ASSESSING THE SPATIOTEMPORAL DISTRIBUTION OF LARVAL LAKE STURGEON *ACIPENSER FULVESCENS* WITHIN THE ST. CLAIR RIVER DELTA, MICHIGAN

by

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Abstract

Historically, the St. Clair River provided ample spawning grounds for many native fish species including lake sturgeon *Acipenser fulvescens*. Anthropogenic alterations to the river's hydrology and substrate have resulted in the loss or degradation of important spawning and rearing habitat, which along with overharvest have reduced lake sturgeon populations to less than 1% of their former abundance. Recent research and management has recognized critical knowledge gaps relating to early life stages, with focused need for understanding movement patterns and habitat use of larval lake sturgeon. To assess larval drift and movement patterns, I deployed a series of D-frame drift nets and depth-stratified (i.e. surface, middle, and bottom) conical net sets in the lower St. Clair River. These surveys provided insight on the spatiotemporal distribution of larval lake sturgeon, longitudinally throughout the North and Middle channels and vertically within the water column.

From 2013-2014, 874 lake sturgeon larvae were collected. Catch per unit effort (CPUE; No. larvae/hour), total length (TL; 0.1 mm), and developmental stage (i.e. full, partial, or no yolk sac) of larvae were quantified to assess changes in catchability and growth over time (i.e. weeks) and space (i.e. river zones). Significance of differences in CPUE and developmental stage were assessed using Kruskal-Wallis nonparametric tests, followed by Dwass-Steel-Critchlow-Fligner post hoc procedure for multiple comparisons, and TL was assessed using generalized linear model two-way ANOVAs followed by Least Squares Means post hoc procedure for multiple comparisons. Results showed that larvae drifted predominantly along the river bottom and were capable of maintaining their position in the river in spite of strong currents, suggesting the nature of larval lake sturgeon drift is more active than passive, indicating that riverine habitat is important for their early survival. This information has broad implications when setting

management priorities for lake sturgeon in large river systems, by identifying the interactions and attributes important for their early survival, which help managers consider feasible management options and implement the appropriate response.

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Table of Contents

List of Tables

List of Figures

Introduction

The 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 (Becker 1983, Auer 1996, Peterson et al. 2007) and is currently listed as threatened or endangered in most states and provinces surrounding these waters (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), wherein the loss of important spawning and rearing habitat has hindered successful recovery of the species. Strategies for rehabilitating remnant populations of lake sturgeon within the Great Lakes are continuously adapting in response to new scientific data and sociocultural perspectives (CRITFC 1995, Kearney and Fetterolf 2006, LRBOI 2008). Previous lake sturgeon rehabilitation efforts focused on reproductive enhancement of the adult stage or stocking of advanced fingerlings (e.g., Lake Winnebago system, Wisconsin; Lyons and Kempinger 1992, Auer 1999, Bruch 1999), but recent research has recognized critical knowledge gaps relating to early life history (Auer 1999, Secor et al. 2002, Peterson et al. 2007). Successful rehabilitation of lake sturgeon populations requires a more thorough understanding of the movement patterns and habitat preferences of early life stages.

Environmental conditions experienced during early life stages are largely determined by timing and stream characteristics associated with parental selection of spawning sites (Kamler 2002). Lake sturgeon are passive broadcast spawners, highly selective of spawning habitat, depositing their eggs over hard rocky substrates composed of cobble, gravel, and boulders (Chiotti et al. 2008). Fertilized eggs adhere to the river substrate and incubate for an average period of 10 days (Kempinger 1988, Smith and King 2005). Embryonic and larval developmental times vary as a function of environmental (e.g., temperature and stream discharge) and maternal effects (e.g., egg size; Gillooly et al. 2002, Kamler 2002, O'Connor et al. 2007). Upon hatch, larvae actively seek refuge in deep interstitial spaces of nearby substrates (Auer and Baker 2002, Peterson et al. 2007). They remain hidden for approximately 1-2 weeks until transitioning from endogenous (i.e. yolk absorption) to exogenous feeding (Kempinger 1988, Smith and King 2005). Sturgeon larvae are negatively phototactic, disperse at night (Auer and Baker 2002, Kynard and Parker 2005, Smith and King 2005), and may drift up to several kilometers before settling on the river bottom (e.g., 26 km in 15-27 days and 45 km in 25-40 days; Auer and Baker 2002). The lower portion of some rivers (e.g., last 10 km of the Sturgeon River, Michigan) may serve as important nursery habitat for lake sturgeon during their first year of life (Auer and Baker 2002).

Densities of drifting larvae depend on the number of gravid females, quality of spawning habitat, and egg-to-larvae survival rate (Verdon et al. 2013), and may be an important factor affecting year-class strength and recruitment for lake sturgeon populations. It is during the initial period of dispersal that fish larvae are most susceptible to mortality (Paradis et al. 1996, Cowen and Sponaugle 2009). Mortality can be influenced by a combination of density-dependent (e.g., predation and competition; Garvey et al. 1994, Paradis et al. 1996) and density-independent factors (e.g., temperature and dissolved oxygen levels; Chandler and Bjornn 1988, Einum and Fleming 2000). Generally, density-independent factors are most important during early life stages, whereas density-dependent factors become important later in life (Larkin 1978). Understanding how these factors limit recruitment will contribute to successful management of the species, by identifying the interactions and attributes important for their early survival, which help managers consider feasible management options and implement the appropriate response.

Numerous studies have shown climatic and hydrological conditions to be important determinants of year-class strength for sturgeon populations. For example, Nilo et al. (1997) observed significant positive correlations between year-class strength and daily rate of increase in water temperatures for lake sturgeon populations in Ontario waters of the St. Lawrence River. Dumont et al. (2011) found a positive correlation between year-class strength and June flow rates in the Des Prairies River, Québec, with higher flows associated with the strongest cohorts. Kohlhorst et al. (1991) found a positive correlation between year-class strength and seasonal discharge for a population of white sturgeon *Acipenser transmontanus* in the estuary of the Sacramento and San Joaquin rivers, California. Variable climatic and hydrological conditions can influence year-class strength by affecting the spatiotemporal distribution of spawning, amount or quality of spawning and nursery habitat, and timing and duration of larval drift (Dumont et al. 2011).

This study focused on lake sturgeon inhabiting the St. Clair River (SCR), Michigan. Unlike many large floodplain rivers where seasonal discharge fluctuates widely (Junk et al. 1989, Bayley 1995), annual discharge for the SCR is relatively stable, with only a 22-25% difference between low and peak flows (Hondorp et al. 2014). Because of relatively stable hydrological conditions (Hondorp et al. 2014) it is unlikely that differences in discharge are an important determinant of year-class strength for lake sturgeon populations in the SCR. The SCR is part of the larger St. Clair-Detroit River System (SCDRS), a 160 km river and channel network (including Lake St. Clair and Detroit River) connecting lakes Huron to Erie (Boase et al. 2014). It supports one of the largest remnant populations of lake sturgeon in the Great Lakes

(Nichols et al. 2003). Historically, the SCDRS contained 15 reputed lake sturgeon spawning areas (Goodyear et al. 1982). However, channelization and extensive shoreline armoring have resulted in the loss or degradation of all but two areas (Goodyear et al. 1982; Nichols et al. 2003). The largest and most suitable area for lake sturgeon spawning is a natural reef in the upper SCR (i.e. Port Huron Reef, 16 ha; Nichols et al. 2003), where surface flow velocities often exceed 1 m/s (Griffiths et al. 1991). High flow velocities impede cross channel mixing, restrict sediment deposition, and contribute to short residence time (e.g., <22 hours; Hondorp et al. 2014). Another spawning area is located in the North Channel of the SCR (i.e. North Channel Reef, 0.25 ha), where coal powered steamships deposited a bed of coal cinders in the late 1800s (Baker 1980, Manny and Kennedy 2002, Nichols et al. 2003). Flow velocities decrease substantially in the delta region (e.g., North Channel, $\bar{x}=0.46\pm0.17$ SD (Table 1); Middle Channel, $\bar{x}=0.55\pm0.1$ SD (Table 2)) due to reductions in slope and expansion of surface flow area. In 2012, an artificial spawning reef consisting of rounded fieldstone and angular limestone was constructed in the Middle Channel of the SCR (i.e. Middle Channel Reef, 0.4 ha) to enhance production of native fish and restore fish spawning habitat (Michigan Sea Grant 2011). This reef was immediately utilized by spawning adult lake sturgeon and may also serve as an important refuge area for drifting larvae.

The importance of available spawning and nursery habitat to the persistence of sturgeon populations has been well established (Buckley and Kynard 1981, Parsley et al. 1993, McCabe and Tracy 1994, Gard 1996, Williot et al. 1997, Paragamian et al. 2001). However, information about the quality, quantity, and spatial distribution of riverine habitats utilized by early life stages is limited. Numerous studies document age-0 lake sturgeon utilizing riverine areas with low flow velocities and shallow water depths, composed of sand substrates that lack aquatic macrophytes and structure (Kempinger 1996, Peake 1999, Hughes 2002). Studies in larger rivers document juveniles utilizing areas with strong flow velocities and deep water depths (e.g., >9 m), composed of sand and gravel substrates intermixed with zebra mussels (Barth et al. 2009, Boase et al. 2014).

In general, the movements and habitat preferences of juveniles are less certain in large rivers due to the logistical issues associated with capturing and monitoring fish (Houston 1987, Auer 1996, Secor et al. 2002, Thomas and Haas 2002). Strategies employed to inventory juveniles in the SCR include barge electrofishing, crab trapping, drift netting, fyke netting, gillnetting, minnow trapping, set-lining, spotlighting with dip nets, and trawling. Although these strategies have largely been ineffective capturing age-0 lake sturgeon, some have reliably captured age 2-7 year-old individuals (Manny and Mohr 2013, Boase et al. 2014). Year-class strength can be assessed from these older individuals, but conditions that have detrimental effects on survivorship prior to these ages may go unnoticed or unrepresented. Understanding the behaviors and movements of larval lake sturgeon will help managers identify critical nursery habitats that warrant protection, enhancement, and/or restoration.

The main objective of this study was to assess the spatiotemporal distribution of larval lake sturgeon, longitudinally throughout the North and Middle channels and vertically within the water column. Goals of this study were to: (1) examine larval lake sturgeon drift to determine if larvae are drifting passively (i.e. free floating particles) or actively (i.e. individuals at least partially capable of controlling their movements); (2) determine the likelihood of larvae to remain in the river in spite of strong currents; and (3) determine catch per unit effort (CPUE; No. larvae/hour), the size distribution (TL, 0.1 mm), and developmental stage (i.e. full, partial, or no yolk sac) of larvae at time and location of drift. I expected larvae to drift passively in a series of pulses, moving out of the river into Lake St. Clair within a few days after emergence, indicating that riverine habitat is not important for their early survival. Regarding the size distribution and developmental stage of larvae, I expected to find smaller larvae with full yolk sacs upstream early during drift, and larger larvae with partial or no yolk sacs downstream later during drift.

