete. This hinders resource managers who must accurately predict the implications of present practice and future plans, and develop rational restoration and rehabilitation strategies.

Great strides have been made in understanding interactions between species and their local environments. Niche theory describes an organism as occupying a specific N-dimensional ecological space in the natural environment (Rosenzweig 2001, Holt and Barfield 2008). In doing so, each species provides a particular ecological role, allowing it to survive within that range of conditions and circumstances. Our understanding of a species niche is often limited to the most dominant, well-studied stage of the organism's life (Kennedy and Gray 1993). However, in many cases, a species may occupy multiple distinct habitats and appear to fill varying niches throughout its life cycle. Stages of life history are defined by milestones in physiological development (i.e., beginning of exogenous feeding, gonad development), which result in the use of different resources at each stage (Hendry and Stearns 2004). Often, the relationship between these individual life stages and their environments is not understood,

preventing or hindering efforts to accurately measure the impacts of environmental perturbations on a population (Biette et al. 1981, Secor et al. 2002).

To add further complication, recent anthropogenic influences have altered species – environment relationships, often with dramatic, unforeseen consequences. For example, damming of most major U.S. rivers and tributaries has had disastrous impacts on mussel, fish, and amphibian populations nationwide, through isolation and segregation of communities (Watters 1996, Jager et al. 2001), disruption of spawning migrations (Hay-Chmielewski and Whelan 1997, Holey et al. 2000), and alteration of riverine, wetland, and shoreline habitat (Leopold 1994). Upon examining data from more than 230 overfished populations, Hutchings and Reynolds (2004) found factors attributed to habitat change, such as disruption of local food web dynamics and impacts on physiological condition, were largely responsible for failed recovery efforts. Human-driven habitat destruction and modification have altered substantial tracts of the global landscape, resulting in the forced relocation, extirpation, and extinction of thousands of species (Tilman et al. 1994, Vitousek et al. 1997, World Health Organization 2005).

Site-specific field surveys and monitoring efforts have been instrumental to formulating effective conservation strategies for combating effects of anthropogenic habitat alteration (Hay-Chmielewski and Whelan 1997, Detenbeck et al. 1999). However, habitat characteristics where a given species occurs can have a tremendous influence on the ability of researchers to monitor and understand how organisms use and interact with their surroundings (Storms and Estes 1993, Mihuc and Feminella 2001). This is especially true in habitats that pose obstacles and hazards that make them more difficult for researchers to sample. Here, local conditions may warrant sampling modifications or necessitate experimental approaches as traditional methods prove impractical (Casselman et al. 1990, Dettmers et al. 2001). As such, logistically challenging areas

are often poorly evaluated, resulting in gaps in knowledge of species – environmental interactions.

Large river systems exemplify habitat that offer logistically challenging obstacles to traditional assessment methodologies. The relatively large size, depth, and swift flow in these systems may hinder accurate assessments of fish communities residing within them (Casselman et al. 1990, Mihuc and Feminella 2001, Flotemersch et al. 2006). In many instances, sampling strategies and equipment that work to great effect in small river systems are ineffective or impossible to utilize in large rivers (Dettmers et al. 2001, Lapointe et al. 2006). Recently, the EPA conducted a variety of field-based sampling assessments in large river systems throughout the Midwest. This study concluded that depth, channel width, and discharge play a critical role in the response of fish assemblages to sampling efforts and that current monitoring protocols may not fully capture local fish community composition or functional state (Flotemersch et al. 2006). These difficulties with sampling of particular habitat are of great concern to researchers interested in understanding the various aspects of a population's life history, as individuals at different life history stages may utilize different, preferred habitat types (Biette et al. 1981, Ihssen et al. 1981, Secor et al. 2002). Thus, difficulties in sampling specific habitat types can result in information gaps for specific life-stages of organism that reside in these areas (Casselman et al. 1990). Resultant gaps in life history information pose many challenges to conservationists because a comprehensive understanding of habitat requirements through life history development is essential for assessing population viability, and identifying potential impediments to species recovery and success (Schlosser 1991).

Knowledge of ontogenetic shifts in resource requirements is especially critical for the management of fishes, which have very distinct stages (Balon 1975) and may utilize several

distinct habitats throughout their development (Gross 1985, Stearns 1992). Species – environmental relationships during early life history stages are of particular importance in fishes, as these stages typically represent periods when individuals have unique habitat associations and are most prone to high mortalities (Secor et al. 2002, Young et al. 2006), which result in the greatest influence on year-class success (Diana 2004). However, the early period of life for many fish species is poorly understood, especially in large river systems (Pepin 1991, Young et al. 2006, Barth et al. 2009). In order to fully comprehend the dependence of an organism on its environment, resource requirements and environmental relationships must be understood for each life history stage. Thus, strategies for effectively sampling fishes during their early life history stages are crucial for understanding fish community dynamics.

Lake Sturgeon (*Acipenser fulvescens*) provide an excellent case study of the ways in which changing habitat use and ontogenetic niche shifts have implications for management. Lake Sturgeon are long-lived, possessing multiple, and discrete life-history stages with each requiring a varying set of environmental conditions for successful development (Harkness and Dymond 1961). Once abundant throughout their historic range, overharvest, habitat alteration and destruction, and pollution reduced Lake Sturgeon populations to less than 1% of their former abundance (Brousseau and Goodrich 1989). Lake Sturgeon are now deemed threatened in all states and provinces bordering the Great Lakes with the exception of Wisconsin (The Nature Conservancy 1994, Auer 1999, Chiotti et al. 2008).

There is currently a gap in knowledge of early life history characteristics during the first 1 - 2 years of the Lake Sturgeon's life. It is during this time that they are most susceptible to severe population bottlenecks and may suffer mortalities as high as 99% (Caroffino et al. 2010). This gap in understanding of age-1 and -2 Lake Sturgeon found in large rivers stems primarily from a

lack of knowledge of habitat preference and utilization, hindering efforts to effectively survey these animals in systems such as the Great Lakes Connecting Channels (GLCCs; Holey et al. 2000).

I studied habitat relationships and dispersal during the early life-stages of Lake Sturgeon in two large connecting channels in the Laurentian Great Lakes; the St. Clair and Detroit rivers. To better inform restoration efforts in these systems, a more comprehensive understanding of Lake Sturgeon dispersal and habitat selection during early life is essential. As such, my overarching goal in this study was to evaluate habitat use by age 0 – 2 Lake Sturgeon in the GLCCs. In doing so, I sought to develop effective strategies for studying species – environment interactions in large, poorly understood, and generally difficult to sample rivers. Several ongoing management and restoration strategies aimed at rehabilitating known Lake Sturgeon populations are based on information from small river stocks where individuals are more easily surveyed and Lake Sturgeon ecology is better understood (Auer and Baker 2002, Smith and King 2005, Benson et al. 2006). Conservation efforts derived from these studies operate under the assumption that habitat requirements for young Lake Sturgeon are the same across their range, despite variations in local stream and river habitat characteristics (Bruch 1999, Holey et al. 2000). However, recent research suggests that dispersal and habitat use of young Lake Sturgeon varies and should be accounted for in future restoration and management efforts (Benson et al. 2006, Barth et al. 2009, Krieger and Diana 2016).

I developed tools and methodologies to improve our understanding of habitat use by age 0 – 2 Lake Sturgeon in large river channels and investigated life-stage specific relationships between Lake Sturgeon and their habitat. My overall research objective was to determine if dispersal of larval Lake Sturgeon differs in small and large river systems and results in a corresponding

difference in habitat use for age 0 – 2 individuals. Local habitat characteristics have a strong influence on early-stage survival and development (Schlosser 1982, Hayes et al. 1996), yet the influence of environmental factors on habitat selection and dispersal patterns for many fishes is not well understood in larger rivers (Hay-Chmielewski and Whelan 1997, Peterson et al. 2007). I addressed this objective using three complementary studies. First, I characterized drift patterns of larval Lake Sturgeon in the North and Middle channels of the St. Clair River, Michigan, and investigated the patterns of dispersal and habitat selection in those channels (Chapter 2). Second, I used information on larval drift patterns and habitat characteristics (depth, substrate, invertebrate density, and benthic current velocity) to construct a habitat suitability model (HSM) for larval, young-of-year (YOY) and juvenile Lake Sturgeon in the North Channel of the St. Clair River (Chapter 3), and tested that model with details on larval and juvenile sampling in that location. Finally, I tested the generality of this model using habitat and larval drift data for Lake Sturgeon collected in the Detroit River and Middle Channel of the SCR (Chapter 4) to predict habitat use and quality in other regions of the GLCCs. Through this work, I furthered the understanding of dispersal and habitat use of young Lake Sturgeon in large river systems, aiding restoration efforts for this species.

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CHAPTER 2

Assessing the distribution of larval Lake Sturgeon (*Acipenser fulvescens*) in the lower St. Clair River, Michigan

Introduction

The spatial ecology and habitat use by Lake Sturgeon (*Acipenser fulvescens*) at different life stages are not fully understood (Smith and King 2005). Most studies of the behavior of Lake Sturgeon have focused on adult movement and habitat selection (Fortin et al. 1993, Auer 1999). Comparatively few studies have been conducted on the distribution patterns of Lake Sturgeon larvae (Kempinger 1988, Auer and Baker 2002, Smith and King 2005), and these have largely been limited to Lake Sturgeon populations found in small rivers. Upon hatching, Lake Sturgeon larvae actively seek refuge in deep interstitial spaces of nearby substrate (Kempinger 1988, Smith and King 2005), where they remain hidden for 3 – 14 days until transitioning from yolk sac nutrition to exogenous feeding (Smith and King 2005, Crossman et al. 2014). Once this change occurs, negatively phototactic larvae emerge from the substrate at night to disperse downstream in search of suitable nursery habitat (Kempinger 1988, Auer and Baker 2002). Larvae collected during their drifting phase are of relatively homogenous size, ranging from 12 – 16 mm TL, and predominately possess a partial or fully absorbed yolk sac (LaHaye et al. 1992, Auer and Baker 2002). The ability of larval Lake Sturgeon to orient or maneuver while drifting downstream is thought to be limited (Kempinger 1988), and downstream dispersal of larvae is commonly described as “passive” (Kempinger 1988, Auer and Baker 2002). As such, duration of larval drift in these rivers is dependent on local current velocity and distance from spawning

source to nursery habitat (LaHaye et al. 1992, Benson et al. 2006). Nursery habitat has been identified in the lower portions of small and moderate sized rivers where water drains into small lakes, water velocity is slower, and larvae are able to exit the current (LaHaye et al. 1992, Auer and Baker 2002).

While informative, observations of Lake Sturgeon behavior derived from populations found in smaller rivers may not be comparable to those of fish in larger rivers, such as the Great Lakes Connecting Channels (GLCCs), where several populations of Lake Sturgeon reside (Hay-Chmielewski and Whelan 1997, Thomas and Haas 2002). In the GLCCs (the upper St. Lawrence, St. Mary's, Niagara, St. Clair, and Detroit rivers) depth, discharge, width, current velocity, and hydrologic conditions (e.g., seasonal range in current velocity, floodplain stage) differ from conditions found in smaller rivers and may result in dramatic differences in Lake Sturgeon behavior and habitat use. For example, unlike many rivers where seasonal discharge fluctuates widely (Junk et al. 1989, Bayley 1995), annual discharge for the St. Clair River (SCR), is relatively stable, with only a 22 – 25 % difference between low and peak flows (Hondorp et al. 2014). The climatic and hydrological conditions may influence larval Lake Sturgeon dispersal by affecting the spatiotemporal distribution of spawning, access to critical nursery habitat, and timing and duration of larval drift (Dumont et al. 2011). As such, an understanding of larval Lake Sturgeon dispersal in large rivers is needed to better inform restoration efforts in the SCR and other large river systems.

The goal of this study was to better understand how dispersal of larval Lake Sturgeon in large rivers differs from dispersal in small rivers. To accomplish this, the main objective of this study was to assess drift and dispersal patterns of larval Lake Sturgeon in the lower SCR; in areas where Lake Sturgeon spawning habitat is known to exist. Based on previous studies of larval

Lake Sturgeon dispersal from smaller rivers, I hypothesized that larvae would drift passively with the current, moving out of the river into slower moving waters of Lake St. Clair or surrounding wetlands within hours or days after emerging from their natal spawning reef. Further, I expected larvae collected together in locations downstream of spawning reefs to be of similar size and yolk sac stage, indicative of passive passage from the natal reef to settlement locations in Lake St. Clair.

Methods

I selected portions of the North Channel (NC) and Middle Channel (MC) of the SCR for assessment (Figure 2.1). The SCR is 64 km in length and drains water from Lake Huron into Lake St. Clair. It has an average discharge of 5,200 m³/s, which remains relatively constant seasonally. Flow velocities in the SCR range from ~ 0.3 to 1.7 m / s (Schwab et al. 1989) with mid-channel depth ranging from 13 – 15 m and scattered deep holes > 21 m. In the NC, Lake Sturgeon largely spawn on one small reef (1350 m²) formed by dumping of coal cinders during shipping in the early 1900s (Maslinka Reef, Figure 2.1, Boase et al. 2011). In the MC, Lake Sturgeon eggs have been regularly collected from an artificial spawning reef (4040 m²) constructed in 2012 (MC Reef, Figure 2.1, Bouckaert et al. 2014). Larval fish from these reefs are believed to drift downstream into the lower river and possibly into Anchor Bay.

Information on Lake Sturgeon larval distribution was collected during the seasonal larval drift period with the use of D-frame drift nets (area of opening = 0.35 m², 1600 µm mesh), which sample the bottom 0.75 m of the water column (Auer and Baker 2002, Roseman et al. 2011). Larval drift surveys took place from 10 June to 9 July 2013 (14 nights) and 8 June to 29 July 2014 (23 nights). In each year, drift nets were deployed beginning approximately eight days after eggs were collected on either reef by personnel from the US Geological Survey (minimum

incubation time needed prior to hatch) and concluded after three consecutive nights passed without encountering larval sturgeon.

Drift net locations were selected systematically in the NC and MC of the SCR and grouped based on river kilometer (RKM) distance downstream of the Blue Water Bridge (42.9992 N, - 82.4238 W; Figure 2.1), where a third spawning reef is located near the head of the SCR (Port Huron Reef, Boase and Hill 2002). The Blue Water Bridge was selected as the point of reference due to its location at the head of the SCR and the assumption that it includes the most upstream spawning location for Lake Sturgeon in this system. In 2013, 2 sites were sampled in the NC between RKM 51-52 and 20 sites were sampled in the MC between RKM 51-60 (Figure 2.1). Sites located at RKM 61-62 were not sampled in 2013. In 2014, 23 sites were sampled in the NC between RKM 51-60 and 29 sites were sampled in the MC between RKM 51-62. The NC splits at RKM 56 and some flow diverges into the Chenal A Bout Rond, resulting in overlap with RKM sites in the NC located downstream of this split. Sample sites from the Chenal A Bout Rond are denoted with a 'b' (e.g., RKM 57b).

Drift nets were fished passively between 20:00 and 06:00 hours and were retrieved at 2 – 5 hour intervals. All drift samples were washed with water, drained, soaked in MS-222 solution to euthanize larval fish, and preserved in 95 % ethanol. In the lab, photographs of individual larvae were taken at 60x magnification using a microscope with digital analysis software (Image Pro Plus 7.0). Total length (TL, mm) and yolk sac absorption stage (full, partial, or no-yolk sac) were measured for each larva from magnified images. Lake Sturgeon larvae with full yolk sacs were identified by a pronounced yolk sac extending to the pectoral fin and the lack of distinct pigmentation along the lateral portion of the head and trunk. Larvae with partially absorbed yolk sacs possessed a less pronounced yolk sac, which often appeared wrinkled or deflated, and had

dark pigmentation along the head and trunk. Individuals with no-yolk sac lacked a yolk sac, had fully formed mouths, and possessed a prominent lateral band, which extended the entire length of the body (Wang et al. 1985, Kempinger 1988, Petersen et al. 2007). Catch-per-unit-effort (CPUE; No. larvae/ hour) of larval Lake Sturgeon was calculated for each site.

Significant differences in CPUE, TL, and yolk sac stage were assessed using Kruskal-Wallis (KW) nonparametric tests followed by Dwass-Steel-Critchlow-Fligner (DSCR) post hoc procedure for multiple pairwise comparisons (Hollander and Wolfe 1999). These analyses were performed using SYSTAT-v 13.1. Alpha was set at 0.05 for all comparisons.

Results

Larval Lake Sturgeon were not randomly distributed in the two river channels, but were collected in larger numbers at specific locations throughout both rivers. In 2013, 163 larvae were collected from both the NC and MC during 1181 hours of sampling. Mean CPUE in the MC was highest in nets near the MC reef at RKM 51-52 (0.18) and remained low further downstream (< 0.02) until increasing in abundance at RKM 57-58 (0.06, Table 2.1). Larval CPUE at RKM 51-52 was significantly higher than CPUE collected from sites further downstream (KW, $T = 28.233$, $P = 0.01$, $DF = 4$; DSCF, $P < 0.05$). In the NC, in 2013, sampling occurred upstream of the Maslinka reef at RKM 51-52 and mean CPUE was 0.32.

Distribution of larval Lake Sturgeon in 2014 was similar to 2013 in that larvae were also collected in high abundance at discrete locations throughout both river systems and did not appear randomly distributed in either river. In 2014, sampling effort was increased to 1979 hours and 680 larvae were collected in both the NC and MC. Mean CPUE in the MC was highest downstream of the MC reef at RKM 54-55, followed by areas near the reef at RKM 51-52, and then again downstream at RKM 58-59 (Table 2.1). Larval CPUE at these three sites was

significantly higher than CPUE sampled from all other sites in the MC during 2014 (KW, $T = 28.233$, $P = 0.01$, $DF = 4$). Larvae from these sites made up > 90% of the total larvae collected from the MC in 2014. Only 6 larvae were caught further downstream than RKM 59.

In the NC, larvae were collected mainly in several distinct locations and only 4 were found further downstream than RKM 57. Upstream of Maslinka reef, mean CPUE at RKM 51-52 was 0.91. Downstream of the reef, CPUE was highest at sites sampled near the Chenal A Bout Rond – NC split (RKM 56-57b), followed by collections at RKM 55-56 and 53-54 (Table 2.1). Larval CPUE from these three sites was significantly higher than CPUE sampled from all other sites downstream of the reef during 2014 (KW, $T = 32.11$, $P = 0.001$, $DF = 6$) and made up 94% of total larval collected downstream of the reef.

Distribution patterns for length and yolk sac stage of larval Lake Sturgeon were relatively homogenous throughout both channels, but considerable variation was observed between individuals collected in single nets. In 2013, 53 larvae were collected upstream of the Maslinka reef at RKM 51-52. Larval TL ranged from 11.4 – 23.7 mm ($\bar{x} = 17.8 \pm 2.7$; Table 2.2) with lengths of larvae recorded in individual nets differing by 2 – 6 mm. A full yolk sac was evident in 30.2% of larvae, while 26.4 % had a partially absorbed yolk sac, and 43.4% had no yolk sac. Variation in lengths and yolk sac stages of larvae collected in a single location suggest individuals of different ages occurred together in time and space (Kempinger 1988, Peterson et al. 2007), and some larvae remained in the river rather than passively drifting downstream. Larvae collected in 2013 from the MC ranged in size from 14.6 – 32.9 mm ($\bar{x} = 18.7 \pm 2.6$). Larvae collected in nets near the MC reef were significantly larger than those collected at sites further downstream (KW, $T = 25.31$, $P = 0.02$, $DF = 5$; Table 2.2). However, no significant difference in larval size was found between sites located downstream. While lengths of larvae

varied little between sites in the MC, lengths of larvae recorded in individual nets also showed considerable variation, at times differing by 3 – 8 mm.

Larval Lake Sturgeon collections from upstream of the MC reef had higher proportions of larvae with full or partially absorbed yolk sacs compared to collections downstream. At RKM 51-52, I found full yolk sacs on 22.6% of individuals, partially absorbed yolk sacs on 34.7%, and no yolk sacs on 42.7% (n = 84). Downstream of this site, no-full yolk sac larvae were collected and catch was composed of nearly equal proportions of individuals with no and partially absorbed yolk sac (Table 2.1). Larvae utilize yolk nutrition as they age and move downstream (Auer and Baker 2002, Peterson et al. 2007); indicating larvae collected upstream of the MC reef were younger and less developed than those collected downstream. No significant difference in yolk sac composition was found between sites in the MC, but the proportion of full yolk sac individuals was significantly less than that of partially absorbed and no yolk sac larvae (KW, T = 13.34, P = 0.01, DF=4).

In the 2014, surveys in the NC and MC found little difference in larval length and yolk sac composition from different locations in either channel, though considerable variation was found in larvae collected in single nets at some locations. In the NC, larval Lake Sturgeon ranged in size from 11.7 – 24.5 mm ($\bar{x} = 18.4 \pm 2.2$), and individuals collected in single nets differed by 3 – 8 mm. While the largest larvae were found downstream at RKM 58-59b ($\bar{x} = 22.5 \pm 2.9$), mean lengths of larvae collected at this site were not significantly larger than those collected further upstream at RKM 55-56, 56-57, and 57-58, nor than collections of larvae above Maslinka reef at RKM 51-52 (DSCF, P > 0.05 for all comparisons; Table 2.2). This differs from larvae studied in some smaller rivers where individuals found further downstream are larger than those further upstream (LaHaye et al. 1992, Auer and Baker 2002, Smith and King 2005). Yolk sac stage

composition of larvae collected upstream of the Maslinka reef was made up of 23.0% individuals with full yolk sacs, 47.5% with partially absorbed, and 29.4% with no yolk sac (n = 177).

Significantly more full yolk sac individuals were collected from this site compared to combined total of all sites downstream from Maslinka reef (n = 9, KW, T = 29.42, P = 0.01, DF = 7). While few full yolk sac larvae were found downstream of Maslinka reef, larvae with partially absorbed yolk sacs dominated collections at RKM 53-54 and 55-56 (85.2% and 94.1% of total larval catch, respectively), and those with no yolk sac dominated at RKM 56-57b (61.1%). Though there was no significant differences in yolk sac composition between collection sites (DSCF, P > 0.05 for all comparisons), variation was observed between individuals collected in single nets, with some samples containing full, partial, and no yolk sac larvae together. Similar to 2013 findings, the occurrence of larvae with varying lengths and yolk sac stage in single nets suggests some individuals remained in NC.

Similar to the NC, larvae collected from the MC in 2014 were found to vary in size and yolk sac composition, indicative of larvae taking up residence in suitable habitat there. Larval lengths ranged from 12.5 – 31.3 mm ($\bar{x} = 18.2 \pm 2.6$) and differed by 2 – 7 mm in a given net. Also similar to collections in the NC, the largest mean larval length in the MC was found in individuals collected downstream at RKM 59-60 ($\bar{x} = 21.3 \pm 0.5$). However, no significant differences were found in larval lengths between sites, with the exception of mean length collected at RKM 58-59 ($\bar{x} = 16.3 \pm 1.3$) which was significantly smaller than mean lengths at RKM 53-54, 57-58, and 59-60 (DSCF, P < 0.05 for all comparisons, Table 2.2). Near the MC reef at RKM 51-52, I collected 201 larvae and 28.9% possessed full yolk sacs, 39.3% had partially absorbed yolk sacs, and 31.8% had no yolk sac. Again, few of the larvae collected downstream of the MC reef had full yolk sacs (n = 4). There were no statistically significant

differences in larval yolk sac stage composition found between sites, with the exception of RKM 54-55 where significantly more larvae with partially absorbed yolk sacs were found compared to larvae with no or fully absorbed yolk sacs (87.5% of site catch, KW, $T=15.221$, $P = 0.02$, $DF=3$). As in the NC, larvae in the MC with full, partial, and no yolk sacs were found together in single nets in some samples.

Discussion

Distributions of larval Lake Sturgeon collected in this study, along with patterns of larval morphometric characteristics, suggest that young Lake Sturgeon remain within the lower SCR, in multiple distinct locations, after drifting a short distance (2 – 6 km) from their natal reef. This is evidence against my original hypothesis that larvae would be found in greatest abundance just downstream of their natal reef and show a longitudinal decline in abundance as they drifted quickly into Lake St. Clair or surrounding wetlands. Further, distinct locations of high larval abundance with different sizes and yolk sac stages of larvae suggest young Lake Sturgeon of various ages remained in the river and utilized these locations as nursery habitat.

The finding that some larvae may remain in the river and use nursery habitat there is supported by observations of Lake Sturgeon from previous studies. Larval surveys annually conducted by state, federal, and university personnel throughout the SCR system regularly demonstrate variation in larval densities throughout the river and catch few individuals close to or in the lake itself. While this may be a result of high larval mortality during drift (Caroffino et al. 2010), I believe it suggests that larvae settle in areas as they move downstream and do not quickly drift out of the channel in a passive manner. Using drift nets similar to those utilized in my study, Auer and Baker (2002) also noted that while some larvae appeared to drift quickly down the Sturgeon River into Portage Lake, a large number were found in the river for > 40

days. Larval Lake Sturgeon collected in my study occurred in high concentrations at three distinct locations throughout both the NC and MC. Previous studies have noted high abundances of larval, YOY, juvenile, and sub-adult Lake Sturgeon at similar settings in largely different rivers. Boase et al. (2014) showed high degrees of site fidelity to locations similar to my areas with high larval abundance in the NC for young Lake Sturgeon (580 – 800 mm) implanted with ultrasonic transmitters and tracked over three separate summers. High concentrations of larvae were collected in areas just downstream of their natal hatching points in the Black, Sturgeon, and Peshtigo rivers, where YOY were also collected regularly (Auer and Baker 2002; Smith and King 2005, Benson et al. 2005). Smith and King (2005) examined distribution patterns of Lake Sturgeon in the Black River – Black Lake system and suggested that YOY and juvenile Lake Sturgeon used “core activity centers” in the lower river where they congregated in high densities. Similar to my study, Bouckaert et al. (2014) noted larvae of variable lengths and densities in distinct locations of the NC and MC, and high larval CPUE in close proximity to natal reefs. However, while their study concluded that larval abundance decreased consistently as drift progressed downstream, I noted several distinct areas of high larval CPUE downstream of reefs. In comparison to my study, Bouckaert et al. (2014) had considerably lower sampling effort, sampled fewer sites, and may have sampled in years with lower egg deposition, which may explain discrepancies in larval abundance and distribution patterns between our studies.

I believe trends in larval abundance indicate that larval Lake Sturgeon choose to remain in areas downstream of their natal spawning reefs, rather than drifting into Lake St. Clair or surrounding wetlands. To achieve this, larvae must find refuge from strong current velocities present in the SCR. In other systems, larval Lake Sturgeon are known to burrow into sediment during the day and emerge again at night to continue drifting downstream (Kempinger 1988,

Peterson et al. 2007). Benthic substrate of the SCR is comprised largely of sand, silt, and gravel (Boase et al. 2014), and previous studies have shown the ability of larval Lake Sturgeon to burrow into these substrate types (Benson et al. 2005, Hastings et al. 2013). As current velocity should also be quite low at the river bottom (Kim et al. 2000), larvae remaining in the top-most layer of sediment would escape high current speeds and be able to maintain location. In addition to providing refuge from strong currents, these substrate types are also favorable habitat for Mayfly larvae (*Hexagenia* spp.), bloodworms (Chironomidae), and other small oligochaetes, which are all known prey items for young Lake Sturgeon (Peterson et al. 2007). Further, larvae may be susceptible to predation when drifting above the substrate, but by remaining burrowed or moving within the topmost layer of sediment they are likely less vulnerable to predators (Caroffino et al. 2010).

I found a wider range in size and level of yolk sac utilization in the SCR than would be expected based on studies of larvae from small rivers. Peterson et al. (2007) determined that larval Lake Sturgeon remain on their natal reef for periods of 2 – 4 weeks after hatch as they absorb their yolk sac and continue to develop. After this time, larvae of relatively homogenous lengths emerge from the reef, and individuals with partially absorbed or fully utilized yolk sacs dominate the drift downstream from the natal reef (LaHaye et al. 1992, Auer and Baker 2002). However, larvae collected downstream of both the Maslinka and MC reefs in this study ranged in size by as much as 8 mm and showed considerable variation in both lengths and patterns of yolk sac composition. Variation in morphometric characteristics between larvae may indicate individuals entered the drift at different times with some possibly being dislodged from their reef due to turbulence or strong flow (Kempinger 1988, Peterson et al. 2007). However, if larvae were dislodged, collections of larvae immediately downstream of spawning reefs should contain

higher proportions of relatively small (12 – 16 mm) individuals with full yolk sacs, as these larvae would be young and newly hatched (Smith and King 2005, Peterson et al. 2007). This pattern for dislodged larvae is inconsistent with patterns of larval Lake Sturgeon composition found in my study, where individuals of larger size and more depleted yolk sacs were found just downstream of reefs. As such, I believe variation in length and yolk sac stage composition found in this study compliment larval CPUE patterns and indicate larvae of variable lengths and developmental stages remained in distinct locations downstream of natal reefs in the NC and MC.

Collections of larval Lake Sturgeon upstream of the spawning reefs in the NC and MC indicate the input of larvae from sources further upstream in the SCR. I found relatively large numbers of larvae upstream from both the Maslinka (178) and MC (54) reefs, and most (64%) had either a full or partially absorbed yolk sac; indicative of individuals who had recently emerged from their natal reef (Kempinger 1988, Peterson et al. 2007). At the time of this study, only one confirmed natural spawning location was known to exist upstream of my study sites in the SCR, located approximately 45 km upstream from the MC reef near Port Huron, Michigan. Given the distance these larvae would have to travel had they originated from the Port Huron reef, it is unlikely they would have arrived at either the NC or MC with any yolk sac remaining. This finding suggests the presence of one or more spawning sites in unknown locations upstream of the NC and MC, which likely contributed larvae to my collections further downstream.

While larval collections upstream of the Maslinka and MC reef suggest the input of larvae from alternative sources, I believe this input does not influence my results indicating larvae remained in the river at downstream locations. Larvae collected upstream of the Maslinka and MC reefs showed nearly identical proportions of full, partial, and no yolk sac stages to larvae

collected below the reefs. Lengths of larvae collected from upstream and downstream of these reefs were not statistically discernible. Larvae in both rivers concentrated in distinct areas downstream of each reef, indicating larvae resided in areas downstream of these reefs, regardless of their origin. Given distinct concentrations of larvae and the similarities in morphometric characteristics in upstream and downstream collections, I believe larvae from upstream sources drifted past the Maslinka and MC reefs, mixed with larvae emerging from these reefs, and used similar habitat downstream.

My observations of high larval CPUE in distinct areas downstream of the Maslinka and MC reefs, and of high variation in length and yolk sac composition of larvae found in similar locations support three main conclusions. My first conclusion is that larval Lake Sturgeon in the SCR possess the ability to orient and direct themselves during their drifting phase, indicating a drift behavior that is better described as “guided” rather than “passive”. This is supported by high concentrations of larvae collected in distinct locations downstream of the Maslinka and MC reef, and few individuals collected elsewhere. My second conclusion is that Lake Sturgeon spawning habitat exists upstream of the Maslinka and MC reefs in unknown locations. This is supported by collections of larvae upstream of my study reefs with full or partially absorbed yolk sacs which is not indicative of larvae having traveled from the Port Huron reef. My third conclusion is that suitable nursery habitat exists downstream of the Maslinka and MC reefs which is being utilized by larval Lake Sturgeon. This is supported by collection of few larvae further than 2 km downstream of the Maslinka reef or 6 km downstream of the MC reef, high concentrations of individuals caught at RKM 53, 55, and 56b in the NC; and RKM, 53, 56, and 58 in the MC, and by the occurrence of larvae with variable lengths and yolk sac stages in single nets at similar locations.

As with many species of fish, recruitment success of Lake Sturgeon is largely influenced by conditions experienced during their first year of life (Hay-Chmielewski and Whelan 1997, Peterson et al. 2007). In the Great Lakes, access to and availability of suitable spawning and nursery habitat is believed to be the greatest impediment to Lake Sturgeon recovery (Hay-Chmielewski and Whelan 1997, Hayes and Caroffino 2012). In this study, I identified areas with concentrated numbers of larval Lake Sturgeon, which likely serve as nursery habitat for newly emerged larvae. While some studies have described nursery habitat characteristics for young Lake Sturgeon in smaller river systems (Kempinger 1996, Chiasson et al. 1997, Benson et al. 2005), at present, a description is not available for Lake Sturgeon population in the GLCCs. Understanding species – environmental interactions as they change and develop throughout early life stages is critical for linking ongoing and future habitat restoration activities. Currently, efforts to restore spawning habitat in the GLCCs is a top priority for managers (Hay-Chmielewski and Whelan 1997, Hayes and Caroffino 2012). However, without sufficient knowledge of habitat use by larvae after they emerge from these reefs, restoring spawning habitat alone may not be sufficient. In order to improve recruitment success for Lake Sturgeon in the SCR, we need to identify the location and extent of unknown spawning sites, and to survey and characterize habitat conditions at sites identified as possible nursery areas.

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Table 2.1. Catch-per-unit-effort (CPUE) and yolk-sac stage (YS) for larval Lake Sturgeon collected in drift samples by channel and RKM in the lower St. Clair River, 2013-2014.

Channel	RKM	Larvae collected in 2013 (163)					Larvae collected in 2014 (680)				
		Full	Partial	No	Net hours	CPUE	Full	Partial	No	Net hours	CPUE
North	51-52	16	14	23	170.3	0.32	41	84	52	200.9	0.91
North	53-54	-	-	-	-	-	0	46	8	193.0	0.3
North	55-56	-	-	-	-	-	8	112	7	189.4	0.72
North	56-57	-	-	-	-	-	0	4	8	45.2	0.09
North	57-58	-	-	-	-	-	0	0	1	7.8	0.13
North	58-59	-	-	-	-	-	0	0	0	6.2	0
North	56-57b	-	-	-	-	-	1	14	22	29.4	1.27
North	57-58b	-	-	-	-	-	0	0	0	7.1	0.00
North	58-59b	-	-	-	-	-	0	0	2	22.1	0.09
North	59-60b	-	-	-	-	-	0	0	0	7.0	0.00
Middle	51-52	16	21	47	458.3	0.18	58	79	64	634.9	0.32
Middle	52-53	-	-	-	-	-	1	0	0	12	0.09
Middle	53-54	-	-	-	-	-	0	7	5	44	0.19
Middle	54-55	-	-	-	-	-	0	35	5	100.1	0.44
Middle	56-57	0	1	3	129.1	0.04	-	-	-	-	-
Middle	57-58	0	3	5	137.7	0.06	1	0	1	110.7	0.02
Middle	58-59	0	4	3	139.6	0.05	2	4	2	81.4	0.29
Middle	59-60	0	3	4	146.6	0.05	0	0	2	164.9	0.01
Middle	61-62	-	-	-	-	-	0	1	1	125.5	0.01

Table 2.2. Length (mean \pm standard deviation) distributions of larval Lake Sturgeon collected from the North and Middle channels during 2013 - 2014.

Year	Channel	RKM	Length (mm)
2013	North	51-52	17.8 \pm 2.7
2013	Middle	51-52	18.7 \pm 2.6
2013	Middle	56-57	21.9 \pm 1.4
2013	Middle	57-58	20.2 \pm 1.7
2013	Middle	58-59	18.8 \pm 1.1
2013	Middle	59-60	21.3 \pm 1.6
2014	North	51-52	18.4 \pm 2.2
2014	North	53-54	18.1 \pm 1.6
2014	North	55-56	17.3 \pm 2
2014	North	56-57	20.4 \pm 1.2
2014	North	57-58	21.6 (1 larva caught)
2014	North	56-57b	19.6 \pm 1.6
2014	North	58-59b	22.5 \pm 2.9
2014	Middle	51-52	18.2 \pm 2.6
2014	Middle	52-53	15.5 (1 larva caught)
2014	Middle	53-54	18.7 \pm 1.4
2014	Middle	54-55	17.9 \pm 1.3
2014	Middle	57-58	19.5 \pm 5
2014	Middle	58-59	16.3 \pm 1.3
2014	Middle	59-60	21.3 \pm 0.5
2014	Middle	61-62	18.7 \pm 1.9

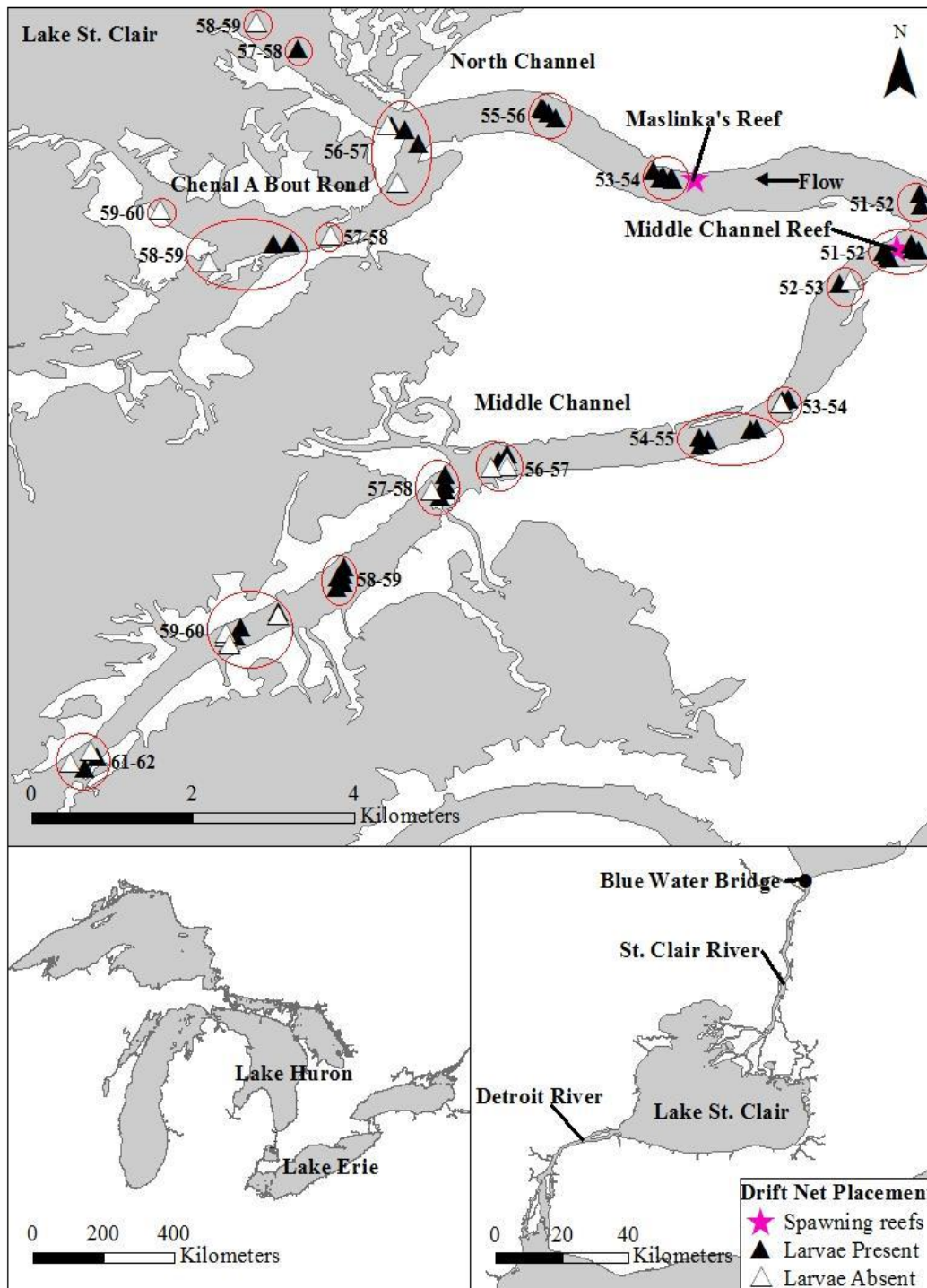


Figure 2.1. Lower St. Clair River, 2013-2014. Spawning reefs (star) and drift net locations (triangles) grouped by distance (river kilometer, red circles) downstream of the Blue Water Bridge, MI.