Methods

Lake sturgeon larvae were collected to assess variation in catchability and growth of larvae at time and location of drift. Data collection was a collaborative effort between researchers from University of Michigan (UM) and U.S. Geological Survey (USGS). D-frame drift nets (area of opening = 0.3487 m^2, 1600 µm mesh) were used to capture larval lake sturgeon, using a sampling design similar to Auer and Baker (2002), but modified by Roseman et al. (2011a) for use in deeper waters (Fig. 1). Depth-stratified (i.e. surface, middle, bottom) conical net sets (area of opening = 0.0707 m^2, 750 µm mesh) were used to capture larval lake sturgeon, using a sampling design similar to D'Amours et al. (2001; Fig. 2). Nets were set 1 m below the river surface, 1 m above the river bottom, and halfway between bottom and surface nets. Date, GPS coordinates, water temperature (ºC), depth (m), and time fished (hours) were recorded at each sampling site. Depth and point velocity (m/s) measurements were not recorded in 2013 due to sampling limitations, but recorded for each site sampled in 2014 at surface, middle, 80%, and bottom depths over 40 second intervals using an OTT MF Pro flow meter.

Study sites were selected systematically along the North Channel (NC) and Middle Channel (MC) of the SCR, and grouped into 9 river zones based on distance (km) from the North Channel Reef (NCR) and Middle Channel Reef (MCR; Fig. 3). In 2013, 25 sites were selected (Fig. 4). NC sites were grouped into 1 zone (NU), which was located upstream of the NCR (2 sites). MC sites were grouped into 4 zones (MU, MD1, MD3, and MD4). MU was located upstream and MD1, MD3, MD4 were located downstream of the MCR (4, 5, 11, and 3 sites, respectively). In 2014, 55 sites were selected (Fig. 5). NC sites were grouped into 4 zones (NU, ND1, ND2, and ND3). NU was located upstream and ND1 and ND3 were located downstream of the NCR (2, 9, and 5 sites, respectively). ND2 was located downstream of the NCR, but was entirely within Chenal A Bout Rond (7 sites). MC sites were grouped into 5 zones (MU, MD1, MD2, MD3, and MD4). MU was located upstream and MD1, MD2, MD3, and MD4 were located downstream of the MCR (4, 5, 10, 4, and 9 sites, respectively).

Water temperatures during larval drift ranged from 12.5-20.2º C ($\bar{x}$=17±2.2 SD) in 2013 and 13.6-19.1° C ($\bar{x}$=16.3±1.9 SD) in 2014. Depths for all sites in the NC ranged from 6.8-15.1 m ($\bar{x}$=11.1±1.5 SD; Table 1). On 22 September 2014, surface velocities for all sites in the NC ranged from 0.09-0.76 m/s ($\bar{x}$=0.46±0.17 SD; Table 1), middle velocities ranged from 0.34-0.76 m/s ($\bar{x}$=0.51±0.1 SD; Table 1), 80% depth velocities ranged from 0.14-0.62 m/s ($\bar{x}$=0.44±0.1 SD; Table 1), and bottom velocities ranged from 0.02-0.52 m/s ($\bar{x}$=0.29±0.13 SD; Table 1). Depths for all sites in the MC ranged from 5.5-13.1 m ($\bar{x}$=10.4±1.8 SD; Table 2). On 22 September 2014, surface velocities for all sites in the MC ranged from 0.34-0.76 m/s ($\bar{x}$=0.55±0.1 SD; Table 2), middle velocities ranged from 0.37-0.68 m/s ($\bar{x}$=0.55±0.09 SD; Table 2), 80% depth velocities ranged from 0.37-0.74 m/s ($\bar{x}$=0.48±0.09 SD; Table 2), and bottom velocities ranged from 0.05-0.49 m/s ($\bar{x}$=0.31±0.09 SD; Table 2).

In 2013, lake sturgeon larvae were collected during 1184 total net hours of sampling, conducted from 10 June-9 July. Up to 14 drift nets (UM, 6 nets; USGS, 8 nets) were deployed over the course of a night for a total of 15 nights, and 3 depth-stratified conical net sets (USGS) were deployed over the course of a night for a total of 9 nights. In 2014, lake sturgeon larvae were collected during 4895 total net hours of sampling, conducted from 5 June-29 July. Up to

20 drift nets (UM, 12 nets; USGS, 8 nets) were deployed over the course of a night for a total of 25 nights, and 4 conical net sets (USGS) were deployed over the course of a night for a total of 16 nights. Drift nets and conical net sets fished passively from approximately 2100-0600 hours. Drift nets were generally retrieved at 3-hour intervals to prevent vegetation and *Holopedium spp.* clogging of nets, while conical net sets were retrieved only once upon completion of the soak period.

All field samples were washed with water, drained, soaked in MS-222 solution to euthanize larval fish, drained again, and preserved in 95% ethanol. Sample bottles were transported to either the USGS Great Lakes Science Center or USEPA National Vehicle and Fuel Emissions Laboratory in Ann Arbor, Michigan for sorting and processing. Larval lake sturgeon were removed from bottles, stored in separate vials, and photographed at a later date. Photographs of individual larvae were taken at 60x magnification using a microscope with digital analysis software (Image Pro Plus 7.0), TL was measured, and developmental stage was recorded. CPUE was calculated for each river zone on every night of sampling, and expressed as number of larvae collected per hour of D-frame net fished.

Significance of differences in CPUE and developmental stage were assessed using Kruskal-Wallis (KW) nonparametric tests, followed by Dwass-Steel-Critchlow-Fligner (DSCF) post hoc procedure for multiple comparisons (Hollander and Wolfe 1999; α=0.05). KW tests compared the median values of all channel-wise zones, and the DSCF procedure compared the median values of all possible combinations of channel-wise zones. These analyses were performed using Systat 13 software. Significance of differences in larval size was assessed using generalized linear model (GLM) two-way ANOVAs, followed by the Least Squares Means (LS-means) post hoc procedure for multiple comparisons. These analyses were performed using R statistical software (R Core Team 2013).

Results

CPUE variation

From 2013-2014, 874 lake sturgeon larvae were collected. Of larvae collected in 2013, 161 were captured in D-frame nets and 6 in conical net sets. Of larvae collected in 2014, 680 were captured in D-frame nets and 27 in conical net sets. No statistics could be done on these collections because they were not standardized by effort, providing an inherently biased assessment of changes in drift density. CPUE of larval lake sturgeon was quantified to reflect changes in larval abundance and catchability, among channel-wise zones (i.e. upstream and downstream of spawning reefs) across each week of larval drift (Fig. 6-7).

In 2013, larval sturgeon first appeared in D-frame samples on 13 June, peaked during the week of 13 June, remained at moderate levels in late June and early July, and were no longer detected after 9 July (Fig. 8). Sturgeon larvae were collected above and below the MCR, but mean CPUE was usually highest at MU, followed by MD1, MD4, and MD3 (Table 3). Differences in CPUE were statistically significant between all river zones in the MC (KW, T=9.348, P<0.05, DF=3), and were statistically significant for all pairwise comparisons of river zones except MD1 and MU (DSCF, P=0.952; Table 4). Differences in CPUE could not be tested statistically in the NC because only NU was sampled.

Mean CPUE was higher in 2014 than 2013, especially during peak drift. In 2014, larval sturgeon first appeared in D-frame samples on 10 June, peaked during the week of 17 June, remained at moderate levels in late June and early July, and were no longer detected after 21 July (Fig. 9). Sturgeon larvae were collected above and below the MCR, but mean CPUE was almost always higher for upstream than downstream zones (Table 5). Sturgeon larvae were also collected above and below the NCR, but mean CPUE was almost always higher for upstream than downstream zones (Table 6). Mean CPUE was higher in the NC than MC and generally declined with distance downstream from spawning reefs (Table 5-6). Differences in CPUE were not statistically significant between all river zones in the MC (KW, T=9.015, P=0.061, DF=4) or NC (KW, T=1.385, P=0.709, DF=3).

Larval size and developmental stage

Lengths of larval lake sturgeon were measured to reflect changes in growth, among channel-wise zones (i.e. upstream and downstream of spawning reefs) across each week of larval drift. For all collections of larval lake sturgeon from the MC in 2013, TL values ranged from 14.6-25.1 mm ($\bar{x}$=19±2.1 SD; Fig. 10). Overall, TL values were significantly different between zones (GLM, P<0.001) and weeks (GLM, P<0.001) sampled, but there was no significant interaction between zone and week (Table 7). During week 3 of larval drift, larvae collected downstream were generally larger than those collected in upstream zones, but at other times there were no significant differences in size between zones. During week 1 of larval drift, TL values ranged from 15.6-20.6 mm ($\bar{x}$=17.9±1.2 SD), but were not significantly different between zones (Table 8). During week 2 of larval drift, TL values ranged from 16.4-22.5 mm ($\bar{x}$=19.5±1.4 SD), but were not significantly different between zones (Table 8). During week 3 of larval drift, TL values ranged from 14.6-25.1 mm ($\bar{x}$=19.2±3.1 SD), and were significantly smaller in MD1 than MD3 (LS-means, P<0.001), MD1 than MD4 (LS-means, P<0.001), and MU than MD4 (LS-means, P<0.05; Table 8). During week 4 of larval drift, TL values ranged from 18-22.9 mm ($\bar{x}$=20.6±1.9 SD), but were not significantly different between zones (Table 8).

For all collections of larval lake sturgeon from the MC in 2014, TL values ranged from 11.3-31.3 mm ($\bar{x}$=18.1±2.4 SD; Fig. 11). Overall, TL values were significantly different between zones (GLM, $P<0.05$) and weeks (GLM, $P<0.001$) sampled, and there was a significant interaction between zone and week (GLM, $P<0.05$; Table 9). During week 3 of larval drift, larvae collected downstream were generally smaller than those collected in upstream zones, but at other times there were no significant differences in size between zones. During week 1 of larval drift, TL values ranged from 11.3-17 mm ($\bar{x}$=14.8±1.5 SD), but were not significantly different between zones (Table 10). During week 2 of larval drift, TL values ranged from 14.4-22.4 mm ($\bar{x}$=18.2±1.8 SD), but were not significantly different between zones (Table 10). During week 3 of larval drift, TL values ranged from 13.6-24 mm ($\bar{x}$=18.2±2.5 SD), and were significantly larger in MD2 than MD3 (LS-means, $P<0.05$; Table 10). During week 4 of larval drift, TL values ranged from 12.7-23 mm ($\bar{x}$=19.1±2.2 SD), but were not significantly different between zones (Table 10). During week 5 of larval drift, TL values ranged from 16.1-31.3 mm ($\bar{x}$=19.7±3.6 SD), but were not significantly different between zones (Table 10).

For all collections of larval lake sturgeon from the NC in 2014, TL values ranged from 11.4-24.5 mm ($\bar{x}$=18.2±2.1 SD; Fig. 12). Overall, TL values were significantly different between zones (GLM, $P<0.001$) and weeks (GLM, $P<0.001$) sampled, and there was a significant interaction between zone and week (GLM, $P<0.05$; Table 11). During week 1 of larval drift, larvae collected downstream were generally smaller than those collected in upstream zones. During week 2 of larval drift, sizes of larvae were more variable between upstream and downstream zones. At other times, there were no significant differences in size between zones. During week 1 of larval drift, TL values ranged from 11.4-17.4 mm ($\bar{x}$=15.4±1.8 SD), and were significantly smaller in ND1 than NU (LS-means, $P<0.05$; Table 12). During week 2 of larval drift, TL values ranged from 12.8-21.9 mm ($\bar{x}$=17.6±1.6 SD), and were significantly smaller in ND1 than NU (LS-means, $P<0.05$), ND2 than ND1 (LS-means, $P<0.001$), ND2 than NU (LS-means, $P<0.001$), and ND2 than ND3 (LS means, $P<0.05$; Table 12). During week 3 of larval drift, TL values ranged from 13.8-24.5 mm ($\bar{x}$=20.2±1.8 SD), but were not significantly different between zones (Table 12). During week 4 of larval drift, TL values ranged from 18.4-22.2 mm ($\bar{x}$=20.2±1.7 SD). During week 5 of larval drift, TL values ranged from 18.3-21.9 mm ($\bar{x}$=20.1±1.8 SD). During week 6 of larval drift, only 1 larva was captured with a TL value of 21.7 mm. No differences were observed during weeks 4-6 because NU was the only zone sampled.

Developmental stages of larval lake sturgeon were recorded to reflect changes in growth, among channel-wise zones (i.e. upstream and downstream of spawning reefs) across each week of larval drift. Of 54 larvae collected upstream of the MCR in 2013, I observed full yolk sacs in 16.7%; partial yolk sacs in 27.8%; and no yolk sacs in 55.6% (Fig. 13). Of 61 larvae collected downstream of the MCR, I observed full yolk sacs in 14.8%; partial yolk sacs in 27.9%; and no yolk sacs in 57.4% (Fig. 13). Differences in developmental stage of larvae were not statistically significant between all river zones in the MC (KW, T=0.818, P=0.845, DF=3). Differences in developmental stage of larvae could not be tested statistically in the NC because only NU was sampled.

Of 152 larvae collected upstream of the MCR in 2014, I observed full yolk sacs in 34.9%; partial yolk sacs in 37.5%; no yolk sacs in 26.3%; and 1.3% were unknown due to damage (Fig. 14). Of 144 larvae collected downstream of the MCR, I observed full yolk sacs in 13.2%; partial yolk sacs in 56.3%; and no yolk sacs in 30.6% (Fig. 14). Differences in developmental stage of larvae were statistically significant between all river zones in the MC (KW, T=12.116, $P<0.05$, *DF*=4), and were statistically significant for all pairwise comparisons of river zones (DSCF, *P*<0.001; Table 13). Although these differences were significant, there was no observable pattern in the distribution of larvae with full, partial, or no yolk sacs between upstream and downstream zones.

Of 178 larvae collected upstream of the NCR in 2014, I observed full yolk sacs in 23%; partial yolk sacs in 47.2%; no yolk sacs in 29.2%; and 0.6% were unknown due to damage (Fig. 15). Of 233 larvae collected downstream of the NCR, I observed full yolk sacs in 3.9% of larvae; partial yolk sacs in 75.5% of larvae; and no yolk sacs in 20.6% of larvae (Fig. 15). Differences in developmental stage of larvae were statistically significant between all river zones in the NC (KW, *T*=27.371, *P*<0.001, *DF*=3), and were statistically significant for all pairwise comparisons of river zones except ND1 and NU (DSCF, *P*=0.980; Table 14). More larvae with partial or no yolk sacs were found in downstream than upstream zones, and more larvae with full yolk sacs were found in upstream than downstream zones.

Discussion

This study provides a detailed assessment of larval lake sturgeon drift within the lower SCR. Statistical analyses showed significant differences in CPUE, TL, and developmental stage of larvae across time (i.e. weeks) and space (i.e. river zones), but did not explain the biotic or abiotic factors underlying these differences. Examining trends in biological terms helps to answer important questions regarding lake sturgeon early life history, such as: *Do larvae drift passively or actively? What is the likelihood of larvae to remain in the river in spite of strong currents? What habitats are utilized by age-0 fish? What is the size distribution and developmental stage of larvae at time and location of drift?* I expected larvae to drift in a series of pulses, hatching in some synchrony and moving out of the river into Lake St. Clair within a few days after emergence. Although I never observed a large pulse of larvae moving through the lowermost river zones, I did capture a few larvae at sites <0.75 km upstream of Lake St. Clair, indicating that some larvae may settle out near the river mouth or move out into Lake St. Clair. The majority of larvae were not found near the river mouth at any time, but appeared to maintain their location in the river in spite of strong currents, suggesting the nature of larval lake sturgeon drift is more active than passive, and riverine habitat is important for their early survival. Additionally, I expected to find smaller larvae with full yolk sacs upstream early during drift and larger larvae with partial or no yolk sacs downstream later during drift. Instead, I found a mixture of larvae of different sizes and developmental stages to occupy the uppermost river zones, which further suggests that larvae are utilizing upper riverine areas as nursery habitat.

I only observed 1 spawning peak during both years of sampling. Adult lake sturgeon may spawn in multiple peaks in a single river system (e.g., 2-4; Kempinger 1988, LaHaye et al. 1992) and spawn multiple days for each peak (Forsythe 2010). Eggs develop similarly, but not exactly at the same rate (e.g., larger eggs may require more time for embryonic development; Pepin et al. 1997, Gillooly and Dodson 2000), so hatching will add more variance to the peaks identified above. Upon hatch, larvae may successfully hide in the reef or be dislodged from substrate by strong currents (Elliot 1987, Kynard et al. 2007). The former would have larger sizes and smaller yolk sacs and the latter would have smaller sizes and larger yolk sacs. Therefore, larvae should exhibit full yolk sacs early during drift and partial or no yolk sacs later during drift, with some overlap resulting from different peaks. As larvae drift, they may choose to remain in a suitable habitat if they can (Duong et al. 2011), be eaten by a predator, or continue to drift. If larvae are washed out, they may quickly depart the river. If larvae settle regularly in search of suitable habitat, they may stay longer, perhaps indefinitely. At any given time, larvae in the drift may represent fish from different spawning peaks with different drift histories, and those that were not eaten.

I observed four major trends in CPUE of larval lake sturgeon during both years of sampling: (1) CPUE peaked during mid to late June and was lower before and after; (2) larvae were collected upstream and downstream of spawning reefs; (3) CPUE was almost always higher for zones upstream than downstream of spawning reefs; and (4) CPUE generally declined with distance downstream from spawning reefs. Bouckaert et al. (2014) showed similar trends in CPUE as 1-3 listed above for larval lake sturgeon collected from the SCR in 2012, but CPUE did not generally decline with distance downstream from spawning reefs. Peaks in larval drift either represent peaks in egg laying and hatching or peaks in dispersal. The former would show up as high numbers of younger larvae near spawning reefs. The latter would show up as smaller groups of larger larvae intermixed with younger larvae at spawning reefs, indicating larvae are drifting in a series of pulses. Differences in the number of peaks between years may be attributed to variation in annual reproductive spawning success. For example, Bouckaert et al. (2014) estimated variable egg densities for lake sturgeon in 2010, 2011, and 2012 (490, 1,726, and 50-222 eggs/m^2, respectively). Declines in CPUE with distance downstream from spawning reefs may be attributed to larvae remaining in the drift or factors affecting larval survival (described in more detail later on), which may reflect variability of year-class strength (Smith and King 2005).

The timing of larval emergence and dispersal from spawning areas may depend on environmental factors such as water temperature or river discharge, larval age or size (Elliot 1987, Day and Rowe 2002), larval behavior (Shanks 2009), lunar cues (Hernandez-Leon 2008) and adult spawning behavior (Copp et al. 2002, Hogan and Mora 2005, Shanks 2009). In 2013, I observed larvae dispersing at 14.6-25.1 mm TL ($\bar{x}$=19±2.1 SD) in the MC and 11.4-23.7 mm TL ($\bar{x}$=17.7±2.7 SD) in the NC. In 2014, I observed larvae dispersing at 11.3-31.3 mm TL ($\bar{x}$=18.1±2.4 SD) in the MC and 11.4-24.5 mm TL ($\bar{x}$=18.2±2.1 SD) in the NC. LaHaye et al. (1992) observed larvae dispersing at 13 mm TL in the Des Prairies and L'Assomption rivers, Québec. Roseman et al. (2011b) observed larvae dispersing at 17-20 mm TL in the SCR. Smaller larvae may disperse shorter distances than larger larvae because they have lower levels of endogenous yolk sac reserves, although dispersal distance may vary as a function of genotype, conditions experienced during embryonic development, and the availability or distribution of substrates of different sizes (Hastings et al. 2013). I observed two major trends relating to the size distribution of larvae during both years of sampling: (1) sizes of larvae generally increased as drift progressed (i.e. week to week); and (2) sizes of larvae were variable between upstream and downstream zones. Trend 1 reflects growth of larvae during drift or slower drift by larger larvae. Trends 2 may reflect a combination of the different factors listed above, and possibly size selective predation, meaning smaller larvae were eaten first, and thus were not observed in the lowermost river zones.

I observed three major trends relating to larval development during both years of sampling: (1) higher proportions of drifting larvae with full yolk sacs upstream of spawning reefs; (2) higher proportions of drifting larvae with partial yolk sacs downstream of spawning reefs; and (3) higher proportions of drifting larvae with no yolk sacs downstream of the MCR, but upstream of the NCR in 2014. Trend 1 may reflect continual emergence of larvae from natural spawning habitat upstream of the two targeted spawning reefs (i.e. NCR and MCR). The Port Huron Reef is the largest natural sturgeon spawning area in the SCR. Collection of yolk sac larvae upstream of targeted spawning reefs may reflect larvae from the Port Huron Reef getting flushed out into the delta region by swift currents. However, it is unlikely that these yolk sac larvae originated from the Port Huron Reef because they would not have enough energy reserves to travel such a distance, nor would they need to because suitable habitat likely exists closer to that reef. It is possible that these larvae originated from isolated pockets of spawning habitat somewhere along the 65 km of riverine habitat between the Port Huron Reef and targeted spawning reefs, although these areas have not yet been identified. Trend 2 may reflect factors forcing larvae out of the substrate (e.g., predation, competition, or disturbances) or larvae transitioning from endogenous to exogenous feeding. Trend 3 may reflect larger larvae moving greater distances in search of suitable nursery habitat or larger larvae settling at reef locations. Bouckaert et al. (2014) showed different trends relating to larval development in the SCR: (1) higher proportions of drifting larvae with full yolk sacs downstream than upstream of spawning reefs; (2) higher proportions of drifting larvae with partial yolk sacs downstream than upstream of the NCR in 2011, but upstream than downstream of the MCR in 2012; and (3) higher proportions of drifting larvae with no yolk sacs upstream than downstream of spawning reefs. Observed differences between studies may be attributed to unequal sample sizes (54, 116, 167, and 707 larvae collected in 2011, 2012, 2013, and 2014, respectively), potentially obscuring trends.