CHAPTER 3

Development and evaluation of a habitat suitability model for young Lake Sturgeon (*Acipenser fulvescens*) in the North Channel of the St. Clair River, MI.

Introduction

Lake Sturgeon (*Acipenser fulvescens*), like many species of fish, have complex life histories with varying stages being defined by discrete ontogenetic milestones (Brousseau and Goodrich 1989). For Lake Sturgeon, these milestones are typically defined as egg, larva (12 mm – 40 mm), young-of-year (YOY), juvenile (50 mm – 500 mm), sub-adult (> 500 mm but lacking gonads), and adult (Harkness and Dymond 1961, Peterson et al. 2007). During their early life stages, Lake Sturgeon populations may experience a natural bottleneck due to the lack of suitable foraging and nursery habitat, as well as high rates of predation (Peterson et al. 2007, Daugherty et al. 2009). However, unlike most other species, once Lake Sturgeon reach ~ 200 mm in length, they have developed protective, armored scutes along the sides of their body and have achieved sufficient size to render them virtually free from predation (Peterson et al. 2007). This shift makes conditions experienced during early-life stages of particular importance. Despite our growing understanding of sturgeon ecology, studies of riverine habitat characteristics on which these stocks depend during early life stages are limited, especially in large river systems such as the Great Lakes Connecting Channels (GLCCs, Benson 2004).

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Most restoration and rehabilitation projects in the GLCCs have focused on improving reproductive success of adult sturgeon through the construction of artificial spawning reefs or in stocking of advanced YOY (Lyons and Kempinger 1992, Auer 1999, Bruch 1999). However, our poor understanding of habitat connectivity for early stages of Lake Sturgeon hinders attempts to assess the effectiveness of these efforts, as well as to determine what other factors may be limiting recovery. Habitat suitability models (HSMs) have been developed to evaluate the quality and quantity of habitat for a number of species (O'Neil et al. 1988), to assess the impact of both past and future management activities (O'Neil et al. 1988, Roloff and Kernohan 1999), to assess changes in habitat quantity or quality (Bray 1996), and to link population changes to habitat supply (Chu et al. 2006). The strength of HSMs lies in their potential to explicitly identify limiting habitats that can then be used as concrete targets for conservation action and protection (Boisclair 2001). HSMs have been developed for Lake Sturgeon in several lakes and small to medium sized river systems (Threader et al. 1998, Daugherty et al. 2009). These studies have highlighted ideal habitat for young Lake Sturgeon as possessing lower stream gradients, finer substrate composition, and a broad range of water depths (0.5 – 8 m). While HSMs have proven useful for Lake Sturgeon management efforts in these systems, a model examining habitat qualities for large river systems (such as the Laurentian GLCCs), taking into account greater depths and faster current speeds is currently lacking. Historically, the GLCCs supported large numbers of Lake Sturgeon and still contain some of the largest remnant populations today (Thomas and Haas 2004, Peterson et al. 2007).

With the goal of improving efforts to manage and identify limiting factors to the recovery of this threatened species in the St. Clair River (SCR, one of 5 GLCCs), this study had two primary objectives. The first objective was to develop a HSM to estimate the quantity, quality, and spatial

distribution of riverine nursery habitat for larval and juvenile Lake Sturgeon in the North Channel of the SCR. The second objective was to use this HSM in combination with dispersal patterns of larval Lake Sturgeon to identify key relationships between local habitat characteristics and young Lake Sturgeon presence in an effort to inform improved sampling and future restoration activities in this and other large river systems. While considerable effort has been made over the course of this study to further our understanding of habitat connectivity for < 2-year-old Lake Sturgeon in this system, few fish from the larval settlement to age 2 have been collected, resulting in a significant gap in knowledge during a critical period of their life history. Given the limited sampling success for YOY and juvenile Lake Sturgeon in this system, I hypothesized that suitable nursery habitat was not available to newly emerged Lake Sturgeon larvae or if present, was not located in close enough proximity to existing spawning habitat to be readily utilized. Thus, larvae emerging from known spawning sources were believed to drift quickly out of the North Channel of the SCR and into surrounding wetlands or possibly into Lake St. Clair where favorable habitat conditions were believed to exist.

Methods

Study Site

I selected a portion of the SCR for assessment of Lake Sturgeon nursery habitat (Figure 3.1). The SCR, along with the St. Lawrence, St. Mary's, Detroit, and Niagara rivers, is one channel segment of the GLCCs and St. Lawrence River System. The SCR spans 64 km and drains water from Lake Huron into Lake St. Clair. It has an average discharge of 5,200 m³/s which remains relatively constant seasonally. Flow velocities in the SCR range from ~ 0.3 to 1.7 m/s (Schwab et al. 1989) with water depth averaging 13 to 15 m and scattered deep holes > 21 m. The shorelines have been extensively armored and developed for commercial, residential, and recreational use

and benthic habitat has been greatly altered to allow safe passage of commercial ships through the corridor (Bennion and Manny 2011).

In the lower section of the North Channel, Lake Sturgeon are believed to primarily spawn on one small reef formed by the dumping of coal clinkers during shipping in the early 1900s (Figure 3.1; Maslinka Reef, Boase et al. 2011). Larval fish from this reef drift downstream into the lower river and possibly into Anchor Bay, where they settle in unknown locations.

Field Data Collection

I conducted habitat assessments throughout the North Channel of the SCR, the surrounding delta areas, and downstream in Chenal A Bout Rond during the summer of 2015.

Characterization of river habitat was accomplished following both a random-grid (0.1 km²) based approach within the North Channel and by randomly choosing locations throughout the SCR delta (109 total sampling locations). At each sampling location, GPS coordinates, water depth, substrate composition, and benthic invertebrate composition data were collected. The geographic coordinates of each sample location were recorded using a wide-area augmentation system (estimated positional accuracy < 3 m), and water depth was measured to the nearest 0.1 m using boat-mounted sonar. Two to three ponar grabs (232 cm² jaw opening) were made at each location. Ponar samples were first placed in a metal tray and substrate composition was determined as being sand, silt, clay or a mix of two or more substrate types by visual and tactile inspection following the Wentworth Sediment Classification Scheme. Samples were then washed through an elutriator where invertebrates were separated from sediment and other river debris. Invertebrate samples were placed in 95% ethanol and transported to the lab where they were sorted into 1 of 6 major taxa: Chironomidae, Gammaridae, Ephemeroptera (*Hexagenia*), Hirudinea, Gastropoda, and Dreissenidae. These taxa were selected based on their known

influence on Lake Sturgeon presence (Kempinger 1996, Chiasson et al. 1997, Smith and King 2005, Nilo et al. 2006, Boase et al. 2011). Benthic water velocity was also measured to the nearest 0.1 m/s approximately 0.3 m above the river bottom using a Sontek Acoustic Doppler Profiler (ADP). To collect benthic velocities, the ADP probe was attached to our research vessel which was driven in a zig-zag pattern from bank to bank, throughout the entire sampling area. ADP datafiles containing velocity profiles were then exported into the software program Sontek CurrentSurveyor where readings taken from the last cell in a given vertical velocity profile were then extracted and converted into a GIS data layer in ArcGIS[®] 10.3.

Information on Lake Sturgeon larval distribution was collected during the seasonal larval drift period with the use of D-frame drift nets (as modified by Roseman et al. 2011), which sample the bottom 0.75 m of the water column. Larval drift surveys took place from June to July 2014 and 2015, after the first larval sturgeon were collected from the Maslinka Reef sampling location and concluded after three consecutive nights passed without encountering larval sturgeon. Beginning approximately eight days after eggs were collected on the reef by personnel from the US Geological Survey (minimum incubation time needed prior to hatch), two nets were deployed immediately downstream of the reef. Once larval sturgeon were collected, nets were deployed in a stratified configuration with three levels of placement consisting of two nets per level. Nets were placed with approximately 0.2 – 0.4 km between each level. Lake Sturgeon drift has been characterized as a ‘plug’ or pulse when the majority of larvae from a single spawning event drift downstream as a group (Auer and Baker 2002). Once a plug was recognized in nets placed immediately downstream of the reef, I began to move the net array further downstream on a nightly basis to track the plug’s progression until no larval sturgeon were collected. Nightly placement of nets in the third level was sufficiently downstream of second level nets so as to

detect any larvae that may drift past our array and possibly exit undetected from our sampling area. As such, collection of individuals in third level nets was infrequent.

Over the course of two consecutive field seasons, two separate collection ideologies were utilized. Larval sampling conducted during the 2014 survey was focused on locating areas of high larval densities, while sampling done in 2015 focused on following high density pulses of larvae as they dispersed down the North Channel. In an effort to identify and track dispersal patterns of drifting larvae, nets utilized throughout this study system were moved to a total of 26 locations (Figure 3.1), beginning approximately 50 m from Maslinka Reef, and continuing both down Chenal A Bout Rond and to the mouth of the North Channel (~ 3.0 km downstream from the reef). Collected larvae were euthanize in MS 222 solution and then preserved in a 95% ethanol solution for transportation back to our lab. Photographs of individual larvae were taken at 60x magnification using a microscope with digital analysis software (Image Pro Plus 7.0) and TL (mm) was recorded.

Habitat Modeling

A submersed channel extent map was prepared using base layers delineating lake and river features (i.e., boundaries and islands) that were digitized using available satellite image basemaps of the terrain area contained in the ArcGIS® 10.3 software package (Environmental Systems Research Institute [ESRI], Redlands, CA, U.S.A.). A river layer shapefile was created to establish study boundaries for each habitat model that was constructed.

All layers used were projected using the World Geodetic System 1984 datum and WGS 84 coordinate system. Spatially explicit models of each habitat variable were then constructed in ArcMAP® 10.3 for water depth, benthic current velocity, invertebrate density and substrate composition, and larval abundance.

ADP output parameters (depth (m), location, benthic current velocity (m / s)) were converted into excel files and imported as shapefiles. Raster models containing values for water depth and benthic current velocity for the entire study area were then interpolated using inverse distance weighting. The interpolation was parameterized using a variable search radius with six nearest neighbors, a power of 2 and a cell size of 5 m² (Daugherty et al. 2009). A power of 2 was used to produce a sharper image to better capture sudden changes in water depth present throughout the study system. The interpolated rasters were then clipped using the previously mentioned river layer as the input shapefile to restrict the interpolation output to include only areas located within our study field. A power of 0.5 was used to produce a smooth raster surface.

Point data containing values for invertebrate density and substrate from each sampled location were converted to vector points and projected within the working directory. Thiessen polygons were then created around each point to assign values across the entire study surface and the resulting layer was clipped using the river layer shapefile. These vector shapefiles were converted into raster files using the polygon to raster tool.

Prior to raster conversion, substrate data collected from field surveys were combined with a previously constructed shapefile containing substrate composition for the North Channel created by the US Geological Survey (USGS, Boase et al. 2014). The USGS shapefile contained a finer scale survey of select areas within the study site and matched well to independently surveyed locations in our study. To ensure that this detail was not lost when merging the two shapefiles, an erase tool was utilized, using the USGS shapefile as the erase input field to overlay onto our shapefile, resulting in a single substrate layer which was then converted into a raster layer.

A shapefile containing point values was created for all locations where drift nets were placed. At each net location, geographic position, net hours (total time a net was placed in a given

location throughout the study), and total number of Lake Sturgeon larvae collected was recorded and imported into ArcMAP® 10.3.

Lake Sturgeon Habitat Suitability Modeling

The models of each habitat variable were reclassified into habitat suitability index (HSI) values based on suitability criteria developed by Threader et al. (1998) for substrate and initially water depth and Benson et al. (2005) for benthic current velocity (Table 3.1) in medium and small rivers. Suitability values for invertebrate density have not been previously defined for young Lake Sturgeon. For this study, suitability values for invertebrate densities were determined based on review of literature focusing on known influence of invertebrate density and taxa to Lake Sturgeon presence (Chiasson et al. 1997, Nilo et al. 2006, Nellis et al. 2007), personal experience and observations of local associations, and accounting for the range of sampled values within our data (such as occurrence of natural breaks in density values). The geometric mean of the reclassified models for each habitat variable was then calculated using the raster calculator and the formula:

$$(CurrentLayer * DepthLayer * InvertLayer * SubstrateLayer) ^ 0.25$$

This provided a composite model of habitat suitability throughout the study system. Cells of the composite model with a value of 0 were defined as unsuitable habitat, whereas cell values ranging from 0.01 and 0.6 were defined as poor habitat, cell values ranging between 0.61 and 0.8 were defined as moderate habitat, and cells with a value between 0.81 and 1.0 were considered high-quality habitat for YOY and juvenile Lake Sturgeon (modified from Threader et al. 1998 and Daugherty et al. 2009).

A second model using HSI values for water depth based on collected habitat data from the SCR was also constructed and compared to the above HSM, in an effort to account for the larger

size and greater range of water depths experienced in this large river system. Areas within one standard deviation of the mean water depth taken from points where larval Lake Sturgeon were collected were assigned an HSI value of 1 (10.3 – 13.2 m). Areas with water depths of < 5.0 m were assigned a score of 0, depths of 5.1 – 10.2 m a score of 0.8, and depths of > 13.3 m a score of 0.5. HSI values for depth were determined based on comparison to Threader et al. (1998) and by taking into account depth profiles and channel morphology within the North Channel (e.g. system defined by shallow, vegetated nearshore waters giving rise to dramatic, steep drop-offs).

Data Analyses

The HSM was used to determine spatial distribution, habitat patch size, and quality characteristics for young Lake Sturgeon habitat within the North Channel. Raster models of habitat suitability were converted to polygon feature classes, and the total area (km²) of all habitat patches was calculated by multiplying the pixel count of each patch type by the area of a single cell (0.0034 km²).

Linear models were generated for both sets of HSI predictor values discussed above in response to larval CPUE throughout the study site. A One-Way Analysis of Variance (ANOVA) incorporating both iterations indicated a significant difference between models ($F = 35.6$, $P = 0.03$). The model utilizing water depth HSI values scaled to be more reflective of large river habitat characteristics in the SCR was found to account for a greater portion of variance in our larval CPUE data (r -squared = 0.842 and 0.756, respectively) and was utilized throughout the remainder of our analysis.

To assess ability of the model to accurately identify Lake Sturgeon habitat, I qualitatively compared locations of collected larvae and known YOY and juvenile capture locations taken

from previous research in the SCR to HSI values at each capture location (USFWS and MDNR unpublished data, Chapter 2).

I examined the relationship between catch rates and individual habitat parameters through a series of multiple linear regressions using larval Lake Sturgeon catch per unit effort (CPUE) as the response variable and varying combinations of habitat variables as predictors. Akaike information criterion (AIC) was used to measure the relative quality of each regression and to assess the degree to which each habitat variable combination was most useful in predicting larval Lake Sturgeon catch. Pearson's correlation coefficients were calculated to further evaluate relationships between habitat variables. All statistical analyses were performed using R-v 3.1.3 (R Development Core Team 2008). Pearson's Correlation Matrix was accomplished using the "Hmisc" package and model performance testing using AIC was accomplished using the "AICcmodavg" package.

Results

Habitat Sampling

The modeled study site in the North Channel area of the SCR system included a total area of 16.74 km², with 274 habitat samples collected (Table 3.2). Model output indicated high quality habitat accounted for 29.1 % of the study area (4.85 km²), while 53.5 % of the habitat was classified as moderate (8.96 km²). Greater than 85% of the high quality habitat was located near the apex of river bends (Figure 3.2), which were areas generally characterized as possessing moderate invertebrate densities, a mix of sand and silt substrate, along steep drop offs with water depths typically exceeding 11 m, and possessing highly varied water velocities. Areas designated as poor quality habitat made up 17.2% of the study area (2.88 km²), and 0.26 % was designated

as unsuitable for young Lake Sturgeon (0.04 km²). These areas were characterized as shallow, low velocity, wetland areas.

Over the summers of 2014 and 2015 a total of 283 larval Lake Sturgeon (11.4 – 24.5 mm TL, Figure 3.3) were collected from 19 different locations in the study area during ~ 1420 net hours of sampling. Of the 283 larvae collected, 230 were taken from areas designated as high quality habitat, 52 in areas of moderate quality habitat, 1 in an area of poor quality habitat, and 0 individuals were collected in areas deemed unsuitable for young Lake Sturgeon (Table 3.3). The majority of larvae (202, 71%) were collected in areas with a composite HSI score between 0.80 and 0.90. Model output classified 21.9% of available habitat within the study area with a HSI score between 0.80 and 0.90 (3.68 km²), and 82.8% with a score > 0.60 (13.82 km², Table 3.4). CPUE (larvae caught per hour of net soak time) was significantly greater for nets located in high quality habitat areas (0.285) then for nets located in moderate quality habitat areas (0.144; One-Tailed T-Test, P = 0.0251, T = 2.112).

Three distinct areas with high larval densities were located along the North Channel spanning from just downstream of Maslinka Reef to where the main flow of the North Channel splits off at the head waters of Chenal A Bout Rond (Figure 3.1). The majority of larval Lake Sturgeon were collected in these areas (91.2%, Table 3.4). Site 2 was completely within an area of high quality habitat, while site 1 and 3 were composed of both high and moderate quality habitat (Figure 3.2). Larval yield decreased dramatically just downstream of the Chenal A Bout Rond split and no larvae were found exiting the North Channel into Anchor Bay.

AIC was used to compare 13 different multiple linear regressions which examined the relationship between CPUE and habitat variables used to produce the HSM (Table 3.5). Only the top model was considered for selection as no other model was within 2 Δ AIC, suggesting a low

probability of the other tested models having the best fit (Burnham and Anderson 2002). The highest ranked model predicted CPUE using continuous velocity, categorical substrate and the interaction between velocity and substrate ($df = 36$, $F = 4.459$, $P = 0.0012$). Both velocity and sand – silt substrate were shown to exert a significant, positive effect with CPUE ($\alpha = 2.26$ and 2.88 , $P = 0.004$ and 0.002 , respectively). The interaction between velocity and clay substrate was also significant and showed a strong, negative effect on CPUE ($\alpha = -2.78$, $P = 0.001$). Sand substrate and invertebrate density had a significant, positive correlation on CPUE ($df = 42$, $F = 1.587$, $P = 0.018$), as did sand substrate and water depth ($df = 42$, $F = 6.03$, $P = 0.018$), and velocity and water depth ($df = 42$, $F = 5.683$, $P = 0.022$).

To corroborate our HSM as an accurate predictor of suitable nursery habitat in the SCR, I compared available information on sampling locations for YOY and juvenile Lake Sturgeon (Lord 2007, Boase et al. 2014) to the habitat quality of these locations as identified by our model. From 2013 – 2015, 11 Lake Sturgeon measuring < 500 mm were collected within our study area of the North Channel of the SCR by personnel from the Michigan Department of Natural Resources (MDNR), U.S. Fish and Wildlife Service (USFWS), and the University of Michigan (U of M, Table 3.6). All of these collected fish were found in areas identified as high quality habitat by our HSM, indicating this models reliability in predicting suitable nursery areas for post-drift larval Lake Sturgeon in the North Channel of the SCR.