One possible explanation for differences in larval abundance between river zones (i.e. upstream and downstream of spawning reefs) is increased mortality rates (Crossman and Hildebrand 2014). The most vulnerable stage for lake sturgeon is the time between hatch and growth to 25 cm TL (Auer and Baker 2002). During this period, larval lake sturgeon are small and only have behavioral defense mechanisms against predation. At 40 cm TL, larvae begin to develop protective bony scutes and become more efficient swimmers (Auer and Baker 2002).

The impacts of predation on early life stages of lake sturgeon are not well understood and few studies have documented predation in natural systems (Caroffino et al. 2010). Studies conducted in the Wolf River, Wisconsin, St. Clair River, and Black River, Michigan verified consumption of lake sturgeon eggs by fish and benthic macroinvertebrates (Kempinger 1988, Nichols et al. 2003, Forsythe et al. 2013). These studies made no attempt to examine the effects of predation on larvae or juveniles (Caroffino et al. 2010). The present lack of studies of predation on early life stages may be attributed to the inherent difficulties associated with quantifying descriptions of predator diets for relatively rare prey. Also, some prey may be digested rapidly and leave little trace in the digestive tract (Bowen 1983). Only a single study has attempted to quantify sources of predation that affect lake sturgeon eggs, larvae, and juveniles. Caroffino et al. (2010) used barge electrofishing, fyke nets, and gill nets to capture potential predators of larvae and juveniles in the Peshtigo River, Wisconsin. Of the 862 fish stomachs from 22 species examined, only a single sturgeon larva was found.

A second possible explanation for differences in larval abundance between river zones is non-uniform distribution of larvae over time and space. When sturgeon larvae drift, they have potential to move across the width of the channel and vertically within the water column (Smith and King 2005). For example, D-frame drift nets were deployed in pairs at multiple cross-sectional areas of the river during both years of sampling. Larvae were collected almost everywhere, indicating they are capable of moving across the width of the channel. Additionally, of all larvae captured in conical net sets in 2013, 100% of the captures were in bottom nets, whereas in 2014, 88.9% of captures were in bottom nets. Since the majority of the larvae captured were collected in D-frame nets, which are designed to fish the river bottom (Roseman et al. 2011a), and few larvae were captured higher up in the water column, dispersal within the water column is likely a rare occurrence. This indicates that sturgeon larvae choose to remain near the bottom while drifting, rather than passively being mixed by water currents. Kempinger (1988) also found that sampling along the bottom at night resulted in the collection of most drifting larvae.

A third possible explanation for differences in larval abundance between river zones is that larvae are utilizing upper riverine areas as nursery habitat, so the number drifting declines with distance downstream. Larval retention should be affected by riverbed structure, hydrodynamics, and larval behavior. For example, larvae of some fish species can actively adjust their swimming speed to flow conditions, swimming more slowly or remaining in substrates during high flows (Hogan and Mora 2005). Riverbed structure in the delta portion of the NC is characterized by deep water depths, clay ledges, and gravel substrates, surrounded by shifting sand deposits (Boase et al. 2005, Boase et al. 2014). Artificial spawning reefs (e.g., NCR and MCR) increase substrate complexity and the amount of interstitial spaces available to fish eggs and larvae (Crossman and Hildebrand 2014), positively affecting embryo size at hatch, larval emergence, and larval size of multiple species (Tappel and Bjornn 1983, Young et al. 1990, Lisle and Lewis 1992, Merz and Setka 2004). Increased substrate complexity may have positive indirect effects on other habitat characteristics like abundance of macroinvertebrates (Merz and Ochikubo Chan 2005), and numerous studies have shown early life stages of lake sturgeon to feed predominantly on ephemeropteran and dipteran larvae (Choudhury et al. 1996, Kempinger 1996, Chiasson et al. 1997, Beamish et al. 1998). The lake sturgeon is a long-lived and highly migratory fish species, and as such, may encounter a number of potential barriers as they grow and mature into spawning adults. Habitat connectivity between main river channels, bays, and river mouths is essential for the persistence of lake sturgeon populations within the

Great Lakes, and is important to meet changing habitat requirements of fish transitioning between life stages, when faced with threats such as land use and human-induced climate change.

In this study, larval lake sturgeon were collected using passive sampling techniques (i.e. D-frame drift nets and conical net sets), which have shown to be effective capturing sturgeon larvae drifting in rivers (D'Amours et al. 2001, Auer and Baker 2002, Roseman et al. 2011a). This suggests larval lake sturgeon drift passively (i.e. free floating particles) or actively (i.e. individuals capable of fighting the current but not overcoming it). However, in a study evaluating spawning substrate enhancement for white sturgeon in a regulated river, researchers observed that larvae released at an enhanced site were better able to hide, maintain their position in substrate, and disperse by conscious choice or decision compared to larvae released at a control site (Crossman and Hildebrand 2014). Preference for enhanced substrates may reflect an abundance of food and space resources, or lack of suitable structure elsewhere. Loss of suitable fish spawning habitat in the SCR and other large rivers demonstrates the need for carefully planned and strategically placed reef enhancement projects, and monitoring drift densities of larval lake sturgeon may help identify areas with high remediation potential (Bennion and Manny 2014).

One major limitation of this study was that all river zones could not be sampled with equal amounts of effort. This limitation is significant because it creates 'holes' in the dataset, which may obscure trends. Equal amounts of effort could not be applied for the following reasons: (1) sampling would require excessive amounts of time and resources (e.g., gas, boats, gear, and field and laboratory personnel); and (2) unpredictable weather patterns make sampling difficult and dangerous, potentially rendering gear inaccessible and personnel stranded during storms.

Another major limitation was that it was difficult to determine when and where to sample. For example, prior to this study, few locations were sampled several km downstream from spawning reefs. From personal communications with USGS personnel, I was able to roughly determine when and where lake sturgeon spawning occurred, and used this information to direct my own sampling. However, given that lake sturgeon reproduction is highly variable across years, it was difficult to determine if I was sampling too early or too late. This is relevant because sampling too early can cost time and exhaust resources, and sampling too late could miss early peaks. In addition, it was difficult to determine where to deploy nets. Sampling too far downstream early during drift may lead to similar problems. Therefore, in future studies, I recommend focusing fishing effort upstream early during drift, and slowly moving nets downstream as drift progresses. Future work should also focus on determining the origin of drifting larvae, which will help identify additional spawning areas that may require protection, enhancement, and/or restoration. In addition, since efforts to capture age-0 lake sturgeon within the SCR have largely been ineffective, the development of drift and habitat suitability models will be crucial for identifying potential factors limiting juvenile recruitment.

Conclusions

Results from this study demonstrate that larval lake sturgeon in the lower St. Clair River are capable of maintaining their position in the river in spite of strong currents, suggesting the nature of larval lake sturgeon drift is more active than passive, indicating that riverine habitat is important for their early survival. Additionally, artificial reefs may provide important refuge areas for drifting larvae. Furthermore, isolated pockets of natural spawning areas likely exist upstream of the NCR and MCR, and future work should focus on identifying these areas.

Table 1. Depth (m) and velocity (m/s; surface, middle, 80%, and bottom) measurements for all sites sampled in the North Channel of the St. Clair River, recorded on 22 September 2014

		Velocity (m/s)			
Zone	Depth (m)	Surface	Middle	80%	Bottom
NU	11.2	0.62	0.6	0.48	0.41
NU	11.1	0.59	0.6	0.54	0.51
ND1	11.1	0.76	0.76	0.62	0.24
ND1	10.3	0.68	0.61	0.49	0.19
ND1	11	0.61	0.5	0.55	0.2
ND1	12.2	0.64	0.66	0.6	0.39
ND1	11.5	0.37	0.39	0.34	0.52
ND1	11.1	0.41	0.48	0.43	0.33
ND1	11.5	0.37	0.45	0.37	0.28
ND1	11.8	0.38	0.39	0.14	0.02
ND1	10.9	0.39	0.4	0.36	0.28
ND2	12.6	0.28	0.49	0.43	0.3
ND2	9.5	0.49	0.5	0.43	0.24
ND2	9.7	0.49	0.54	0.44	0.45
ND2	11.1	0.53	0.57	0.54	0.38
ND2	11.5	0.42	0.56	0.4	0.09
ND2	12.2	0.44	0.43	0.42	0.09
ND2	6.8	0.09	0.34	0.37	0.27
ND3	11.4	0.53	0.41	0.43	0.33
ND3	15.1	0.15	0.46	0.37	0.19
ND3	10.9	0.17	0.47	0.44	0.42
ND3	10	0.47	0.49	0.49	0.42
ND3	11.3	0.66	0.57	0.48	0.19
$\bar{x}$±SD	11.1±1.5	0.46±0.17	0.51±0.1	0.44±0.1	0.29±0.13

Table 2. Depth (m) and velocity (m/s; surface, middle, 80%, and bottom) measurements for all sites sampled in the Middle Channel of the St. Clair River, recorded on 22 September 2014

		Velocity (m/s)			
Zone	Depth (m)	Surface	Middle	80% Depth	Bottom
MU	10.1	0.52	0.5	0.38	0.43
MU	10.2	0.67	0.61	0.54	0.49
MU	10.5	0.7	0.68	0.66	0.4
MD1	11.7	0.76	0.68	0.74	0.37
MD1	11.1	0.49	0.64	0.53	0.35
MD1	9.2	0.56	0.62	0.57	0.42
MD1	12.5	0.6	0.67	0.6	0.4
MD1	10.5	0.61	0.64	0.51	0.34
MD2	7	0.39	0.49	0.43	0.27
MD2	12.6	0.54	0.67	0.64	0.3
MD2	11.6	0.64	0.57	0.48	0.18
MD2	11.7	0.61	0.66	0.52	0.27
MD2	12.7	0.62	0.63	0.51	0.28
MD2	12	0.51	0.49	0.49	0.28
MD2	11.5	0.59	0.56	0.37	0.31
MD2	10	0.6	0.62	0.58	0.36
MD2	10.3	0.54	0.51	0.46	0.05
MD2	10.2	0.6	0.52	0.48	0.19
MD3	8.5	0.4	0.42	0.41	0.27
MD3	13.1	0.55	0.52	0.41	0.22
MD3	11.4	0.59	0.52	0.39	0.35
MD3	10.6	0.34	0.45	0.4	0.34
MD4	11.9	0.45	0.46	0.37	0.28
MD4	11.6	0.38	0.43	0.43	0.26
MD4	11.2	0.5	0.47	0.39	0.32
MD4	9.3	0.46	0.54	0.49	0.33
MD4	7.7	0.46	0.52	0.47	0.35
MD4	8.3	0.56	0.59	0.47	0.28
MD4	8.4	0.52	0.48	0.41	0.31
MD4	5.5	0.37	0.37	0.39	0.22
MD4	8	0.59	0.54	0.49	0.38
$\bar{x}$±SD	10.4±1.8	0.54±0.1	0.55±0.09	0.48±0.09	0.31±0.09

Table 3. Catch per unit effort (CPUE; No. larvae/hour) of all larval lake sturgeon collected from the Middle Channel of the St. Clair River using D-frame drift nets in 2013 (0 = sampling, but no catch; - = no collection made)

Date	MU	MD1	MD3	MD4
10-Jun	0	0	-	-
13-Jun	0	0	0	-
17-Jun	-	-	0	-
18-Jun	0.6	0.12	0.1	0.07
19-Jun	0.47	0.33	0.02	-
20-Jun	0.54	0.29	0.07	0
24-Jun	0.23	0.08	0.08	-
25-Jun	-	-	0	0.07
26-Jun	0.15	0.16	0.05	-
27-Jun	0.36	0.32	-	-
30-Jun	-	-	0.07	0.06
1-Jul	0.05	0.1	0.09	-
2-Jul	0.13	0.16	0	0.04
8-Jul	0.05	0.12	-	-
9-Jul	0.05	0.05	-	-
$\bar{x}$±SD	0.22±0.22	0.14±0.11	0.04±0.04	0.05±0.03

Table 4. Significance of differences in catch per unit effort (CPUE; No. larvae/hour) of larval lake sturgeon collected from the Middle Channel of the St. Clair River using D-frame drift nets, for all channel-wise comparisons of river zones sampled in 2013 (*P*-value from Dwass-Steel-Critchlow-Fligner analysis)

Zone (i)	CPUE (No. larvae/hour) $\bar{x}$±SD (i)	Zone (j)	CPUE (No. larvae/hour) $\bar{x}$±SD (j)	*P*-value
MD1	0.14±0.11	MD3	0.04±0.04	<0.001
MD1	0.14±0.11	MD4	0.05±0.03	<0.001
MD1	0.14±0.11	MU	0.22±0.22	0.952
MD3	0.04±0.04	MD4	0.05±0.03	<0.001
MD3	0.04±0.04	MU	0.22±0.22	<0.001
MD4	0.05±0.03	MU	0.22±0.22	<0.001

Table 5. Catch per unit effort (CPUE; No. larvae/hour) of all larval lake sturgeon collected from the Middle Channel of the St. Clair River using D-frame drift nets in 2014 (0 = sampling, but no catch; - = no collection made)

Date	MU	MD1	MD2	MD3	MD4
8-Jun	-	-	-	0	0
10-Jun	0.13	0.04	-	0	0
11-Jun	-	-	-	0	0
12-Jun	0.09	0.24	-	0	0
13-Jun	-	-	0.08	-	-
15-Jun	-	-	-	0	0
16-Jun	0.14	0.14	-	0.08	0
17-Jun	-	-	-	0	0
18-Jun	0.59	0.43	0.74	-	-
19-Jun	0.96	0.29	0.88	-	-
20-Jun	-	-	-	-	-
23-Jun	0.71	0.32	-	-	0.04
24-Jun	-	-	0.2	0	-
25-Jun	0.88	0.46	-	0.47	0.04
26-Jun	1.21	0.5	-	-	0.02
28-Jun	-	-	0.17	-	-
30-Jun	0.43	0.37	-	-	-
1-Jul	-	-	-	0.09	0
2-Jul	0.16	0.09	-	-	-
7-Jul	0.36	0.48	-	-	-
9-Jul	0.26	0.27	-	-	-
14-Jul	0.14	0	-	-	-
21-Jul	0	0	-	-	-
$\bar{x}$±SD	0.43±0.38	0.26±0.18	0.41±0.37	0.06±0.15	0.01±0.02

Table 6. Catch per unit effort (CPUE; No. larvae/hour) of all larval lake sturgeon collected from the North Channel of the St. Clair River using D-frame drift nets in 2014 (0 = sampling, but no catch; - = no collection made)

Date	NU	ND1	ND2	ND3
8-Jun	-	-	-	-
10-Jun	0.23	0.02	-	-
11-Jun	-	0	-	-
12-Jun	0.21	0	-	-
13-Jun	-	-	-	-
15-Jun	-	-	-	-
16-Jun	1.23	-	-	-
17-Jun	-	0.61	-	-
18-Jun	4.67	0.23	-	-
19-Jun	2.32	1.48	-	-
20-Jun	-	0.96	-	-
23-Jun	1.71	0.91	-	0.27
24-Jun	-	0.52	2.45	0
25-Jun	1.26	0.79	2.34	0.13
26-Jun	1.33	-	0.12	0
28-Jun	-	-	-	-
30-Jun	0	0.15	0.22	-
1-Jul	-	-	-	-
2-Jul	0.2	-	-	-
7-Jul	0.14	-	-	-
9-Jul	0.21	-	-	-
14-Jul	0	-	-	-
21-Jul	0.07	-	-	-
$\bar{x}$±SD	0.97±1.3	0.52±0.49	1.28±1.29	0.1±0.13

Table 7. Significance of differences in total length values of larval lake sturgeon collected from the Middle Channel of the St. Clair River using D-frame drift nets, for river zones sampled during each week of drift in 2013 (*P*-value from general linearized model two-way ANOVA)

X-variable	Y-variable	*DF*	*F*-value	*P*-value
Zone	Total length	3	7.437	<0.001
week	Total length	3	6.426	<0.001
Zone:week	Total length	7	1.692	0.119

Table 8. Significance of differences in total length values of larval lake sturgeon collected from the Middle Channel of the St. Clair River using D-frame drift nets, for all channel-wise comparisons of river zones sampled in 2013 (*P*-value from general linearized model LS-means post hoc test)

Week	Zone (i)	$\bar{x}$±SD (i)	Zone (j)	$\bar{x}$±SD (j)	*P*-value
1	MD1	17.9±1.3	MD3	18.1±0.7	0.999
1	MD1	17.9±1.3	MD4	19.9±0.8	0.535
1	MD1	17.9±1.3	MU	17.6±1.2	0.984
1	MD3	18.1±0.7	MD4	19.9±0.8	0.674
1	MD3	18.1±0.7	MU	17.6±1.2	0.978
1	MD4	19.9±0.8	MU	17.6±1.2	0.373
2	MD1	19.2±1.4	MD3	20.1±1.3	0.672
2	MD1	19.2±1.4	MD4	20.9±1.6	0.651
2	MD1	19.2±1.4	MU	19.1±1.3	1
2	MD3	20.1±1.3	MD4	20.9±1.6	0.955
2	MD3	20.1±1.3	MU	19.1±1.3	0.522
2	MD4	20.9±1.6	MU	19.1±1.3	0.591
3	MD1	17.5±2.5	MD3	21.6±1.7	<0.001
3	MD1	17.5±2.5	MD4	22.5±1.4	<0.001
3	MD1	17.5±2.5	MU	19.1±3.4	0.157
3	MD3	21.6±1.7	MD4	22.5±1.4	0.908
3	MD3	21.6±1.7	MU	19.1±3.4	0.051
3	MD4	22.5±1.4	MU	19.1±3.4	<0.05
4	MD1	21.2±1.7	MU	19.7±2.4	0.82

Table 9. Significance of differences in total length values of larval lake sturgeon collected from the Middle Channel of the St. Clair River using D-frame drift nets, for river zones sampled during each week of drift in 2014 (*P*-value from general linearized model two-way ANOVA)

X-variable	Y-variable	*DF*	*F*-value	*P*-value
Zone	Total length	4	2.613	<0.05
week	Total length	4	16.504	<0.001
Zone:week	Total length	9	2.078	<0.05

Table 10. Significance of differences in total length values of larval lake sturgeon collected from the Middle Channel of the St. Clair River using D-frame drift nets, for all channel-wise comparisons of river zones sampled in 2014 (*P*-value from general linearized model LS-means post hoc test)

Week	Zone (i)	x̅±SD (i)	Zone (j)	x̅±SD (j)	*P*-value
1	MD1	15±1.5	MD2	15.5±0	0.999
1	MD1	15±1.5	MD3	15.5±0.6	0.999
1	MD1	15±1.5	MU	14.4±1.6	0.97
1	MD2	15.5±0	MD3	15.5±0.6	1
1	MD2	15.5±0	MU	14.4±1.6	0.987
1	MD3	15.5±0.6	MU	14.4±1.6	0.966
2	MD1	19±1.7	MD2	17.6±0.9	0.092
2	MD1	19±1.7	MU	18.1±2	0.429
2	MD1	19±1.7	MD4	20.5±0.7	0.89
2	MD2	17.6±0.9	MU	18.1±2	0.797
2	MD2	17.6±0.9	MD4	20.5±0.7	0.357
2	MU	18.1±2	MD4	20.5±0.7	0.551
3	MD1	18.7±2.5	MD2	19.4±1.4	0.898
3	MD1	18.7±2.5	MD3	16.5±1.2	0.118
3	MD1	18.7±2.5	MU	17.8±2.7	0.365
3	MD1	18.7±2.5	MD4	19.5±3.1	0.99
3	MD2	19.4±1.4	MD3	16.5±1.2	<0.05
3	MD2	19.4±1.4	MU	17.8±2.7	0.099
3	MD2	19.4±1.4	MD4	19.5±3.1	1
3	MD3	16.5±1.2	MU	17.8±2.7	0.573
3	MD3	16.5±1.2	MD4	19.5±3.1	0.428
3	MU	17.8±2.7	MD4	19.5±3.1	0.815
4	MD1	19.5±1.6	MD3	23±0	0.532
4	MD1	19.5±1.6	MU	18.4±2.5	0.732
4	MD3	23±0	MU	18.4±2.5	0.251
5	MD1	19.1±1.4	MU	20.2±4.8	0.844

Table 11. Significance of differences in total length values of larval lake sturgeon collected from the North Channel of the St. Clair River using D-frame drift nets, for river zones sampled during each week of drift in 2014 (*P*-value from general linearized model two-way ANOVA)

X-variable	Y-variable	*DF*	*F*-value	*P*-value
Zone	Total length	3	10.875	<0.001
week	Total length	4	71.717	<0.001
Zone:week	Total length	4	4.167	<0.05

Table 12. Significance of differences in total length values of larval lake sturgeon collected from the North Channel of the St. Clair River using D-frame drift nets, for all channel-wise comparisons of river zones sampled in 2014 (*P*-value from general linearized model LS-means post hoc test)