Discussion

The HSM developed in this study, along with patterns generated from Lake Sturgeon larval drift surveys, suggest that larval Lake Sturgeon remain within the North Channel of the SCR, completing a short drift distance (< 1.5 km) after emerging from their spawning reef. This refutes my original hypothesis that larvae would drift out into Lake St. Clair or the surrounding wetlands

of the St. Clair Delta in search of suitable habitat. Furthermore, model outputs highlight an abundance of suitable and readily accessible habitat for newly emerged larval sturgeon located just downstream of the Maslinka reef, suggesting these areas may provide suitable habitat for YOY and juvenile Lake Sturgeon as well and indicating lack of nursery habitat is not a factor limiting Lake Sturgeon recovery in the lower North Channel of the SCR.

These findings are supported by several previous observations of Lake Sturgeon behavior. Larval surveys which are annually conducted by state, federal, and university personnel throughout the SCR system regularly demonstrate that larval densities decrease significantly the further the pulse of larvae moves downstream and few individuals are caught close to or in the lake itself (USGS, unpublished data, Chapter 2). While this may be a result of high larval mortality during the drift (Caroffino et al. 2010), I believe it suggests that larvae settle in areas of high quality habitat as the pulse moves downstream (Barth et al. 2009, Barth et al. 2011).

In Chapter 2, I examined larval drift behavior in both the North and Middle channels of the SCR and noted that larvae of variable growth stages (sac-fry to fully absorbed yolk sacs) appeared to remain in the river in spite of strong currents. From that study, I suggested that larvae did not just passively disperse downstream but rather exhibited a “guided” drift behavior whereby individuals possess some ability to orient and direct themselves toward areas of preferred habitat. These conclusions were supported by collection of larvae of various lengths and yolk sac stages in single nets and by patterns of high CPUE in distinct zones throughout the SCR. Further, Chapter 2 findings suggested that larvae were able to hold station in these areas by burrowing into river sediments, seeking refuge from swift currents behind benthic debris (boulders, depressions, or sunken logs), or maintaining close proximity to the benthic boundary layer. Larval Lake Sturgeon surveyed in other river systems have shown similar patterns of

larval dispersal. Using drift nets similar to those utilized in our study, Auer and Baker (2002) noted that while some larvae appeared to drift quickly down the Sturgeon River into Portage Lake, a significant number were found to stay in the river for > 40 days.

Larval Lake Sturgeon collected in the present study were also found to occur in high concentrations at 3 distinct locations throughout the North Channel. Previous studies have noted similar cohesive behavior in Lake Sturgeon. Boase et al. (2014) showed high degrees of site fidelity in the North Channel of SCR for young Lake Sturgeon measuring 580 - 800 mm. In that study, fish were implanted with ultrasonic transmitters and tracked over the course of three separate summers. Tagged individuals demonstrated a high degree of home range overlap in areas at water depths > 9 m. Sampling and monitoring efforts for larval and YOY Lake Sturgeon in the Black, Sturgeon, and Peshtigo rivers have noted high concentrations of larvae collected in areas just downstream of their natal hatching points where YOY could also be collected regularly (Auer and Baker 2002, Smith and King 2005, Benson et al. 2006). Smith and King (2005) examined distribution patterns of YOY and juvenile Lake Sturgeon in the Black River – Black Lake system and suggest that Lake Sturgeon used “core activity centers” where individuals congregated in high densities. Using mark re-capture techniques, Barth et al. (2011) found that 90.8% of YOY and juvenile fish caught in the Winnipeg River (n = 714) were re-captured within 2 km of their initial capture location, despite having access to > 45 km of river. These authors concluded that year-round habitat requirements may be met in relatively short sections of a river and that these short migrations may be attributed to larvae encountering good juvenile habitat during their drifting phase and remaining in these locations. This is further evidenced by YOY, juvenile, and sub-adult Lake Sturgeon in the SCR all located in proximity to one-another in a single stretch of the North Channel (Lord 2007, Boase et al. 2014).

These observations support two main conclusions. My first conclusion is that the North Channel of the SCR contains an abundance of suitable nursery habitat just downstream of Maslinka Reef which is being utilized by newly emerged larval, YOY, and juvenile Lake Sturgeon. This is supported by collection of few (< 10) larvae further than 1.5 km downstream from this reef and high concentrations of individuals caught in close proximity to one another in areas identified as suitable habitat by our HSM (Figure 3.2). My second conclusion is that larval Lake Sturgeon possess some ability to orient and direct themselves during their drifting phase, indicated by high concentrations of collected individuals in 3 distinct areas of the North Channel identified by our HSM as possessing high quality habitat.

HSM Output and Limitations

The HSM developed in this study revealed an abundance of suitable nursery habitat throughout the North Channel of the SCR. Velocity and substrate composition were habitat parameters highlighted by our AIC analysis as best predicting observed patterns of larval CPUE in the SCR. Several studies on early-stage Lake Sturgeon conducted in smaller rivers have identified substrate composition (Threader et al. 1998) and benthic current velocity (Threader et al. 1998, Auer and Baker 2002, Benson 2004) as key variables determining larval dispersal patterns and subsequent YOY nursery areas. Benthic current velocity is known to affect drifting sturgeon larvae and it is little surprise that this variable would have significant influence on larval dispersal (Harkness and Dymond 1961).

Composition of substrate is known to influence the ability of larval Lake Sturgeon to burrow into sediment to escape high current velocities and potential predators during the day (Kempinger 1988, Auer and Baker 2002, Smith and King 2005). Additionally, substrate composition may also be related to local invertebrate community composition and thus, prey

availability for young Lake Sturgeon (Chiasson et al. 1997, Hayes and Werner 2004). While I did not find invertebrate densities to have a statistically significant correlation to larval CPUE, there was a significant positive correlation between invertebrate density and substrate composition. Since invertebrate density is associated with substrate composition, either factor may indicate similar habitat quality. This is supported by a similar study on YOY and juvenile Lake Sturgeon in the SCR which attempted to evaluate ability of prey composition to predict YOY and juvenile Lake Sturgeon presence (Boase et al. 2011). While these authors did not find a significant association, they concluded young sturgeon likely select areas of high prey abundance.

While HSMs are useful in identifying areas possessing desired habitat characteristics, some have questioned their ability to accurately assess fish habitat quality (Haxton et al. 2008), as few have been independently validated in the field. In the present study, I found larval abundance significantly correlated with high quality habitat as predicted by our model, with > 80% of all captured individuals found in areas possessing a composite HSI score > 0.80 even though these locations were only 29% of the available habitat. However, since two of the four input variables to my HSM were not found to have a significant influence on larval catch, a system specific re-evaluation of HSI values may be warranted for this and other large river systems (Figure 3.4). Although HSI values used for water depth in the present study were based on data collected directly from the SCR, other values were derived from studies of Lake Sturgeon behavior in smaller river systems (Threader et al. 1998, Benson et al. 2005). While similarities exist among these systems, further work is needed to evaluate the transferability of HSI values from one system to another (Haxton et al. 2008, Pollock et al. 2015). This study provides an essential first step in the attempt to link HSI relationships across different systems by demonstrating strong

associations between observed larval patterns and available data on YOY and juvenile Lake Sturgeon presence and habitat characteristics modeled in our HSM constructed with HSI values from other river systems.

Management Implications

Availability of and accessibility to suitable habitat is believed to be the greatest impediment to recovery of Lake Sturgeon stocks throughout the Great Lakes Basin (Hayes and Caroffino 2012). As Lake Sturgeon are prone to high rates of mortality through early developmental stages, whereupon survivorship increases dramatically (Harkness and Dymond 1961, Kempinger 1996), efforts to identify the quantity and quality of available spawning and nursery habitat in Lake Sturgeon systems must be a top priority for resource managers.

Larval distribution patterns observed in the SCR in relationship to the HSM developed here suggest this and similarly constructed models may be useful in identifying locations for future restoration efforts. In the SCR and Detroit River, construction of artificial spawning reefs has continued since 2004 (Read and Manny 2006, Bouckaert et al. 2014), with documented evidence of successful spawning on these reefs in both rivers and at multiple locations (Read and Manny 2006, Roseman et al. 2011, Bouckaert et al. 2014). In the SCR, spawning events have been witnessed at three recently constructed reefs located throughout the river (the Middle Channel in 2012, and Point Au Chene and Hart's Light in 2015), where Lake Sturgeon eggs were collected within one year of reef construction. However, while evidence supports successful spawning and survival from eggs to larvae, documented accounts of YOY and young juveniles in these areas are still rare. This suggests two possibilities. First, constructed spawning reefs may not be located in areas readily accessible to suitable nursery habitat, thus forcing larvae to move out of the system in search of suitable conditions and be exposed to high mortality rates. Second, the

lack of recent YOY and juvenile survey success is the result of ineffective gear selection or high larval mortality.

HSM outputs from our model predict that ~ 80% of available habitat located downstream from the Maslinka reef is high or moderate quality for young Lake Sturgeon, therefore I believe the lack of suitable nursery habitat is not a factor limiting recruitment success in the North Channel. From 2013-2015, only 11 individuals < 500 mm in length have been captured even after > 9000 hours of sampling effort (Table 3.4). However, age – 3 and older individuals are regularly taken during annual surveys conducted by MDNR, demonstrating survival of some larvae and YOY to the juvenile stage (MDNR, unpublished data; Thomas and Haas 2004). Experimentation in available sampling methods may allow for more effective sampling of this life stage in the future, providing a better indication of recruitment success. Extended, single linked tickler chains on deep water trawls, baiting setlines with smaller hooks (< size 5), utilization of electric trawls, and development of modified minnow and crab traps for benthic organisms are all candidate methods. The abundance of suitable nursery habitat highlighted by our HSM as present in the SCR, and the annual collections of juvenile Lake Sturgeon by cooperating agencies leads me to believe recruitment success in this population should be improved by increases in available spawning habitat upstream of locations with high quality nursery habitat.

As different river systems have experienced many types of anthropogenic modification, factors impeding recovery of Lake Sturgeon stocks will likely also vary among populations. Modeling techniques aimed at quantifying the linkage between suitable habitat conditions for multiple life stages of Lake Sturgeon within individual river systems is the next logical application of this and other sturgeon HSMs. For example, site locations for spawning reefs are

usually generated by habitat modeling using benthic current velocity and water depth as determinants of suitable sites (Bennion and Manny 2014, Fischer et al. 2015). Recent evidence of sediment infiltration into these reefs has resulted in attempts to include other hydrological variables as such sediment load and seasonal shifts in flow profiles in the factors used to identify proper sites for reef construction (Manny et al. 2015). Linking future reef placement in proximity to high quality habitat for young fish should improve success and aid in future habitat restoration efforts.

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Table 3.1. Input values for the identification of high, moderate, poor and unsuitable quality habitat for larval and YOY Lake Sturgeon. Depth values for both evaluated models are shown.

Habitat Variable	Suitability Index	Source
Substrate Composition		Threader et al. (1998)
Clay	0.2	
Silt	1	
Sand	1	
Gravel	1	
Cobble	0.8	
Boulder	0.5	
Benthic Current Velocity (m / s)		Benson et al. (2005)
> 1.0	0	
0.6 - 1.0	1	
0.3 - 0.59	0.9	
0	0.5	
Water Depth (m)		Present Study
< 5.0	0	
5.1 - 10.2	0.8	
10.3 - 13.3	1	
>13.3	0.5	
< 0.5	0	Threader et al. (1998)
0.5-1.9	0.9	
2.0-4.0	0.8	Not Included in HSI
4.0-7.9	1	
8.0-14.0	0.5	
Invertebrate Density (# / m ²)		
> 3000	1	Chiasson et al. 1997;
701 - 2999	0.7	Nilo et al. 2006;
< 700	0.4	Nellis et al. 2007

Table 3.2. Summary of environmental variables (median (range) collected in the SCR by quality of patch type. Substrate composition was excluded from this table as it is a categorical variable.

Patch Type	Benthic Current Velocity (m/s)	Invertebrate Density (#/m ²)	Depth (m)
High Quality	0.71 (0.55-0.98)	3107 (2654-3321)	11.6 (9.4-15.8)
Marginal Quality	0.43 (0.34-0.83)	2611 (1920-3002)	7.8 (6.7-17.1)
Poor Quality	0.21 (0.12-0.56)	2103 (100-2231)	3.4 (1.4-9.8)
Unsuitable	0	0	0

Table 3.3. Summary statistics of larval Lake Sturgeon catch from drift nets in each habitat type in the SCR.

Patch Type	Area (km ²)	Larvae Collected	Net Hours	CPUE
High Quality	4.85	230	808	0.285
Moderate Quality	8.96	52	361	0.144
Poor Quality	2.88	1	135	0.007
Unsuitable	0.04	0	116	0

Table 3.4. Summary catch statistics of larval Lake Sturgeon in three high density areas. Area of each high density area is given along with (% area relative to total study area). Cluster ID corresponds to point locations on Figure 3.1.

Cluster ID	Habitat Quality	Area (km ²)	Larvae Collected	Net Hours	CPUE	Percent of Total Yield
1	High and Moderate	0.034 (0.2 %)	45	62.55	0.719	16%
2	High	0.031 (0.18 %)	136	247.03	0.551	48%
3	High and Moderate	0.051 (0.3 %)	77	314.17	0.211	27%

Table 3.5. Highest ranked regression models using AIC. Relationships between CPUE and HSM habitat variables were modeled using simple and multiple linear regression. The possible predictor variables are substrate composition, benthic current velocity, invertebrate density, and depth. Interaction terms for models are shown in parentheses.

Model Comparison Summary						
Rank	K*	AICc	Δ AICc	w_i	Cum. w_i	Model Variables
1	9	28.95	0	0.86	0.86	CPUE * Substrate + Velocity + (Velocity : Substrate)
2	9	34.07	5.12	0.07	0.93	CPUE * Substrate + Depth + (Substrate : Depth)
3	11	34.52	5.56	0.17	0.98	CPUE * Substrate + Invert + Velocity + Depth (Velocity : Substrate)
4	2	37.42	8.47	0.13	0.99	NULL
5	3	39.61	10.66	0.10	1.00	CPUE * Velocity
6	6	41.71	12.76	0.00	1.00	CPUE * Substrate
7	7	43.33	14.38	0.00	1.00	CPUE * Substrate + Invert
8	7	44.34	15.39	0.00	1.00	CPUE * Substrate + Velocity
9	7	44.48	15.53	0.00	1.00	CPUE * Substrate + Depth
10	8	46.22	17.27	0.00	1.00	CPUE * Substrate + Invert + Depth
11	8	47.19	18.24	0.00	1.00	CPUE * Substrate + Depth + Velocity
12	9	48.52	19.57	0.00	1.00	CPUE * Substrate + Invert + Depth + (Invert : Substrate)
13	9	49.27	20.32	0.00	1.00	CPUE * Substrate + Invert + Velocity + Depth

* Number of model parameters (K).

Table 3.6. Sampling method, gear type, catch, and fish length for YOY and juvenile Lake Sturgeon collected in the North Channel of the SCR from 2013-2015. Table includes only fish collected within the boundaries of this study.

Agency	Gear Type	Effort (hours fished)	Number Collected	Length (mm)
MDNR	Setlines	6840	2	352, 420
U of M	Setlines	724	7	182, 221, 230, 330, 347, 421, 488
	Hoopnets/Minnow Traps	1400	0	X
	Bottom Trawls	12	0	X
USFWS	Gillnets	X	2	190, 335

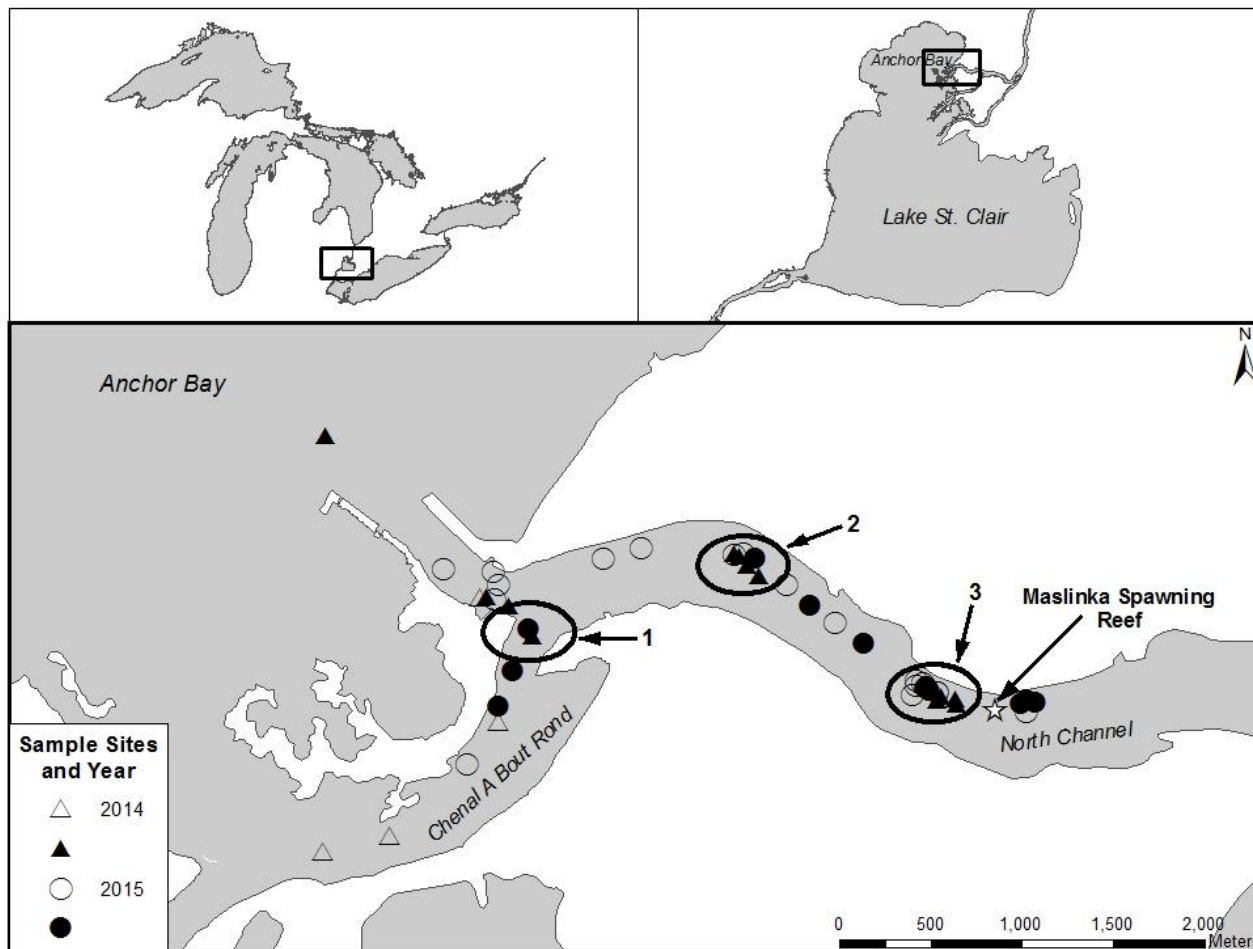


Figure 3.1. Map of study site with larval drift net sampling locations shown. Hollow symbols represent net sites where no larval Lake Sturgeon were collected while filled symbols represent sites where larvae were collected. Numbered and circled areas represent locations of high larval Lake Sturgeon densities.