Week	Zone (i)	$\bar{x}$±SD (i)	Zone (j)	$\bar{x}$±SD (j)	*P*-value
1	ND1	11.4±0	NU	15.6±1.6	<0.05
2	ND1	17.4±1.5	NU	18.1±1.5	<0.05
2	ND1	17.4±1.5	ND2	15.3±1.4	<0.001
2	ND1	17.4±1.5	ND3	19.4±2.1	0.32
2	NU	18.1±1.5	ND2	15.3±1.4	<0.001
2	NU	18.1±1.5	ND3	19.4±2.1	0.691
2	ND2	15.3±1.4	ND3	19.4±2.1	<0.05
3	ND1	20.5±1.4	NU	20.5±2.1	1
3	ND1	20.5±1.4	ND2	19.7±1.8	0.307
3	ND1	20.5±1.4	ND3	21.6±0.7	0.644
3	NU	20.5±2.1	ND2	19.7±1.8	0.2
3	NU	20.5±2.1	ND3	21.6±0.7	0.627
3	ND2	19.7±1.8	ND3	21.6±0.7	0.203

Table 13. Significance of differences in developmental stage of larval lake sturgeon collected from the St. Clair River – Middle Channel using D-frame drift nets, for all channel-wise comparisons of river zones sampled in 2014 (*P*-value from Dwass-Steel-Critchlow-Fligner analysis)

	Developmental stage (% YS)				Developmental stage (% YS)			
Zone (i)	Full (i)	Partial (i)	No (i)	Zone (j)	Full (j)	Partial (j)	No (j)	*P*-value
MD1	19.5	44.1	36.4	MD2	1.9	79.2	18.9	<0.001
MD1	19.5	44.1	36.4	MD3	30	40	30	<0.001
MD1	19.5	44.1	36.4	MD4	0	25	75	<0.001
MD1	19.5	44.1	36.4	MU	35.3	38	26.7	<0.001
MD2	1.9	79.2	18.9	MD3	30	40	30	<0.001
MD2	1.9	79.2	18.9	MD4	0	25	75	<0.001
MD2	1.9	79.2	18.9	MU	35.3	38	26.7	<0.001
MD3	30	40	30	MD4	0	25	75	<0.001
MD3	30	40	30	MU	35.3	38	26.7	<0.001
MD4	0	25	75	MU	35.3	38	26.7	<0.001

Table 14. Significance of differences in developmental stage of larval lake sturgeon collected from the North Channel of the St. Clair River using D-frame drift nets, for all channel-wise comparisons of river zones sampled in 2014 (*P*-value from Dwass-Steel-Critchlow-Fligner analysis)

	Developmental stage (% YS)				Developmental stage (% YS)			
Zone (i)	Full (i)	Partial (i)	No (i)	Zone (j)	Full (j)	Partial (j)	No (j)	*P*-value
ND1	4.5	84.3	11.2	ND2	2	50	48	<0.001
ND1	4.5	84.3	11.2	ND3	0	20	80	<0.001
ND1	4.5	84.3	11.2	NU	23.3	47.7	29	0.98
ND2	2	50	48	ND3	0	20	80	<0.001
ND2	2	50	48	NU	23.3	47.7	29	<0.001
ND3	0	20	80	NU	23.3	47.7	29	<0.001

Fig. 1 – Sampling design for D-frame drift nets used to capture larval lake sturgeon, from Roseman et al. 2011a

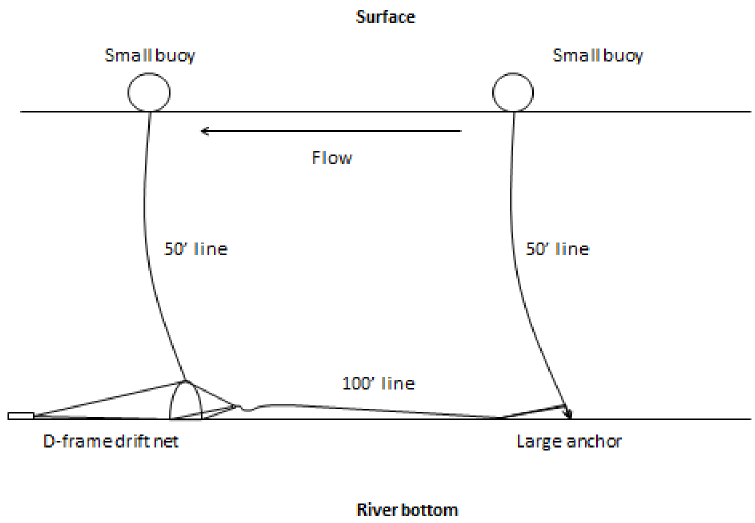


Fig. 2 – Sampling design for conical net sets used to capture larval lake sturgeon, from D'Amours et al. 2001

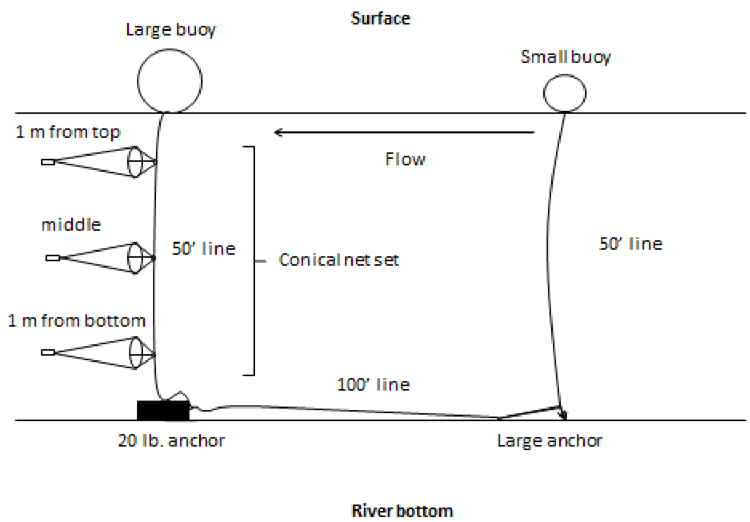


Fig. 3 – Map of the study area showing zone boundaries (pink stars = spawning reefs)