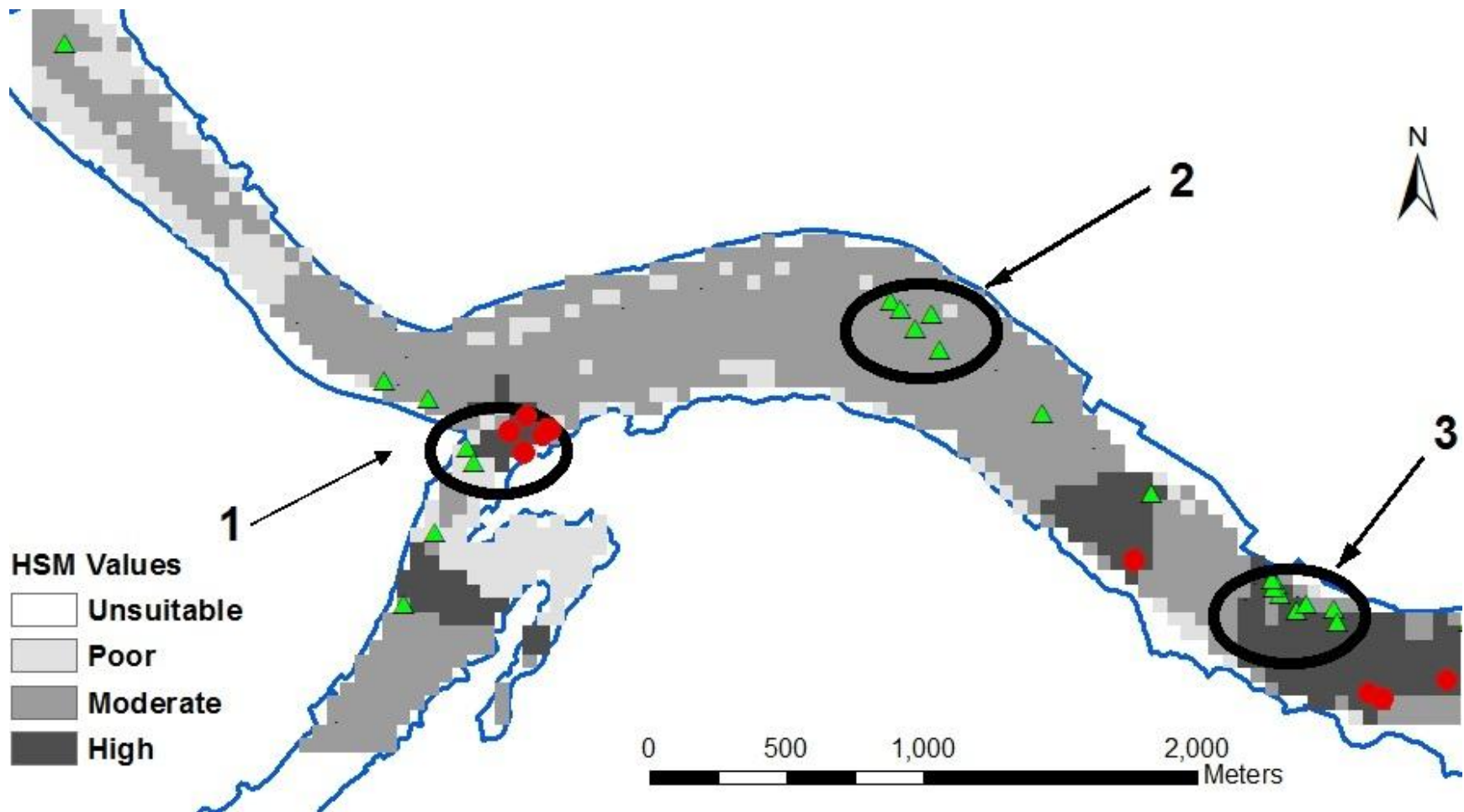


Figure 3.2. Map of Habitat Suitability Model output for larval, YOY, and juvenile Lake Sturgeon in the lower North Channel portion of the St. Clair River. Red circles indicate capture locations of YOY and juvenile Lake Sturgeon and green triangles indicate capture locations of larval Lake Sturgeon. Locations of three areas of high density larval yields are also indicated.

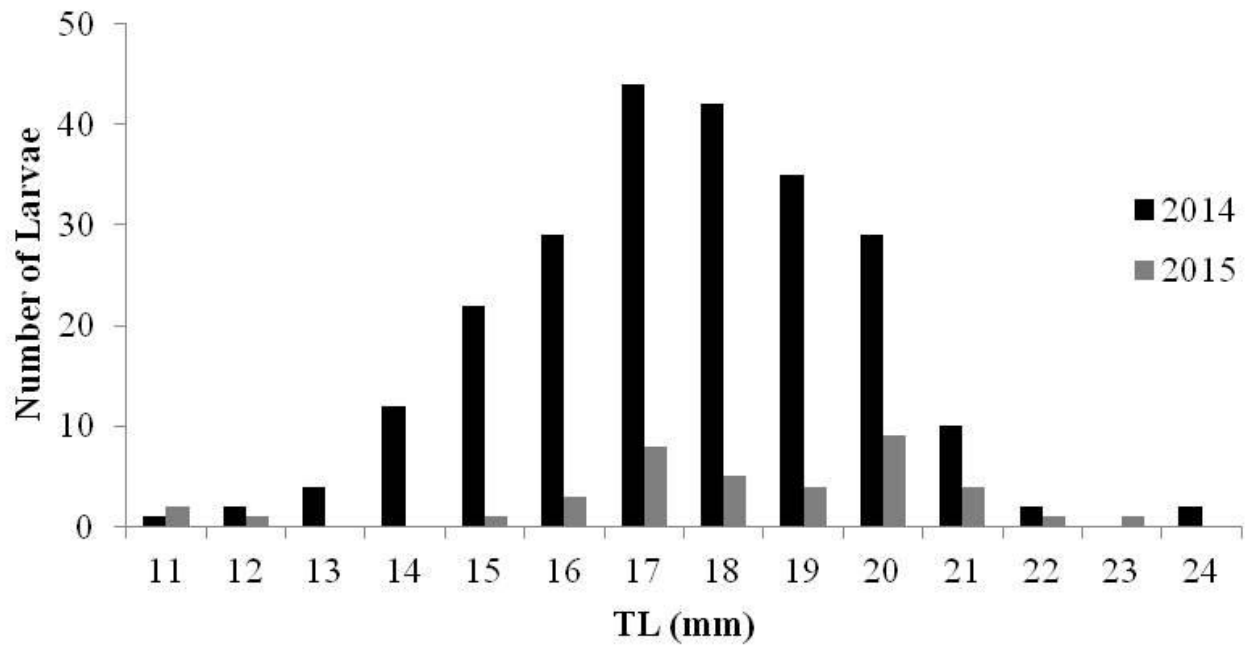


Figure 3.3. Length frequency histogram for larval Lake Sturgeon collected during 2014 and 2015 surveys.

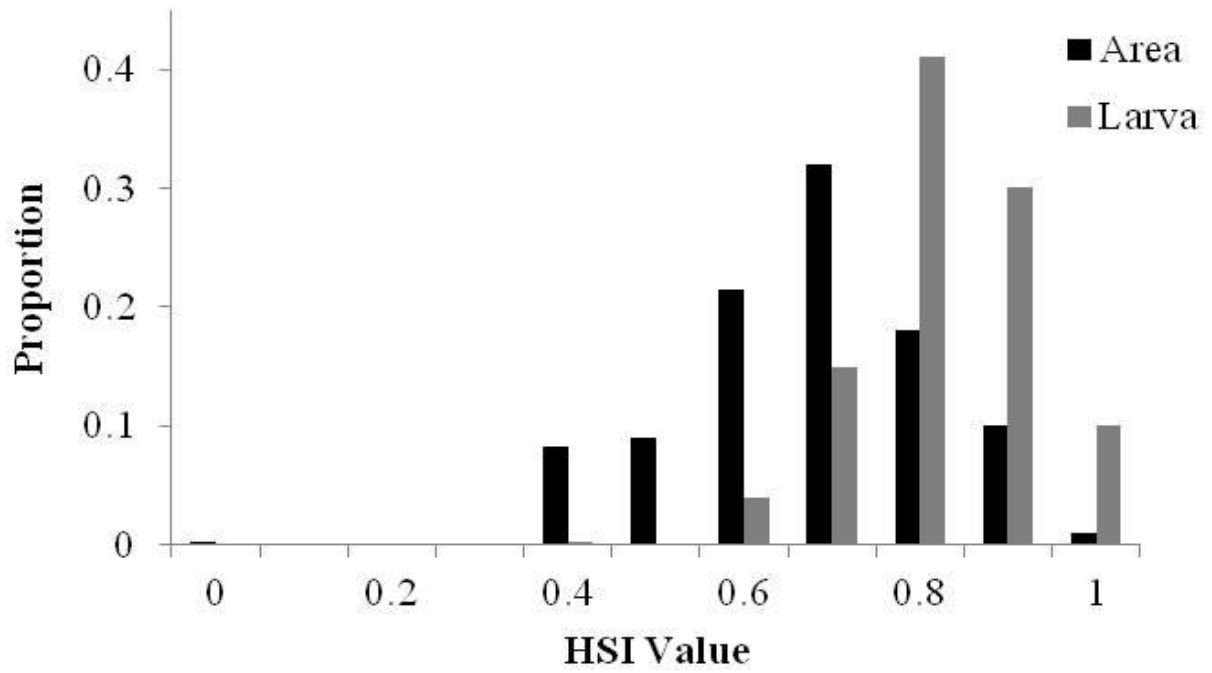


Figure 3.4. Proportional distribution of Lake Sturgeon larvae collected and surface area for each category of HSI value in the study site.

CHAPTER 4

Evaluation of a habitat suitability model for larval, YOY, and juvenile Lake Sturgeon (*Acipenser fulvescens*) in three Great Lakes Connecting Channels.

Introduction

Lake Sturgeon (*Acipenser fulvescens*) is a long-lived, large-bodied, and highly fecund migratory fish species that was once widely distributed throughout North America (MacKay 1963, Scott and Crossman 1973). It is the only sturgeon species endemic to the Laurentian Great Lakes (Auer 1996, Peterson et al. 2007) and currently is listed as threatened or endangered in all states and provinces surrounding these waters except Wisconsin (Chiotti et al. 2008). Excessive harvest and habitat degradation have reduced Lake Sturgeon populations to less than 1% of their former abundance (Brousseau and Goodrich 1989), and the loss of important spawning and rearing habitat has hindered their successful recovery. Previous Lake Sturgeon rehabilitation efforts have focused on restoring spawning habitat or stocking of advanced fingerlings (Lyons and Kempinger 1992, Bruch 1999, Roseman et al. 2011a). However, researchers have recognized critical knowledge gaps relating to early life stages such as habitat preference, mechanisms influencing larval dispersal, and impediments to successful early recruitment (Auer 1999, Secor et al. 2002, Peterson et al. 2007).

Lake Sturgeon, like many species of fish, have complex life histories with varying stages defined by discrete ontogenetic milestones (Brousseau and Goodrich 1989). During their early life stages, Lake Sturgeon populations may experience a natural bottleneck due to lack of suitable foraging and nursery habitat, as well as high rates of predation (Peterson et al. 2007,

Daugherty et al. 2009). However, unlike most other fish, once Lake Sturgeon reach ~ 200 mm in length, they develop protective, armored scutes along the sides of their body dramatically reducing their mortality due to predation (Peterson et al. 2007). This shift in predation pressure makes conditions experienced during their early-life stages of particular importance. Despite our growing understanding of sturgeon ecology, there are few studies of riverine habitat characteristics on which these stocks depend during early life stages in large river systems such as the Great Lakes Connecting Channels (GLCCs, Benson 2004).

The GLCCs (upper St. Lawrence, St. Mary's, St. Clair, Niagara, and Detroit rivers) contained some of the largest and most extensively harvested populations of Lake Sturgeon in the Great Lakes Basin (Thomas and Haas 2004, Hayes and Caroffino 2012). However, anthropogenic activities such as channel dredging (Bennion and Manning 2011), coastal development, wetland degradation and destruction, overfishing, and pollution have greatly reduced Lake Sturgeon abundance in all these systems, resulting in a moratorium on commercial fishing for Lake Sturgeon in these rivers with the exception of a small fishery operating in the St. Lawrence River (Peterson et al. 2007).

Availability of and accessibility to suitable habitat is believed to be the greatest impediment to recovery of Lake Sturgeon stocks throughout the Great Lakes Basin (Hayes and Caroffino 2012). As Lake Sturgeon are prone to high rates of mortality through early development, efforts to identify quantity and quality of spawning and nursery habitat has become a top priority for resource managers (GLFWRA 2006, Hayes and Caroffino 2012) in the St. Clair and Detroit rivers. Artificial spawning reefs have been constructed and Lake Sturgeon have successfully spawned and reared larvae on these reefs (Read and Manny 2006, Roseman et al. 2011a,

Bouckaert et al. 2014). However, there are no documented accounts of increased abundance of young-of-year (YOY, 50 – 200 mm) and young juveniles (200 – 500 mm) in these areas.

In Chapter 3, I developed a habitat suitability model (HSM) using habitat characteristics collected from the North Channel (NC) of the St. Clair River (SCR). The goal of that HSM was to identify and characterize quality of habitat available to larval, YOY, and juvenile Lake Sturgeon in proximity to a known spawning site. I found significant associations between larval drift patterns, locations of YOY collected from multiple surveys, and areas of high quality habitat predicted by the HSM. That study was the first to develop a life-stage specific habitat model for Lake Sturgeon in the GLCCs and will aid in evaluations of future spawning reef placement in other large river systems by providing resource managers with insight into areas of likely YOY and juvenile residence. However, while HSMs have been extensively used to evaluate habitat for species management, the ability to transfer species – habitat associations from one system to another is uncertain (Morris and Ball 2006, Vinagre et al. 2006, Haxton et al. 2008).

The purpose of this study was to examine young Lake Sturgeon dispersal in two other river systems in the GLCCs to compare with dispersal documented previously in the NC (Chapter 3). The objectives of this study were to: (1) parameterize the HSM developed for the NC in Chapter 3, with local habitat characteristics from two additional river systems in the GLCCs; (2) use these HSMs in combination with dispersal patterns of larval Lake Sturgeon to identify relationships between local habitat characteristics and presence of young Lake Sturgeon, and (3) to compare modeled Lake Sturgeon – habitat relationships across three large river systems. Given the range in environmental conditions evident in these systems, I hypothesized young Lake Sturgeon dispersal and occurrence patterns would vary in response to local habitat

characteristics. Larva collected from river reaches that lacked abundant suitable nursery habitat were expected to drift quickly from their spawning point of origin to areas outside the extent of the study areas. I expected individuals collected in reaches possessing more suitable habitat to be found congregated in high quality habitat near their natal spawning reef.

Methods

Study Sites

I selected portions of the NC and Middle Channel (MC) of the SCR and Fighting Island Channel (FIC) of the Detroit River (DR) for assessment (Figure 4.1). The SCR is 64 km in length and drains water from Lake Huron into Lake St. Clair. It has an average discharge of 5,200 m³/s, which remains relatively constant seasonally. Flow velocities in the SCR range from ~ 0.3 to 1.7 m / s (Schwab et al. 1989) with mid-channel depth ranging from 13 – 15 m and scattered deep holes > 21 m. In the NC, Lake Sturgeon largely spawn on one small reef (1350 m²) formed by dumping of coal cinders during shipping in the early 1900s (Maslinka Reef, Figure 4.1, Thomas and Haas 2004, Boase et al. 2011). In the MC, Lake Sturgeon eggs have been regularly collected from an artificial spawning reef (4040 m²) constructed in 2012 (Middle Channel Reef, Figure 4.1, Bouckaert et al. 2014). Larval fish from these reefs are believed to drift downstream into the lower river and possibly into Anchor Bay.

The DR is 51 km long and drains water from Lake St. Clair into Lake Erie. Within the DR, the FIC is located on the east side of Fighting Island in Canadian waters (Figure 4.1). The FIC is 5.5 km long, has an average discharge of approximately 5,200 m³ / s and flow velocities ranging from ~ 0.2 to 0.9 m / s (Schwab et al. 1989) with mid-channel depth ranging from 7 – 11 m. In the FIC, Lake Sturgeon eggs have been regularly collected from an artificial spawning reef (3300

m²) that was constructed in 2008 (Fighting Island Reef, Figure 4.1, Roseman et al. 2011a, Bouckaert et al. 2014).

Field Data Collection

I conducted habitat assessments throughout the SCR and DR study areas during summer and fall 2015 and 2016 using methodologies described in Chapter 3. Characterization of river habitat was accomplished following both a random-grid (0.1 km²) based approach and by randomly choosing locations throughout each study area (1353 total sampling locations). At each sampling location, longitude and latitude, water depth, substrate composition, and benthic invertebrate composition data were collected. Longitude and latitude was recorded using a wide-area augmentation system (estimated positional accuracy < 3 m), and water depth was measured to the nearest 0.1 m using boat-mounted sonar. Two to three ponar samples (232 cm² jaw opening) were taken at each location. Ponar samples were first placed in a metal tray and substrate composition was determined by visual and tactile inspection following the Wentworth Sediment Classification Scheme. Samples possessing 50% or greater of a single substrate type (sand, silt, clay, cobble) were classified in that single category. Samples possessing two substrate types each contributing 35% or more were categorized as a mixed substrate (e.g., sand-silt, sand-clay). Samples were then washed through an elutriator where invertebrates were separated from sediment and other river debris. Invertebrate samples were placed in 95% ethanol and transported to the lab where they were sorted into one of six major taxa: Chironomidae, Gammaridae, Ephemeroptera (*Hexagenia*), Hirudinea, Gastropoda, and Dreissenidae. These taxa were selected based on their known influence on Lake Sturgeon presence (Kempinger 1996, Nilo et al. 2006, Boase et al. 2011). Benthic water velocity was measured to the nearest 0.1 m/s using a Sontek Acoustic Doppler Profiler (ADP, Model: M.78 #870-58-235). To collect benthic

velocities, the ADP probe was attached to my research vessel, which was driven in a zig-zag pattern from bank to bank, throughout the entire sampling area. At each sampling location, a vertical velocity profile was measured while maintaining station in the river. Each profile consisted of 25 to 50 cells covering 0.3 m each. In some cases, return signal interference was generated in the bottom-most cell as ADP emitted wavelengths were absorbed, scattered, or reflected by benthic substrate. As such, benthic water velocities were approximated based on the average reading from the two bottom-most cells and represent currents at depths ranging from 0.1 to 0.5 m off the bottom. ADP data files containing velocity profiles were then exported into the software program Sontek Current Surveyor. Averaged readings taken from the last two cells in a given vertical velocity profile were extracted and converted into a GIS data layer in ArcGIS® 10.3.

Information on larval distribution of Lake Sturgeon was collected during the larval drift period using D-frame drift nets (area of opening = 0.3487 m², 1600 µm mesh), which sample the bottom 0.75 m of the water column (Roseman et al. 2011b). Larval drift surveys took place from June to July in 2013-2014 (MC), 2014-2015 (NC), and 2016 (FIC). Beginning approximately eight days after eggs were collected on a reef by personnel from the US Geological Survey (minimum incubation time needed prior to hatch), two nets were deployed immediately downstream of that reef. Once larval sturgeon were collected, nets were deployed in a stratified configuration with three levels of placement consisting of two nets per level. Nets were placed with approximately 0.2 – 0.4 km between each level. Once larvae were collected in nets placed immediately downstream of a reef, I began to move the net array further downstream on a nightly basis to track the progression of drifting larvae. Nets placed at the third level were sufficiently downstream of second level nets to detect larvae drifting past my array and possibly

exiting from my sampling area. As such, collection of individuals in third level nets was infrequent. In an effort to identify and track dispersal patterns of drifting larvae, nets utilized throughout each study system were moved to a total of 25 – 40 locations (Figure 4.1), beginning approximately 50 m from each reef and continuing downstream 3 – 7.5 km to where the channels emptied into Anchor Bay (from NC or MC) or the main channel of the Detroit River (from FIC).

Photographs of individual larvae were taken at 60x magnification using a microscope with digital analysis software (Image Pro Plus 7.0). Total length (TL, mm) and yolk sac absorption stage (full, partial, or no-yolk sac) from each larva were measured from magnified images. Lake Sturgeon larvae with full yolk sacs were identified by a pronounced yolk sac extending to the pectoral fin and the lack of distinct pigmentation along the lateral portion of the head and trunk. Larvae with partially absorbed yolk sacs possessed less pronounced yolk sacs, which often appeared wrinkled or deflated, and had dark pigmentation along the head and trunk. Individuals with no-yolk sac lacked a yolk sac, had fully formed mouths, and possessed a prominent lateral band, which extended the entire length of the body (Wang et al. 1985, Kempinger 1988, Peterson et al. 2007).

Habitat Modeling

The habitat GIS model followed methodologies detailed in Chapter 3 and is summarized here. For each river system, an extent map of the submersed channel was prepared using base layers delineating lake and river features (i.e., boundaries and islands). These were then digitized using available satellite image basemaps of the study sites contained in the ArcGIS® 10.3 software package (Environmental Systems Research Institute [ESRI], Redlands, CA, U.S.A.). A river layer shapefile was created to establish study boundaries for each habitat model that was constructed. Georeferenced depth (m) and benthic current velocity (m / s) were converted into

MS excel files and imported to shapefiles. Raster layers containing values for water depth and benthic current velocity were then interpolated for each study area using inverse distance weighting. Data on invertebrate density and substrate category from each sample location were also converted to georeferenced shapefiles. Thiessen polygons were created around each point to assign values across the entire study surface, and the resulting layer was clipped using the river layer shapefile and converted into a raster file. In the NC, substrate data collected from field surveys were combined with a previously constructed shapefile containing substrate composition for the NC (Boase et al. 2014).

For each area, a shapefile containing point values was created for locations where drift nets were placed. At each net location, longitude and latitude, net hours (total time a net was placed in a given location throughout the study site), and total number of Lake Sturgeon larvae collected was recorded and imported into ArcMAP® 10.3.

The raster layer of each habitat variable was reclassified into habitat suitability index (HSI) values based on suitability criteria developed by Threader et al. (1998) for substrate and Benson et al. (2005) for benthic current velocity. HSI values for invertebrate density and depth are based on larval – habitat associations found in the NC described in Chapter 3 (Table 4.1). The geometric mean of the reclassified layers was then used to create a composite HSM throughout each system. Cells of the composite model with a value of 0 were defined as unsuitable habitat, whereas cell values ranging from 0.01 and 0.6 were defined as poor habitat, from 0.61 to 0.8 as moderate habitat, from 0.81 and 1.0 as high-quality habitat for larval, YOY, and juvenile Lake Sturgeon.

Data Analyses

To assess ability of the HSM to accurately identify Lake Sturgeon habitat, I qualitatively compared locations of my collected larvae as well as known YOY and juvenile capture locations (USFWS and MDNR; unpublished data, Chapter 2, Chapter 3) to HSI values at each capture location.

To evaluate the input of potential Lake Sturgeon larvae into each river system investigated in this study, I used information on average egg deposition ($\# / \text{m}^2$) collected from various sites at each spawning reef (USGS; unpublished data), during years when larvae were also collected. I then multiplied mean egg density by reef area to estimate total egg deposition by Lake Sturgeon at each reef location during the course of this study.

For all three river systems combined and each individually, I examined the relationship between larval Lake Sturgeon catch per unit effort (CPUE, number per net hour) and combinations of habitat variables using multiple linear regressions. Since habitat patches varied in size between each study site, relative CPUE was calculated per unit area ($\text{CPUE} / \text{km}^2$). Akaike information criterion (AIC) was used to measure relative fit of each regression and to assess the degree to which each habitat variable combination was most useful in predicting relative CPUE. Pearson's correlation coefficients were calculated to further evaluate relationships between habitat variables. A One-Tailed T-Test and a One-Way Analysis of Variance (ANOVA) were used to compare abundance of habitat quality and larval length distributions, respectively, between each river system. All statistical analyses were performed using R-v 3.1.3 (R Development Core Team 2008). Pearson's Correlation Matrix was accomplished using the "Hmisc" package and model performance testing using AIC was accomplished using the "AICcmodavg" package. Alpha was set at 0.05 for all comparisons.

Results

I modeled large areas in the three river systems and found that high quality habitat was much more common in the NC than in the MC or FIC. The NC, MC, and FIC study areas were 16.74, 18.66, and 7.07 km², respectively (Figure 4.2). High quality habitat accounted for 29.1 % of the study area in the NC, and only 14.7 % and 16.8 % in the MC and FIC, respectively. The MC (76.8 %) and FIC (79.3 %) both contained significantly higher portions of moderate quality habitat when compared to the NC (53.5 %; One-Tailed T-Test, P = 0.035, and, One-Tailed T-Test, P = 0.039, respectively). Areas designated as poor quality habitat comprised < 20 % of each study area (Table 4.2).

The most amount of high quality habitat was found in the NC where the highest abundance of larval Lake Sturgeon was also found. Over the summers of 2014 and 2015, 283 larval Lake Sturgeon were collected from 19 different locations downstream of the Maslinka spawning reef in the NC during approximately 1420 net hours of sampling. Larval TL ranged from 11.4 – 24.5 mm ($\bar{x} = 18.1 \pm 2.2$) with 76 % of individuals measuring between 16 – 20 mm (Figure 4.3). Lengths of larvae recorded in individual nets differed by 3 – 7 mm. A partially absorbed yolk sac was evident on 75.5 % of larvae, while 20.6 % had completely utilized their yolk sac. Full yolk sac larvae accounted for only 3.9 % of total larvae collected. Collected larval Lake Sturgeon were most concentrated in three distinct areas of the NC (Figure 4.1), with 71 % of larva collected in areas with a composite HSI score between 0.80 and 0.90.

Though the MC differed in the amount and spatial distribution of high quality habitat, larval Lake Sturgeon collections were similar to those of the NC, although a lower percentage was found in high quality areas and more in moderate quality areas. During the summers of 2013 and 2014, 93 larvae were collected from 24 different locations downstream of the MC spawning reef

as a result of approximately 815 net hours of sampling. Larval TL was similar to the NC, ranging from 14.8 – 23.8 mm ($\bar{x} = 18.7 \pm 2.01$) with 79 % of individuals measuring between 16 – 20 mm (Figure 4.3), and lengths in individual nets differing by 2 – 6 mm. A partially absorbed yolk sac was evident on 27.9 % of larvae, while 57.4 % were found with no yolk sac, and 14.8 % were found with a full yolk sac. Of the 93 larvae collected, 15 were taken from high quality habitat areas, 76 in areas of moderate quality habitat, and 2 were collected in poor quality areas (Table 4.3). Relative CPUE was significantly higher in habitat areas of high quality (0.025) compared to moderate quality (0.011; One-Tailed T-Test, $P = 0.0201$, $T = 4.34$).

As observed in the NC, larval surveys in the MC indicate three areas of relatively high larval concentrations. However, unlike the NC, high quality habitat was less common and did not occur until approximately 4.5 km downstream from the MC reef (Figure 4.2). Additionally, larval Lake Sturgeon were collected sporadically throughout the full extent of the system, with two individuals collected at the mouth of the channel (Figure 4.2). Larval length and yolk sac stage measurements from the NC and MC showed nearly identical proportions with > 76% of individuals measuring between 16 – 20 mm TL and > 85 % of larvae exhibiting either a partially or completely absorbed yolk sac. A comparison of relative CPUE between similar habitat types in the NC and MC found no significant difference between sites ($P > 0.05$ for all comparisons).

In the FIC, high quality habitat was similar in proportional abundance to the MC, though larval Lake Sturgeon were considerably less abundant than in the NC and MC. A total of 25 larval Lake Sturgeon were collected downstream of the Fighting Island spawning reef during summer of 2016 from 16 different locations after approximately 400 net hours of sampling. Larval TL was similar to the NC and MC, ranging from 12.5 – 19.7 mm ($\bar{x} = 17.7 \pm 1.9$; Figure 4.3), with no significant differences in larval length distributions between river systems

(ANOVA, $F = 2.63$, $P = 0.074$). However, larva collected in the FIC from a single net were very homogenous in size (within 1.4 mm of each other), and a significantly higher portion were found with no yolk sac (77.8%) when compared to the NC and MC (One-Tailed T-Test, $P = 0.035$ and 0.041 , respectively). Of the 25 larva collected in the FIC, 6 were taken from areas designated as high quality habitat, 17 in areas of moderate quality, and 1 in an area of poor quality (Table 4.3). Larval abundance in the FIC was significantly lower than in the NC and MC (One-Tailed T-Test, $P = 0.018$ and 0.023 , respectively). There was also not a significant difference in relative CPUE measured for nets located in high versus poor quality habitat areas in the FIC. Larvae were collected beginning 0.25 km downstream from the Fighting Island reef to the mouth of the FIC (approximately 5 km). The highest concentration of larvae occurred just downstream from the reef ($n = 9$) and quickly declined to collections of no more than one or two individuals per site as sampling progressed downstream.

Larval dispersal in the FIC differed from the NC and MC, in that larvae did not concentrate in distinct locations. Similar to the MC, high quality habitat occurred in low abundance and in several small patches throughout the channel. One small high quality area occurred < 0.25 km downstream from the Fighting Island reef. Larvae were collected in relatively low abundance throughout this system and some were collected at the mouth of the FIC. Relative CPUE in poor quality habitat was significantly greater in the FIC when compared to the NC and MC (One-Tailed T-Test, $P = 0.008$ and 0.002 , respectively), and no significant difference was found between CPUE collected from high or moderate quality habitat in the FIC.

Though larval abundance was low in the FIC, estimated Lake Sturgeon egg density was considerably higher there than in the NC and MC. Lake Sturgeon egg sampling in the NC yielded 491 eggs / m^2 from 33 egg mat gangs deployed near the Maslinka reef during 2014 –

2015. From 2013 – 2014, 243 eggs / m² were collected from 263 gangs near the Middle Channel reef (MC reef), while 762 eggs / m² were collected from 56 gangs near the Fighting Island reef during 2016 (USGS unpublished data). Total estimated egg deposition for each reef site was 6.6 x 10⁵, 9.8 x 10⁵, and 2.5 x 10⁶ for the Maslinka, MC, and Fighting Island reefs, respectively.

In the NC, 11 Lake Sturgeon measuring < 500 mm were collected by myself or personnel from the Michigan Department of Natural Resources (MDNR) and U.S. Fish and Wildlife Service (USFWS), from 2013 – 2015. All of these collected fish were found in areas identified as high quality habitat by my HSM. During 2010, 3 Lake Sturgeon measuring < 150 mm were collected within the FIC by personnel from the USFWS. Of the three collected, one was found in an area identified as high quality habitat, while two were found in areas deemed poor quality. No records of < 500 mm Lake Sturgeon were found for the MC.

AIC analysis combining catch and habitat parameters from all three river systems indicated the highest ranked multiple linear regression model predicted CPUE using substrate (presence or absence of sand – silt), and the interaction between substrate and benthic current velocity (df = 93, F = 6.674, P < 0.001, R² = 24.3). Presence of sand – silt substrate had a significant, positive effect on CPUE ($\alpha = 3.99$, P = 0.04), while the interaction between substrate and benthic current velocity exerted a significant, negative effect ($\alpha = -0.33$, P < 0.001). For correlations, substrate values were analyzed as percent composition of sand and silt substrate collected at each location. Substrate and invertebrate density were significantly and positively correlated (P < 0.05).

When each study site was analyzed separately, AIC indicated the highest ranked regression model predicted CPUE in the NC using benthic current velocity, presence of sand and the interaction between benthic current velocity and presence of sand (df = 36, F = 6.887, P = 0.008, R² = 27.8). AIC analysis for the MC indicated the highest ranked regression model predicting

CPUE used only presence of sand – silt ($df = 14$, $F = 1.61$, $P = 0.032$, $R^2 = 25.6$). For the FIC, AIC analysis indicated the highest ranked regression model predicted CPUE using depth and presence of sand. However, contrary to the NC and MC, the regression model for the FIC was not statistically significant ($df = 31$, $F = 2.019$, $P = 0.149$, $R^2 = 3.11$), suggesting that habitat conditions did not result in larvae remaining in the FIC.

Discussion

Dispersal of larval Lake Sturgeon in the GLCCs is strongly associated with habitat conditions found in proximity to their natal spawning reef. I collected concentrations of larvae and found that larvae maintained residence in channels where high quality habitat was abundant within 1 to 2 km of spawning reefs. In contrast, larvae were less concentrated and appeared to disperse out of the study system when high quality habitat was less abundant or not present until 4 to 5 km downstream from the spawning reef. This supports my original hypothesis that young Lake Sturgeon dispersal varies in response to local environmental conditions and is not the same for Lake Sturgeon in all locations throughout the GLCCs.

Variation in dispersal of Lake Sturgeon in relation to presence of high quality habitat supports my hypothesis on Lake Sturgeon – habitat interactions. In the NC, HSM output indicated an abundance of suitable and readily accessible habitat for newly emerged larval sturgeon located in distinct patches approximately 0.25, 0.75, 1.25, and 2 km downstream of the Maslinka reef, and 81 % of young Lake Sturgeon were collected in these patches (Table 4.4). Rather than drifting out of the NC and into the surrounding wetlands or Anchor Bay, larval Lake Sturgeon appeared to remain in areas of high quality nursery habitat within the channel. In chapter 2, I observed a similar pattern of larval dispersal and also collected larvae with yolk sacs ranging from full to completely absorbed in the NC. Collection of larvae with variable length and

yolk sac stages in a single location indicates that individuals of different ages occur together in time and space (Kempinger 1988, Peterson et al. 2007). Based on this, in Chapter 3 I suggested larvae in the NC did not just passively disperse downstream but rather exhibited a “guided” drift behavior whereby individuals could orient and remain in areas of preferred habitat. This conclusion was supported by my collection of larvae of various lengths and stages of yolk-sac absorption in single nets and by patterns of high CPUE in distinct zones throughout the SCR.

Additionally, in the NC, locations where YOY and juvenile Lake Sturgeon have been collected showed considerable overlap with larval locations, indicating individuals of varying developmental stages utilized similar habitat patches. Previous studies have noted similar occurrence patterns for YOY, juvenile and sub-adult Lake Sturgeon in this system (Lord 2007, Boase et al. 2014). Using mark re-capture techniques in the Winnipeg River, Barth et al. (2011) found that 90.8 % of marked YOY and juvenile fish were re-captured within 2 km of their initial capture location (n = 714), despite having access to greater than 45 km of river. They concluded that year-round habitat requirements may be met in relatively short sections of a river and overlapping locations of collected YOY and juvenile fish may be attributed to larvae encountering good habitat during their drifting phase and remaining in these locations throughout their first few years.

Larvae in the MC also concentrated in three locations, and larval CPUE was significantly greater in high quality versus moderate or poor quality habitat, suggesting similar larval dispersal as in the NC (Table 4.4). However, while high quality habitat is available in the MC, it is less common and does not occur until 4.5 km downstream from the MC reef. While MC larvae congregated at 1.5, 3.2, and 4.5 km downstream from the MC reef, they were less densely clustered throughout the channel, as compared to larval collections in the NC. Additionally,

abundance declined with distance from the MC reef and larvae were found throughout the full extent of the channel, indicating that some larvae drifted out into Anchor Bay.

There are several plausible explanations for differing patterns of larval dispersal between the NC and MC. In contrast to the NC, the MC's morphology is comprised of dozens of small outlets leading to shallow wetland areas adjacent to Anchor Bay. These alternative transportation corridors may cause some larval Lake Sturgeon to disperse from the MC into surrounding wetland areas or to settle in the bay, reducing the number that drift to high quality sites further downstream. However, Lynch (2013) failed to collect YOY and juveniles in the surrounding wetlands and bay areas of the MC. In addition, I collected far fewer larvae as compared to the NC even though the MC reef had higher egg densities. This may indicate higher egg mortality and fewer larvae initially dispersing from the MC reef. Given that high quality habitat is not encountered until further downstream from the MC reef, larval fish may experience higher mortality rates due to increased exposure to predators (Caroffino et al. 2010a) or may deplete energy reserves over the course of three to five days if suitable habitat is not found (Kempinger 1988), thus decreasing larval densities further downstream. While there is some variation in larval dispersal patterns between the NC and MC, I believe these patterns are mostly influenced by the spatial distribution of high quality habitat in the MC, rather than a difference in use of habitat by young Lake Sturgeon.

While YOY and juvenile age Lake Sturgeon were collected from the NC during this study, no post-larval fish measuring < 500 mm were collected in the MC, in spite of more than 800 hours of collecting effort. This suggests few, if any, YOY and juvenile Lake Sturgeon reside in the MC. However, few individuals < 500 mm in length have been collected from other sites in the SCR and DR, even after 1200 or more hours of effort (Thomas and Haas 2004, Boase et al.

2014, Chapter 3). Difficulties with locating individuals of this size and age in large river systems have been well documented (Peterson et al. 2007, Hayes and Caroffino 2012) and lack of samples for all sites may simply reflect insufficient effort or ineffective gear (Chapter 3).

Another plausible explanation for the lack of juvenile sturgeon collected from the NC may involve the time that spawning habitat has existed. In the NC, the Maslinka reef was formed in the early 1900s and has been documented as a Lake Sturgeon spawning location for several decades (Boase et al. 2011). Individuals originating from this reef could range in age from 0 to older than 60 years. However, the MC reef was only completed during fall of 2012, with first evidence of egg deposition in 2013 (Roseman et al. 2011b, Bouckaert et al. 2014). As a result, only one or two year classes were generated from this location by my sampling dates in 2013 – 2014. While larvae also entered the MC in 2013 and 2014 from upstream spawning sources (Bouckaert et al. 2014, Chapter 2), the lack of a system specific source of larvae in the MC until 2013 has likely influenced abundance of YOY and juvenile fish as well as the number of age classes available to sample during my study period.

Larval dispersal in the FIC showed a different pattern compared to the NC or MC, with no concentrated abundance of larvae and similar CPUE values from high, moderate, and poor quality habitat. Further, lack of a significant association between relative CPUE and habitat quality suggests that larval Lake Sturgeon did not remain in the FIC, but instead drifted 5.5 km to the DR. This dispersal pattern is similar to that observed for Lake Sturgeon from other river systems where habitat is thought to be a limiting factor to abundance of young. Larvae collected from the Sturgeon River, MI were found to drift more than 60 km from their natal spawning reef in the span of 25 – 40 days post hatch (Auer and Baker 2002). Smith and King (2005) found larval CPUE in the Black River did not increase significantly until at Black Lake, 10 km

downstream from the spawning source. While I found relatively high larval abundance 0.25 to 0.5 km downstream from Fighting Island reef (n = 9, 36 % of total yield), this was likely due to proximity of sampling nets to the spawning source, rather than an indication of suitable nursery habitat at that location. Roseman et al. (2011a) collected seven larvae just downstream of the Fighting Island reef but did not detect individuals further downstream, further supporting my contention of the proximity to the reef explaining this high larval abundance.