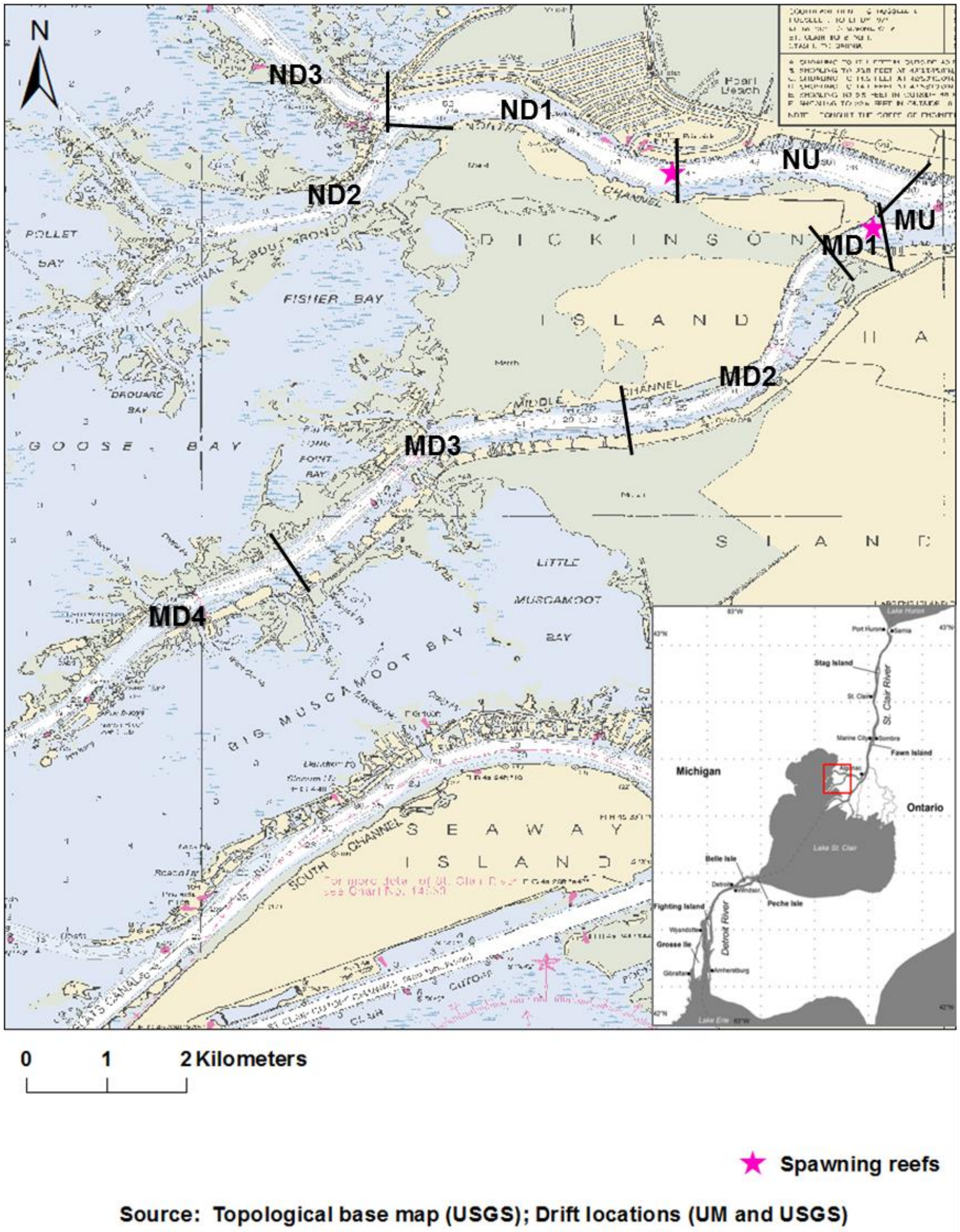
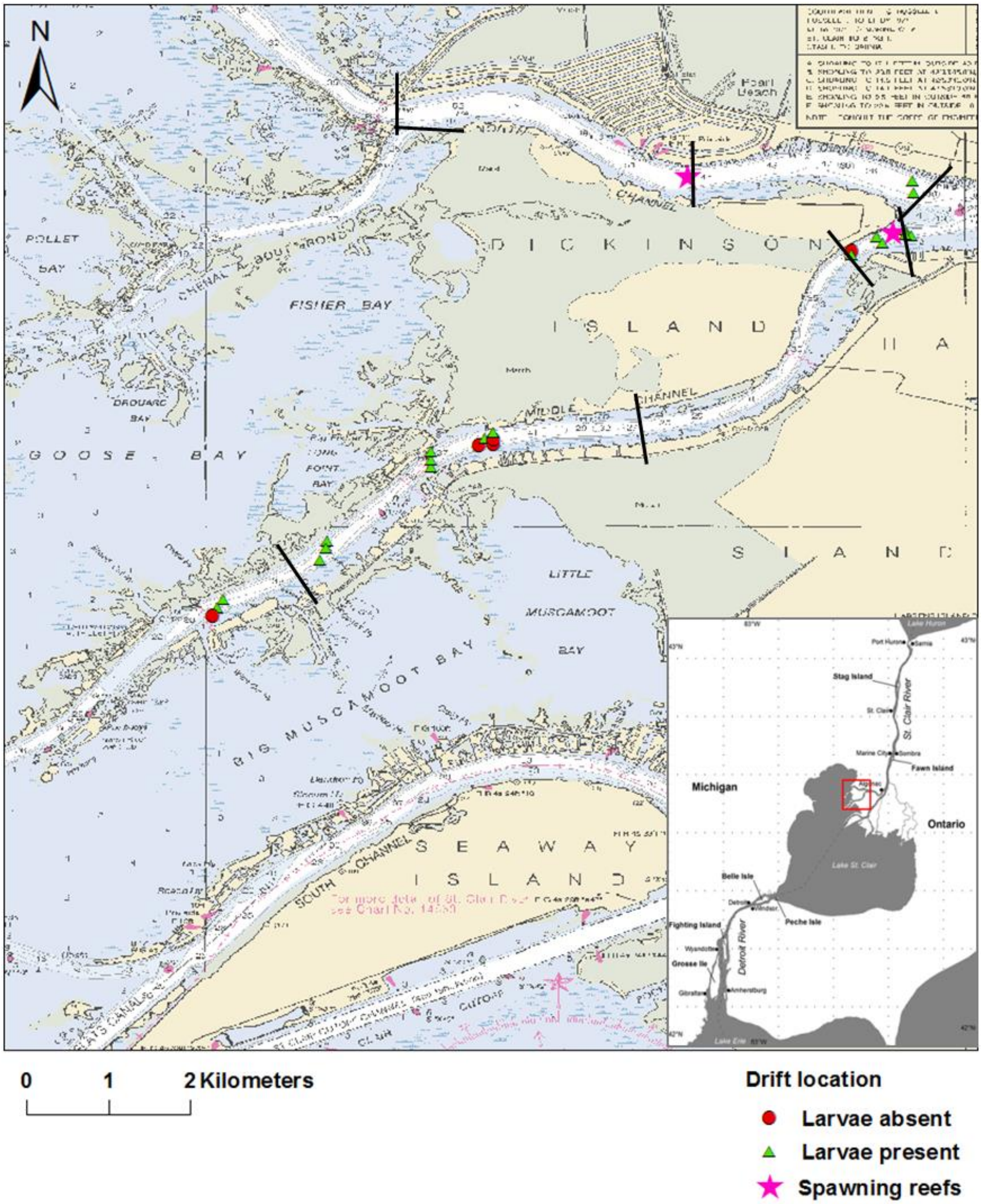
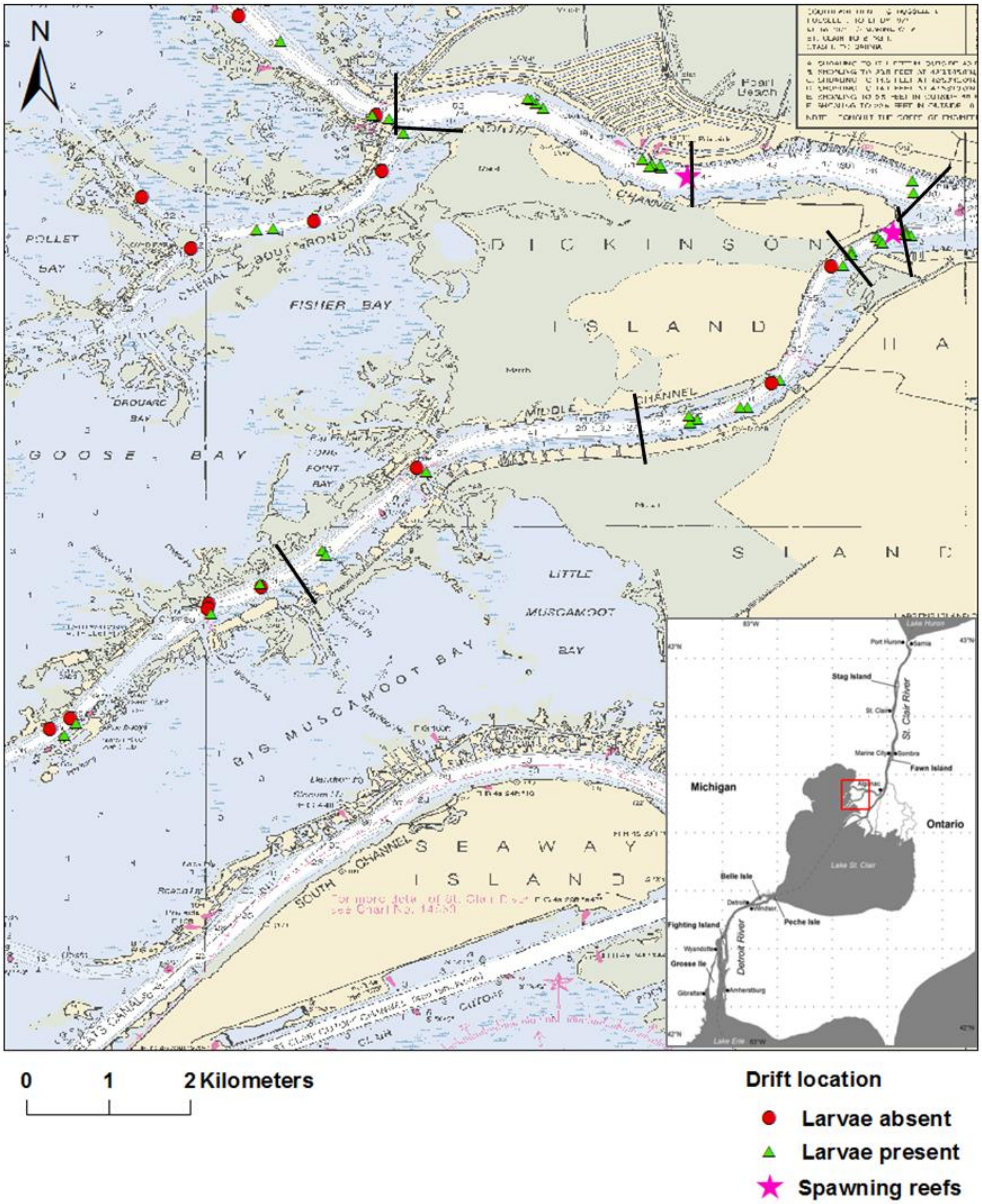


Fig. 4 – Map of the study area showing zone boundaries and sites sampled in 2013 (red circles = larvae absent, green triangles = larvae present, pink stars = spawning reefs)



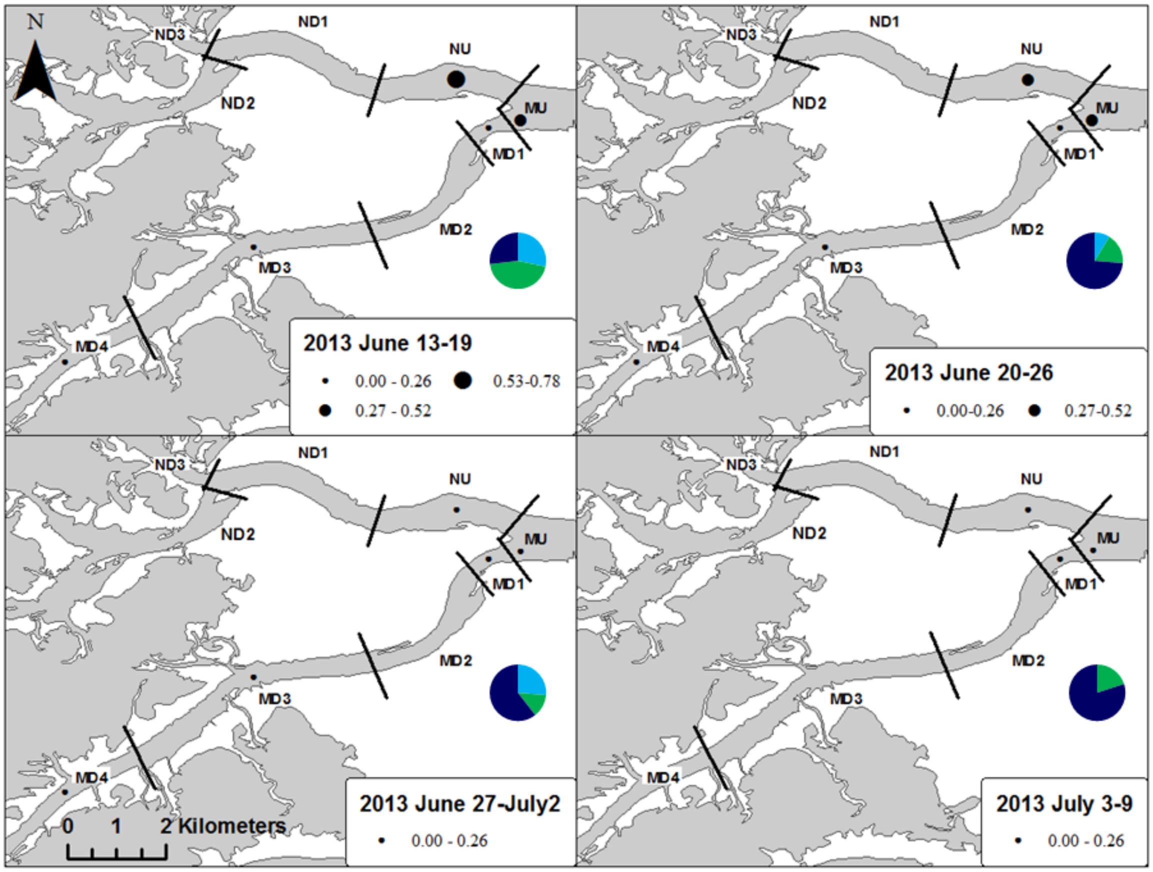
Source: Topological base map (USGS); Drift locations (UM and USGS)

Fig. 5 – Map of the study area showing zone boundaries and sites sampled in 2014 (red circles = larvae absent, green triangles = larvae present, pink stars = spawning reefs)