In addition to differences in dispersal patterns, larval sampling in the FIC yielded far fewer individuals than were collected in the NC and MC, even though estimated egg densities on the Fighting Island reef were much higher than densities from either the Maslinka or MC reef. This may indicate few larvae enter the channel due to high egg mortality, or larvae emerge from the reef and quickly drift through the channel. Large numbers of larvae collected in the NC and MC support the idea that larvae remained there in selected habitat rather than rapidly drifting downstream. I believe egg deposition on the Fighting Island reef is sufficient to produce similar numbers of drifting larvae as found in the NC and MC, but the lack of higher larval CPUE is likely a result of most larvae rapidly drifting through the system due to low abundance of suitable nursery habitat. However, collection of three juveniles (< 150 mm) in the FIC suggests some individuals may remain there or return following adequate ontogenetic development downstream. This behavior has also been observed for YOY and juvenile (< 500 mm) Lake Sturgeon in the Sturgeon River, where larvae were found to drift into the nearby water of Portage Lake and Lake Superior before returning to utilize the last ~ 10 km of the river for nursery habitat (Auer and Baker 2002).

Measurements of length and yolk sac stage of larvae collected downstream from spawning reefs in this study showed that larvae from each system had considerable variation in

development. Peterson et al. (2007) determined that larval Lake Sturgeon remain on their natal reef for periods of two to four weeks after hatch as they absorb their yolk sacs and continue to develop. After this time, larvae of relatively homogenous lengths emerge from the reef and individuals with partially or fully absorbed yolk sacs should dominate drift downstream from their spawning source (LaHaye et al. 1992, Auer and Baker 2002). This description matches the composition of larvae collected downstream from the FIC reef in this study. However, larvae collected downstream of both the Maslinka and MC reefs ranged in size by as much as 13 mm and showed considerable variation in both lengths and patterns of yolk sac composition from individuals collected in single nets. Variation in morphometric characteristics between larvae may indicate individuals entered the drift at different times with some possibly being dislodged from the reef due to turbulence or strong flow (Kempinger 1988, Peterson et al. 2007). However, if many larvae were dislodged, downstream collections should contain higher proportions of small (12 – 16 mm) individuals with full yolk sacs (Smith and King 2005, Peterson et al. 2007). This is not the case for larval Lake Sturgeon in my study, as individuals of larger size and more depleted yolk sacs were found in highest proportions. As such, I believe variation in length and yolk sac stage found in this study is indicative of variable dispersal patterns for larval Lake Sturgeon. Distributions of varying larval length and yolk sac stage as measured throughout areas downstream of reefs in the NC and MC indicate larvae remained within their channel of origin. In the FIC, distributions of similar larval length and yolk sac stage measured throughout areas downstream of the reef indicate larvae exited the channel.

Observed larval dispersal and associations with local habitat quality support three main conclusions. First, larval, YOY, and juvenile Lake Sturgeon in the GLCCs occupy similar habitat throughout early development. Second, larval Lake Sturgeon in the NC and MC selected high

quality nursery habitat if encountered within 2 km downstream of the spawning reef, but either suffered higher mortalities when high quality habitat was further downstream or there was more channel complexity and larvae dispersed outside of the survey area. This conclusion is supported by collections of high concentrations of larvae in three distinct areas in the NC and MC with varying sizes and yolk sac stages, a significantly higher relative CPUE in high quality habitat in the NC and MC, and the presence of alternative dispersal corridors in the MC that are not available in the NC. Finally, though egg deposition was relatively high, fewer larval Lake Sturgeon appeared to emerge from the spawning reef in the FIC and those that did bypassed habitat in this channel. This conclusion is supported by low collections of larval Lake Sturgeon in the FIC, low variation in larval length and yolk sac stage, lack of association between CPUE and habitat parameters, and the collection of larvae exiting downstream into the DR.

Of the four habitat parameters included in this study, substrate composition was the lone variable included in the best multiple linear regressions for both NC and MC predicting abundance of larval CPUE. Composition of substrate influences the ability of larval Lake Sturgeon to burrow into sediment to escape high current velocities and predators during the day (Kempinger 1988, Auer and Baker 2002, Smith and King 2005). Additionally, substrate composition may be related to local invertebrate community composition and thus, prey availability for young Lake Sturgeon (Chiasson et al. 1997, Hayes and Werner 2004). While I did not find invertebrate densities to significantly correlate with larval CPUE, there was a significant positive correlation between invertebrate density and substrate composition in the NC and MC, so either factor may indicate similar habitat quality.

Water depth alone was not a significant predictor of larval CPUE. The lack of a significant association with depth is likely due to relatively consistent depths found throughout each study

system. In all cases, greater than 80 % of measured depths were between 8 and 13 m, which scored between 0.8 – 1.0 in my HSI assignments. Benthic current velocity was a significant predictor of CPUE in the NC but not the MC. The MC has slower average current velocity (0.45 m / s) than the NC (0.55 m / s) which may partially explain the lack of association, as abundance of drifting larval Lake Sturgeon has been shown to increase with increasing current velocity (Harkness and Dymond 1961, Smith and King 2005). Additionally, I derived HSI values for benthic current velocity from studies of Lake Sturgeon behavior in the Peshtigo River, WI, a smaller river with slower current velocities (0.29 to 0.38 m / s, Benson et al. 2005). While similarities exist among these systems, a reevaluation of HSI values for this parameter may be warranted. A comparison of habitat characteristics collected from multiple large rivers where larval Lake Sturgeon are collected may help to inform future HSI rankings for current velocity.

Though not all habitat parameters assessed in this study were identified as significant predictors of young Lake Sturgeon occurrence, I demonstrated strong associations between larval dispersal patterns and modeled outputs of high quality habitat. HSI rankings, which denoted high quality habitat areas, were a composite value, generated by the inclusion of all four-habitat parameters, with each contributing an equal weight to the overall HSM score. As such, I believe the inclusion of all four variables is essential in future HSMs focusing on habitat preferences of young Lake Sturgeon habitat in large rivers.

While models describing species – environmental relationships have received much attention from scientific and resource management communities (Larson et al. 2004, Hirzel et al. 2006), the transferability of modeled relationships predicted by HSMs across systems is uncertain (Peterson et al. 2007, Haxton et al. 2008). In the NC, I found that larval abundance significantly correlated with high quality habitat and larvae concentrated in three distinct areas. Additionally, I

corroborated modeled outputs with data on YOY and juvenile distributions from other studies. Though more dispersed than larvae collected in the NC, I found that larval CPUE in the MC was also significantly correlated with high quality habitat and was concentrated in three distinct areas. In the FIC, I found low abundance of larvae and high quality habitat and lack of a significant relationship between habitat parameters and larval CPUE. Based on this, I concluded larvae exited the channel and dispersed into the DR. Although variation in patterns of larval dispersal occurred across these rivers, this variation was consistent with local habitat conditions in each system. This is an important first step in linking HSI relationships across different rivers for Lake Sturgeon and other species of interest and emphasizes the importance of local habitat conditions in determining dispersal and habitat use of early life-stage fishes.

Limitations and Biases

While the findings and interpretations generated from this study are supported by available data and existing literature, several limitations and assumptions result from sampling technology and lack of available data. The first limitation is that of my methodology for determining benthic current velocity in each study system. Due to return signal interference, ADP readings for velocity were an averaged value, generated by merging the two bottom-most cells of each vertical velocity profile. As such, depth ranges of “benthic” flow speeds were from 0.1 to 0.5 m above the substrate. While larval Lake Sturgeon have been noted to drift throughout the vertical height of the water column (Caroffino et al. 2009), the majority of drift occurs close to the bottom (Kempinger 1988, Auer and Baker 2002), likely within the bottom 0.2 m. My sampling did not allow me to collect accurate current velocities at this depth and forced me to infer benthic velocity from measurements higher in the water column. However, current velocities were measured similarly in the other studies developing HSI values for larval Lake Sturgeon

(Threader et al. 1998, Daugherty et al. 2009). As such, my conclusions generated by extrapolated current velocities are comparable to other studies examining young Lake Sturgeon habitat preference, but likely do not indicate actual velocities where larvae are found.

Another limitation stems from a lack of knowledge in sources of larval Lake Sturgeon from locations upstream of my study sites. My collections of larvae found relatively large numbers of individuals upstream from both the Maslinka (178) and MC (54) reefs (Chapter 2). Most of these larvae (64%) had either a full or partially absorbed yolk sac, indicative of individuals who had only recently emerged from their natal reef. This suggests the presence of spawning sites in unknown locations upstream of my study sites, which contributed larvae to collections further downstream. While I did not attempt to collect larvae upstream of the Fighting Island reef, large (19 – 20 mm) larvae with no-yolk sac were collected just 0.1 km downstream from the reef, suggesting that some larvae collected in the FIC may also have originated from upstream sources.

Larvae collected upstream of the Maslinka and MC reefs showed nearly identical proportions of stages with full, partial, and no yolk sacs to larvae collected from downstream, with only a slightly higher proportion of larvae with full yolk sacs collected upstream versus downstream of the Maslinka reef (Chapter 2). Lengths of larvae collected upstream and downstream from these reefs were not statistically discernible. Larvae in both rivers were found to concentrate in distinct areas of high and moderate quality habitat, downstream of each reef. This indicates that larvae made use of quality habitat when they encountered it, regardless of their spawning point of origin. Given these distinct concentrations of larvae and the similarities in morphometric characteristics in upstream versus downstream collections, I believe larvae from upstream sources drifted past the Maslinka and MC reefs, mixed with larvae emerging from these reefs,

and used similar habitat downstream. Thus, the input of upstream larvae is not influencing larval distribution patterns found downstream.

Finally, I assumed larvae collected during the drift were either found in a location that they had chosen to be (preferred habitat) or were in transit from one location of less ideal habitat to one more preferred. An alternative interpretation is that individuals collected in the drift represent those that had become dislodged from spawning reefs and were drifting passively in the current. Larval mortalities for Lake Sturgeon have been estimated at 99.8 % in some systems (Caroffino et al. 2010b) and larvae collected in this study could simply represent dislodged individuals that were “doomed to die”. Most fish species experience high mortalities during their early development (Diana 2004), and many drifting larvae undoubtedly suffer mortality. However, collections of larva drifting passively in the current should show a more uniform spatial distribution, with more consistent numbers of larvae collected throughout each channel (Kempinger 1988, LaHaye et al. 1992). In the NC and MC, I found larvae of varying yolk sac stages and lengths concentrated in distinct areas of high and moderate quality habitat, with few individuals collected elsewhere. Additionally, larvae dislodged from their reefs should possess fuller yolk sacs (Peterson et al. 2007). In my study, the majority of larvae were found with partial or no yolk sacs. While some unintentionally dislodged larvae may have been collected, they probably represent a small percentage of total larval catch and did not influence distribution or residence patterns discussed in this text.

Conclusion

The abundance and spatial distribution of suitable spawning and nursery habitat is believed to be the limiting factor preventing Lake Sturgeon recovery in the Great Lakes (Roseman et al. 2011a, Hayes and Caroffino 2012). I developed a methodology for assessing quality, quantity,

and spatial distribution of young Lake Sturgeon habitat for three separate systems within the GLCCs. In addition, I incorporated larval, YOY, and juvenile Lake Sturgeon collections from numerous efforts and showed associations between young Lake Sturgeon occurrence and modeled habitat characteristics. High quality nursery habitat was identified in all three river systems explored in this study. However, given variation in larval Lake Sturgeon occurrence observed in the NC, MC, and FIC, I believe the mere presence of suitable habitat within a system is not sufficient. Rather, I believe the amount and location of this habitat in relation to sources of young Lake Sturgeon shapes early behavior and distribution by influencing larval drift.

The distribution of larvae observed in both the SCR and DR showed a strong association between larval drifting patterns and local habitat characteristics. These relationships suggest a level of variability in young Lake Sturgeon behavior that to my knowledge has not been documented for populations in the GLCCs. Understanding how local habitat characteristics may influence larval, YOY, and juvenile Lake Sturgeon dispersal will help to identify locations for future restoration throughout the Great Lakes Basin and aid in the ability to assess system-specific habitat that limit successful recruitment. For example, in the NC where high quality nursery habitat and larval Lake Sturgeon are already abundant, maintaining existing spawning and nursery habitat should be the main focus of managers, and resources for restoration activities should be directed to other systems with less suitable habitat. In the MC, where high quality nursery habitat is less abundant and further downstream from the spawning reef, I believe recruitment success would be improved by increases in available spawning habitat further downstream from the MC reef, closer to existing high quality nursery habitat. In the FIC, where high quality nursery habitat and larval Lake Sturgeon are in low abundance, I believe restoration resources should be used to improve recruitment success elsewhere. This study demonstrates that

with the collection and mapping of habitat information, one could reasonably assess dispersal patterns and habitat limitations of young Lake Sturgeon in a given system. Such information should help to guide future restoration activities and link historic, ongoing, and future conservation attempts for improving the status of Lake Sturgeon throughout the Great Lakes Basin.

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Table 4.1. Input values for the habitat suitability model for larval and juvenile Lake Sturgeon (from Chapter 3).

Habitat Variable	Suitability Index
Substrate Composition	
Clay	0.2
Silt	1
Sand	1
Gravel	1
Cobble	0.8
Boulder	0.5
Benthic Current Velocity (m / s)	
> 1.0	0
0.6 - 1.0	1
0.3 - 0.59	0.9
0.0 - 0.29	0.5
Water Depth (m)	
< 5.0	0
5.1 - 10.2	0.8
10.3 - 13.3	1
>13.3	0.5
Invertebrate Density (# / m ²)	
> 3000	1
701 - 2999	0.7
< 700	0.4

Table 4.2. Median and range (in parentheses) for environmental variables collected in each river system by habitat quality. Substrate composition was excluded from this table as it is a categorical variable.

Site	Habitat Quality	Area (km ²)	Benthic Current Velocity (m / s)	Invertebrate Density (# / m ²)	Depth (m)
NC	High	4.85	0.71 (0.55-0.98)	3107 (2654-3321)	11.6 (9.4-15.8)
NC	Moderate	8.96	0.43 (0.34-0.83)	2611 (1920-3002)	7.8 (6.7-17.1)
NC	Poor	2.88	0.21(0.12-0.56)	2103 (100-2231)	3.4 (1.4-9.8)
NC	Unsuitable	0.04	0	0	0
MC	High	2.74	0.43 (0.36-0.47)	927 (905-1125)	13.26 (12.6-14.03)
MC	Moderate	14.14	0.38 (0.24-0.41)	1336 (129-4181)	12.19 (10.95-15.5)
MC	Poor	1.18	0.25 (0.12-0.56)	450 (124-2253)	4.7 (2.3-7.8)
MC	Unsuitable	0	0	0	0
FIC	High	1.19	0.42 (0.34-0.43)	882 (794-3012)	11.5 (8.9-11.86)
FIC	Moderate	5.61	0.37 (0.33-0.47)	794 (18-1588)	10.7 (8.9-11.28)
FIC	Poor	0.27	0.34 (0.29-0.51)	176 (0-265)	7.85 (8.93-9.24)
FIC	Unsuitable	0	0	0	0

Table 4.3. Summary statistics of larval Lake Sturgeon catch from drift nets in each habitat quality type by river system.

Site	Habitat Quality	Larvae Collected	Net Hours	CPUE	Relative CPUE
NC	High	230	808	0.285	0.059
NC	Moderate	52	361	0.144	0.016
NC	Poor	1	135	0.007	0.002
NC	Unsuitable	0	116	0	0.000
MC	High	15	221	0.068	0.025
MC	Moderate	76	481	0.158	0.011
MC	Poor	2	112	0.018	0.015
MC	Unsuitable	0	0	0	0.000
FIC	High	6	105	0.057	0.048
FIC	Moderate	17	272	0.063	0.011
FIC	Poor	1	25.5	0.039	0.140
FIC	Unsuitable	0	0	0	0.000

Table 4.4. Summary catch statistics in six locations that had high densities of larval Lake Sturgeon within the NC and MC. Area of each high density area is given along with (% area relative to total study area). Cluster ID corresponds to point locations on Figure 4.2.

Cluster ID	Habitat Quality	Area (km ²)	Larvae Collected	Net Hours	CPUE	Percent of Total
1-NC	High and Moderate	0.034 (0.2 %)	45	62.55	0.719	16%
2-NC	High	0.031 (0.18 %)	136	247.03	0.551	48%
3-NC	High and Moderate	0.051 (0.3 %)	77	314.17	0.211	27%
1-MC	High	0.041 (0.22 %)	15	220.33	0.068	16%
2-MC	Moderate	0.094 (0.52 %)	14	270.57	0.052	15%
3-MC	Moderate	0.098 (0.53 %)	51	120.13	0.425	54%

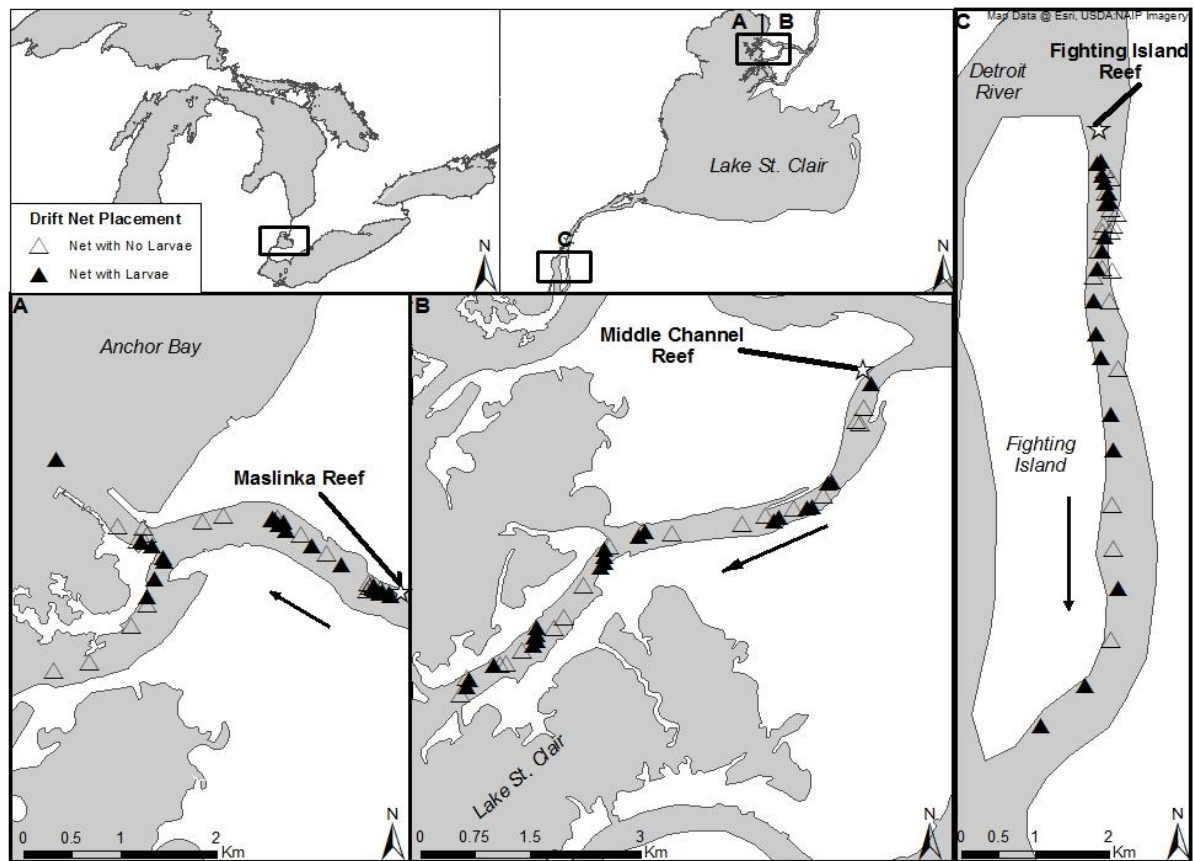


Figure 4.1. Map of study sites with larval drift net sampling locations shown. Hollow triangles represent net sites where no larval Lake Sturgeon were collected while filled triangles represent sites where larva were collected. Stars show location of spawning reefs. Black arrows indicate flow direction.

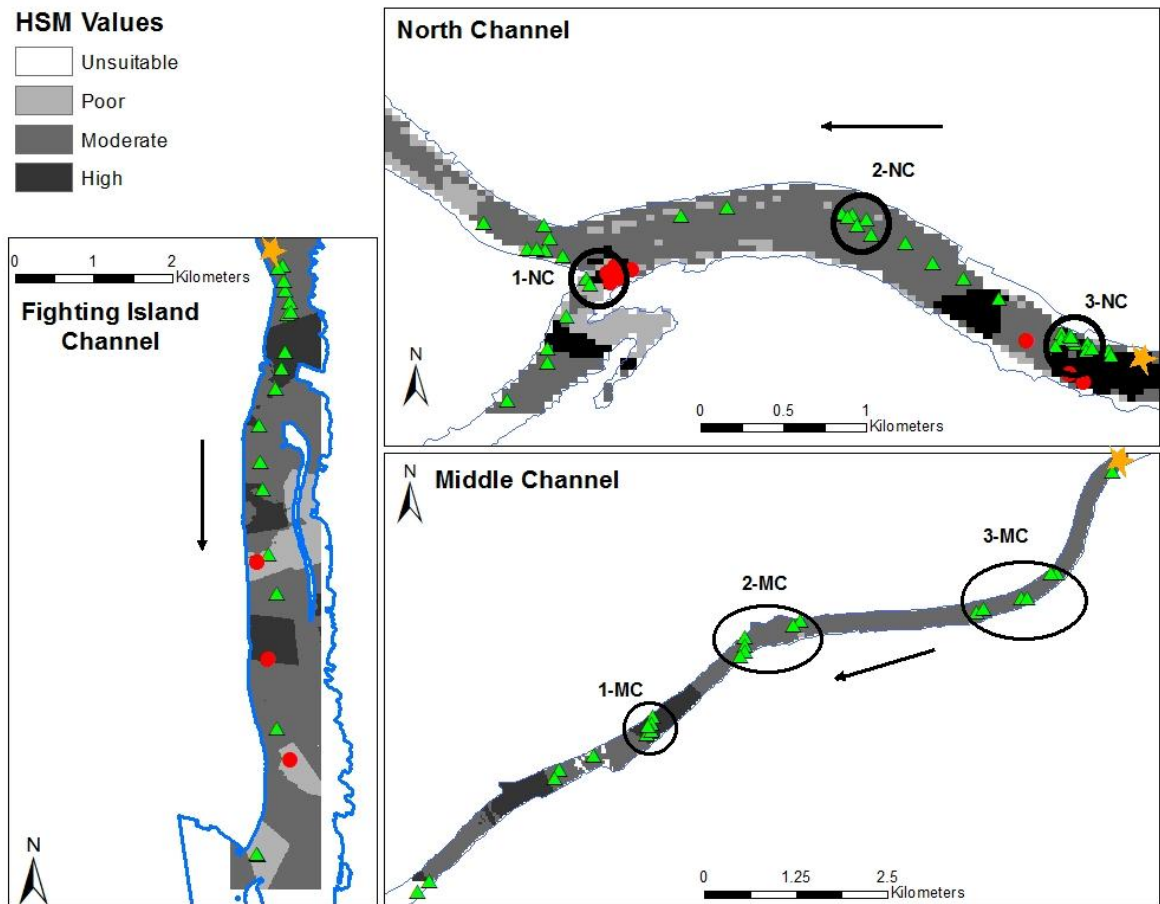


Figure 4.2. Map of Habitat Suitability Model output for larval, YOY, and juvenile Lake Sturgeon in the Fighting Island, North, and Middle channels. Orange stars show location of spawning reefs. Black arrows indicate flow direction. Red circles indicate capture locations of YOY and juvenile Lake Sturgeon and green triangles indicate capture locations of larval Lake Sturgeon. Areas of high larva Lake Sturgeon densities are labeled and detailed in Table 4.4.

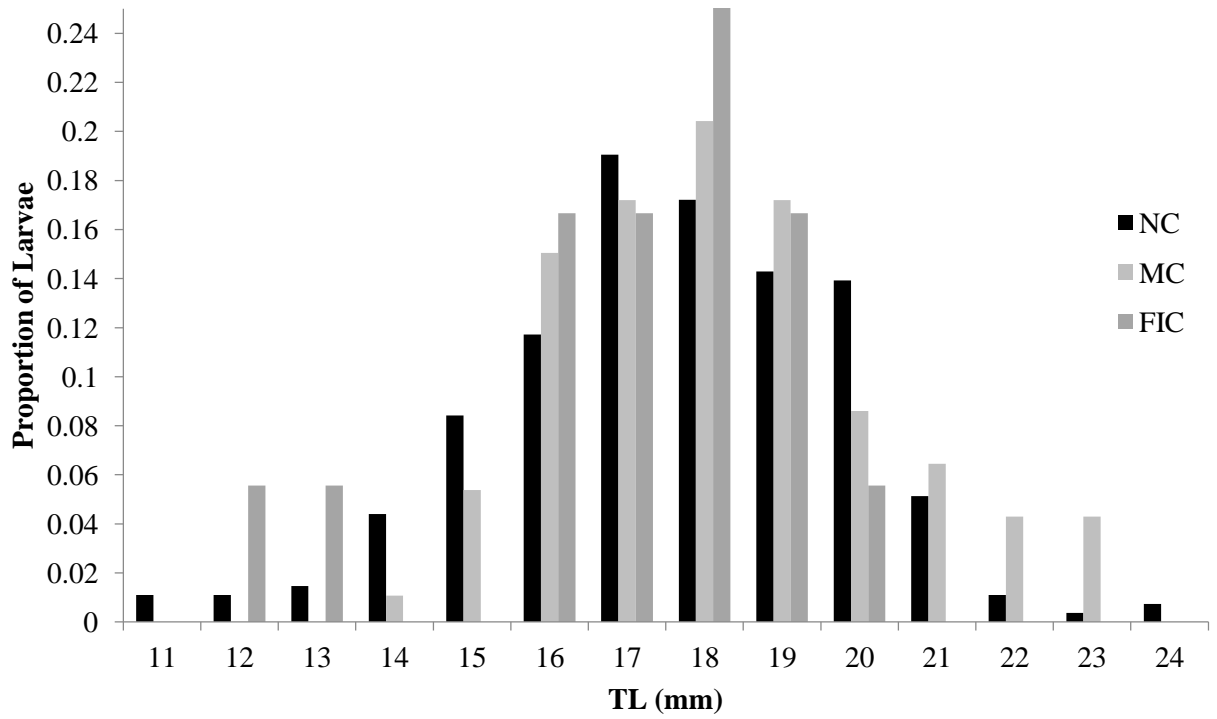


Figure 4.3. Length frequency histogram for larval lake sturgeon collected from the NC, MC, and FIC from 2013 – 2016.

Chapter 5

Conclusion

An organism's behavior is strongly influenced by its surrounding environment. Changes in environmental conditions from anthropogenic or natural processes may disrupt or interfere with the way an organism utilizes its environment, limiting access to vital resources and decreasing fitness. Survivorship of many organisms is highly dependent on conditions experienced early in life (Stearns 1992). Alteration or modification of essential rearing or nursery habitat can have devastating effects on year class success, resulting in low recruitment (Secor et al. 2002, Diana 2004). Most species – environmental relationships have been described based on interactions observed during an animal's most dominant life history stage (Kennedy and Gray 1993), or extrapolated from systems where observations of animal behavior are easier or more convenient (Casselman et al. 1990). As a result, habitat needs of a species during the critical period of early development is often either poorly understood (Secor et al. 2002), or assumed to be consistent throughout the animal's range (Biette et al. 1981). Understanding habitat use of a species, and how it changes throughout the animal's development and geographic range, is critical for gauging the impacts of environmental change on populations of interest.

I used Lake Sturgeon (*Acipenser fulvescens*) as a model species to investigate species – environment relationships during early life history and found that quality, quantity, and spatial distribution of local nursery habitat had a strong influence on dispersal patterns of young Lake Sturgeon from their natal reef. Larval Lake Sturgeon dispersal appears to be variable across river systems, and can be predicted based on simple habitat characteristics. As such, site-specific

evaluations of local habitat condition and young Lake Sturgeon dispersal are essential for developing successful restoration efforts.

In Chapter 2, I investigated a critical gap in the understanding of early life history of Lake Sturgeon in a GLCC, the St. Clair River, Michigan. Drifting patterns of larval Lake Sturgeon were assessed using D-frame drift nets, which provided insight on spatial distribution of larvae in both the North and Middle channels. In addition, morphometric characteristics (total length and yolk-sac stage) of larval sturgeon were measured to characterize growth and development of larvae after they had emerged from natal spawning reefs and begun downstream migrations. I collected larvae in high densities at several distinct locations and found that larvae of variable growth and developmental stages remained in the river in spite of strong currents. This suggests the nature of larval Lake Sturgeon drift is more active than passive and that riverine areas are utilized as nursery habitat or refuge, making them important for early survival.

In Chapter 3, I evaluated the quantity, quality, and spatial distribution of riverine nursery habitat for larval, YOY and juvenile (< 500 mm) Lake Sturgeon in the North Channel of the SCR. I developed a habitat suitability model using georeferenced habitat information on substrate composition, invertebrate densities, benthic flow velocities, and water depth. Habitat models were developed and assigned habitat suitability index values based on known preferences for each habitat condition. Raster models for individual river characteristics were then combined to produce a composite HSM, which identified areas of high, moderate, poor, and unsuitable nursery habitat. Further, I examined the relationship between larval catch rates and individual habitat parameters through a series of multiple linear regressions using larval catch per unit effort as the response variable and varying combinations of habitat parameters as predictors. Akaike information criterion was used to predict the best-fitted regression. I also determined high

concentrations of larval Lake Sturgeon in three distinct areas of high quality habitat in the NC. The multiple linear regression model using substrate composition (presence of sand and silt) and benthic flow velocity produced the best fit to observed larval CPUE patterns. Available data on captured YOY and juveniles were used to corroborate modeled habitat outputs and revealed associations between habitat conditions and presence of young Lake Sturgeon. My results indicated an abundance of suitable habitat for young Lake Sturgeon within the NC, which was utilized by larval, YOY, and juvenile fish. This suggests the availability of suitable spawning habitat may be limiting recruitment success in the NC.

In Chapter 4, I parameterized the HSM developed in Chapter 3 with local habitat characteristics from the Middle Channel of the SCR and Fighting Island Channel of the Detroit River. Using dispersal patterns of larval Lake Sturgeon collected from these three locations, I then compared modeled Lake Sturgeon – habitat relationships for each river system. Larval distribution patterns observed in both the SCR and DR showed an association between early life-stage dispersal and local habitat characteristics. In the NC, there was an abundance of suitable and readily accessible habitat for newly emerged larval sturgeon first occurring < 0.5 km downstream from the known spawning location. Larval, YOY, and juvenile Lake Sturgeon were found in high densities at three locations of high quality habitat and appeared to utilize similar riverine habitat throughout early development. In the MC, larvae also appeared to concentrate in three distinct locations and were collected in high numbers from areas of high quality habitat. However, high quality habitat was less abundant and did not occur until 4.5 km downstream from the MC reef. CPUE of larva decreased as sampling progressed downstream, suggesting increased drift distance to suitable habitat may result in increased larval mortality or alternative dispersal. In the FIC, high quality habitat was less common, larval Lake Sturgeon abundance was

low and larvae were not taken in high concentrations in any specific location. Further, I found no significant association between larval occurrence and local habitat conditions, suggesting that larval Lake Sturgeon did not remain in the FIC, but instead drifted through the system and into the main channel of DR. My results suggest dispersal behavior of young Lake Sturgeon in these large river systems is contingent on local habitat conditions found downstream of their natal reefs. Where high quality nursery habitat was abundant and found within 2 – 3 km downstream of reefs, I found larval Lake Sturgeon concentrated in distinct areas where YOY and juvenile sturgeon were also found. Where high quality habitat was found in less abundance or further downstream, I found larvae were less concentrated and some appeared to disperse out of the river. Variation in larval dispersal in relation to local habitat conditions is a phenomenon not previously documented for Lake Sturgeon in the GLCCs.

Synthesizing results from my research, I believe that age 0 – 2 Lake Sturgeon found in large river systems utilize similar habitat throughout early development. Further, I believe variation in the abundance and spatial distribution of high quality habitat between river systems results in differences in young sturgeon dispersal behavior. Larval Lake Sturgeon in the NC and MC appeared to remain in the river after drifting a short distance, while those in the FIC appeared to disperse quickly from the river to downstream areas (with presumably more preferred habitat). My field collections and morphometric descriptions of larval Lake Sturgeon surveyed from both upstream and downstream of known spawning sites in the NC and MC indicated larvae of variable age and developmental stages remained in these rivers, in spite of strong currents, suggesting the presence and utilization of nursery habitat within these channels (Chapter 2). Prior to my study, larval Lake Sturgeon were thought to drift quickly out of the SCR into Lake St. Clair or surrounding wetlands. However, there is no record of larval, YOY, or juvenile Lake

Sturgeon collected from shallow bays or wetland areas in the SCR. Instead, the assertion that larval Lake Sturgeon utilize these areas was based on findings from other river systems and on the assumed inability of larvae to maintain location against the strong currents found in these rivers. Webb (1986) demonstrated the critical velocity (maximum swimming speed) of a young Lake Sturgeon to be 0.39 m/s, well below the average current velocity of the SCR (~ 0.6 to 1.2 m/s, Schwab et al. 1989). Prior to my study, descriptions of Lake Sturgeon nursery habitat were mainly developed from data on populations in relatively small river systems, which are shallower, more narrow, and may possess locations with slower current speeds compared to the GLCCs (Auer and Baker 2002, Smith and King 2005). In these smaller rivers, larvae settle in areas of slower moving waters, such as at the mouths of rivers (Auer and Baker 2002). However, my larval sampling collected very few larvae near the mouth of either the NC or MC, but instead found high concentrations of larvae at intermediate distances downstream from known spawning reefs. Additionally, while some studies describe the drift behavior of larval Lake Sturgeon as “passive” (Kempinger 1988, D’Amours et al. 2001), my collections of high concentrations of individuals in distinct locations suggested that larvae have the capacity to orient and direct themselves during their drifting phase (chapter 2 and 3). In order to remain in these systems, larvae likely find refuge from strong currents by burrowing into substrate or seeking shelter downstream of submerged structure like vegetation or boulders. Hastings et al. (2013) observed behavior of larval Lake Sturgeon in flume trials and found that larvae would avoid currents by burrowing into substrate, then would later re-enter the current if initial substrate was not of a preferred type (sand or gravel).

In addition to substrate, other habitat characteristics such as benthic current velocity, depth, and prey (invertebrate) density, are known to influence young Lake Sturgeon distribution

(Threader et al. 1998, Benson et al. 2005, Chapter 3). Combining results from the NC, MC, and FIC, only benthic current velocity and substrate composition, were significant predictors of larval Lake Sturgeon abundance. For small, newly hatched fish, the influence of benthic current velocity on dispersal pattern is not surprising. Larvae of many fish species are known to migrate long distances using water current as transport corridors (Norcross and Shaw 1984, Health 1992), but less evidence has been shown on the ability of these fish to terminate their drifting phase and settle into preferred areas (Lasker 1981, Shelton and Hutchings 1982, Humphries and Lake 2000). However, from field surveys of larval Lake Sturgeon in my study systems, I noted several distinct areas of high larval concentrations that occurred in areas of high quality habitat as identified by my HSM. Indeed, > 85% of all larva I collected (n = 400) were found in areas of high quality habitat. I believe that larval Lake Sturgeon are not only able to maneuver and remain in these large rivers, but are also able to avoid the current and move to areas of preferred habitat.

The type and location of substrate may be the single most significant influence on dispersal patterns of larval fish in large river systems (Hastings et al. 2013, Chapters 2 – 4). Areas with substrate consisting predominately of sand and a mixture of sand and silt were found to be significantly associated with larval Lake Sturgeon abundance in both the NC and MC. In addition to being of suitable consistency to allow larvae to burrow, this substrate type is also favorable habitat for Mayfly larvae (*Hexagenia* spp.), bloodworms (Chironomidae), and other small oligochaetes, which are all known prey items for young Lake Sturgeon (Peterson et al. 2007). Burrowing into sand and silt may have additional benefits beyond escapement from high current velocities. By exiting the water column, larval Lake Sturgeon are able to minimize energy expended in swimming, allowing for an increase in energy available for growth and

development (Noakes et al. 1999, Peterson et al. 2007). Larvae may be susceptible to predation when drifting above the substrate, but those that remain burrowed or moving within the topmost layer of sediment are likely less vulnerable to predators.

Models describing species – environmental relationships have received much attention from scientific and resource management communities. Specifically, HSMs have been demonstrated as useful tools for identifying areas possessing desired habitat characteristics and as a reliable technique for predicting dispersal patterns of organisms (Larson et al. 2004, Hirzel et al. 2006). However, the transferability of modeled relationships predicted by HSMs across systems has been called into question (Peterson et al. 2007, Haxton et al. 2008). In the NC, I found that larval abundance was significantly correlated with high quality habitat, and further corroborated modeled outputs with data on YOY and juvenile distributions collected in other studies in the NC (Lord 2007, Boase et al. 2014). I also found that larval CPUE in the MC was significantly correlated with high quality habitat and individuals concentrated in three distinct areas. While two of these areas were composed of moderate quality habitat, given the relatively uniform distribution of larval collection sites within the channel, lower density collections of larvae in upstream habitat of moderate quality may simply represent transient larvae that are still actively drifting to better habitat. In the FIC, larval Lake Sturgeon sampling and modeled habitat outputs indicated that larva left the channel and moved downstream into the DR. Indeed, given the lack of a significant relationship between collected habitat parameters and larval CPUE, the relatively small channel size, and low abundance of high quality habitat; I predict that larval Lake Sturgeon disperse out of the FIC in search of more favorable habitat. Although variation in patterns of larval dispersal occurs across these rivers, this variation is consistent with local habitat conditions present in each system. This is an important first step in linking HSI relationships

across different systems for Lake Sturgeon and other species of interest and emphasizes the importance of local habitat conditions in determining dispersal behavior of early life-stage fishes. Alteration or modification of high quality habitat used during this critical period of fish development may have profound impacts on fish behavior, fitness, and survival.

The availability of and access to suitable spawning and nursery habitat is believed to be the greatest impediment to Lake Sturgeon recovery in the Great Lakes Basin (Hay-Chmielewski and Whelan 1997). In the GLCCs, restoration measures have focused on improving the quantity of available spawning habitat in areas where natural spawning was once thought to occur (Hay-Chmielewski and Whelan 1997), and construction of artificial spawning reefs has been on-going since the early 2000s (Roseman et al. 2011). While there has been successful spawning and larval development on these reefs (Read and Manning 2006, Roseman et al. 2011), the fate of drifting larva is unknown. In part, this uncertainty was the result of insufficient information on habitat preferences for young sturgeon in large rivers (Hay-Chmielewski and Whelan 1997, Peterson et al. 2007). My dissertation research demonstrated links between larval, YOY, and juvenile stage Lake Sturgeon and their surrounding environments and showed that these species – environment relationships may apply across multiple large river systems. I believe that my work will help us better understand species – environmental relationships through early life history development and prove useful in identifying locations for future restoration efforts throughout the Great Lakes. For example, site locations for spawning reefs are usually generated by habitat models using benthic current velocity and water depth as determinants of suitable sites (Bennion and Manny 2014, Fischer et al. 2015). Recent evidence of sediment infiltration into these reefs has resulted in attempts to include other variables as such sediment load and seasonal shifts in flow profiles in the factors used to identify proper sites for reef construction (Manny et

al. 2015). Linking future reef placement in proximity to high quality habitat for young fish should complement existing criteria for citing reef restoration sites and improve recruitment success for fishes throughout the GLCCs.

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