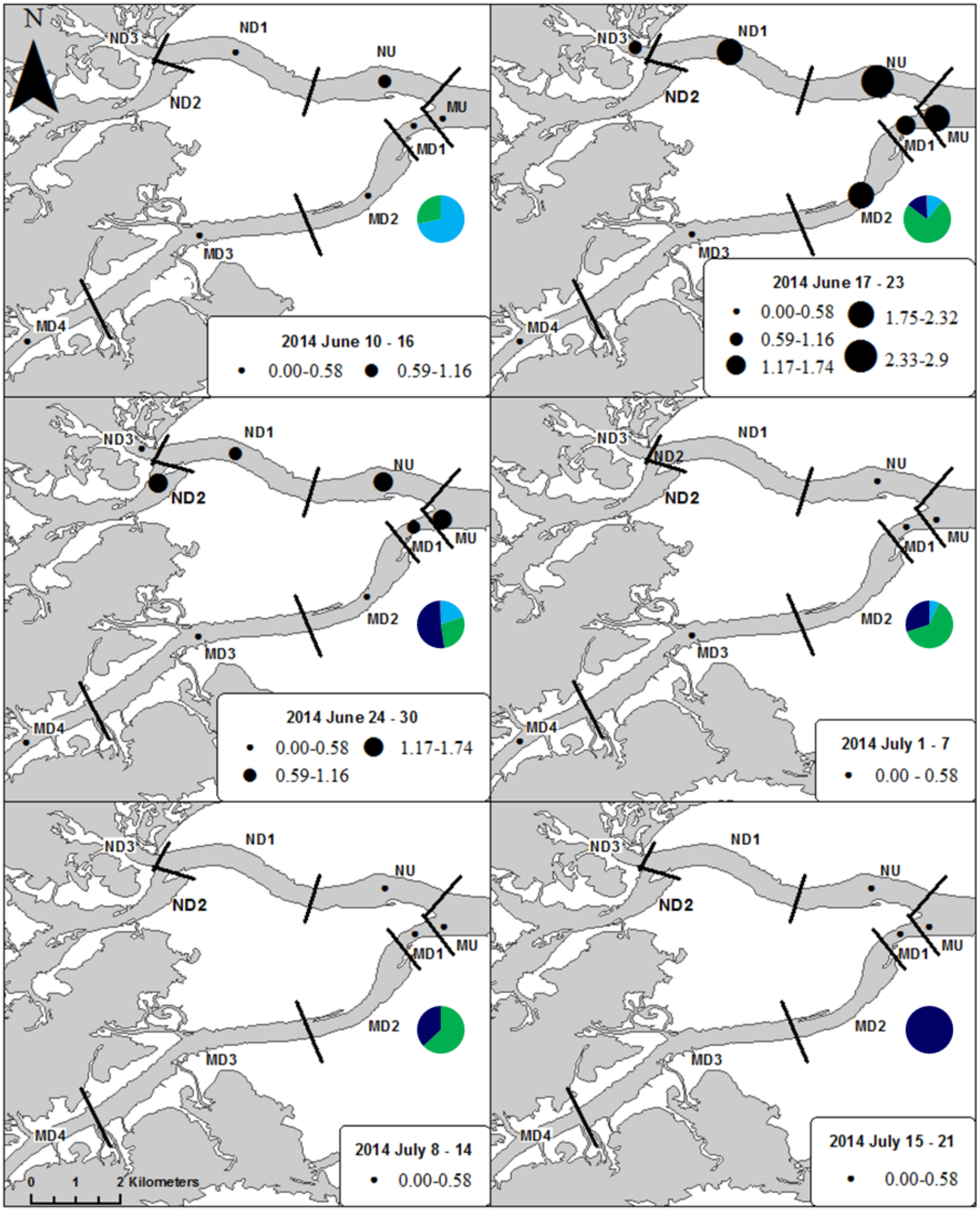
Source: Topological base map (USGS); Drift locations (UM and USGS)

Fig. 6 – Catch per unit effort (CPUE; No. larvae/hour) and developmental stage (Pie Chart: Full YS = sky blue; partial YS = green; no YS = dark blue) of larval lake sturgeon collected from the St. Clair River delta using D-frame drift nets, for each week of larval drift (*n*=4) observed in 2013



Source: Topological base map (USGS); CPUE data (UM and USGS)

Fig. 7 – Catch per unit effort (CPUE; No. larvae/hour) and developmental stage (Pie chart: Full YS = sky blue; partial YS = green; no YS = dark blue) of larval lake sturgeon collected from the St. Clair River delta using D-frame drift nets, for each week of larval drift (*n*=6) observed in 2014



Source: Topological base map (USGS); CPUE data (UM and USGS)

Fig. 8 – Mean weekly catch per unit effort (CPUE; No. larvae/hour) of larval lake sturgeon collected from the North and Middle channels of the St. Clair River using D-frame drift nets in 2013

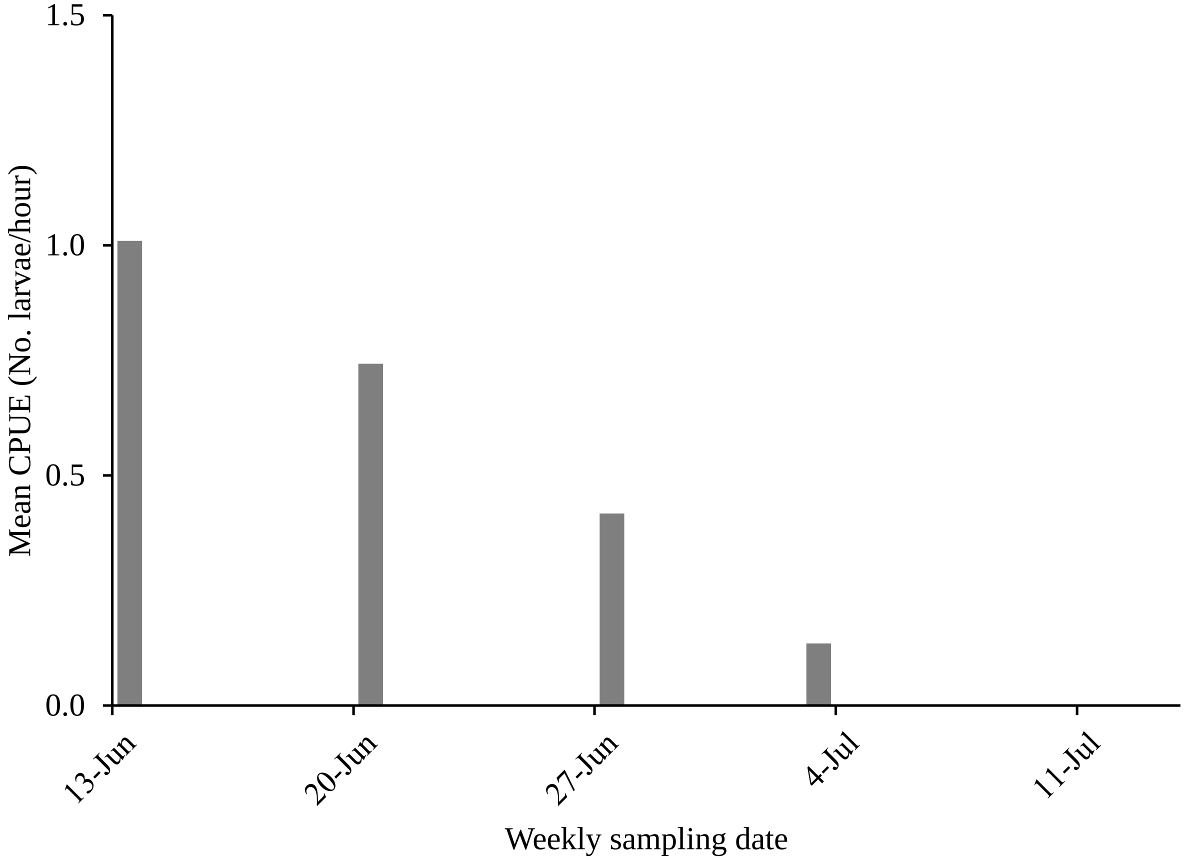


Fig. 9 – Mean weekly catch per unit effort (CPUE; No. larvae/hour) of larval lake sturgeon collected from the North and Middle channels of the St. Clair River using D-frame drift nets in 2014

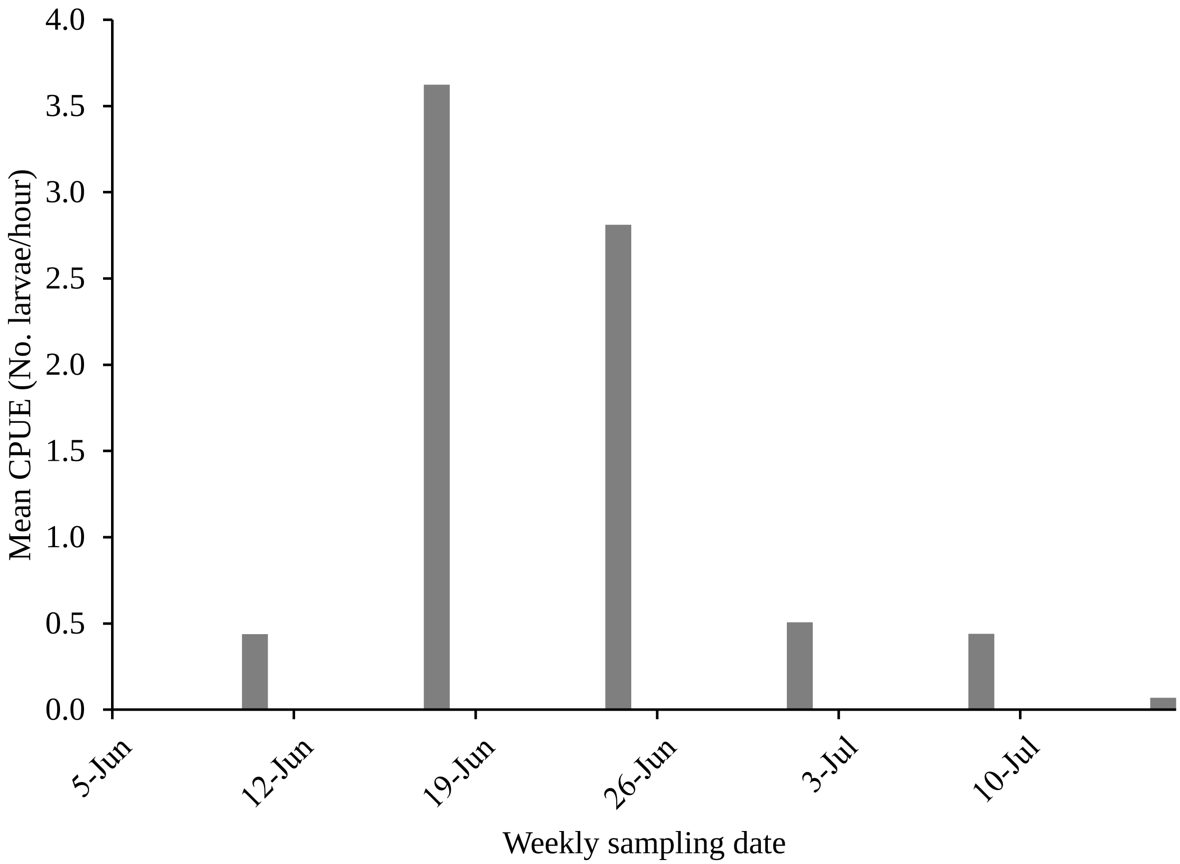


Fig. 10 – Total length values of larval lake sturgeon exhibiting full, partial, or no yolk sacs (YS), for all larvae collected from the Middle Channel of the St. Clair River in 2013

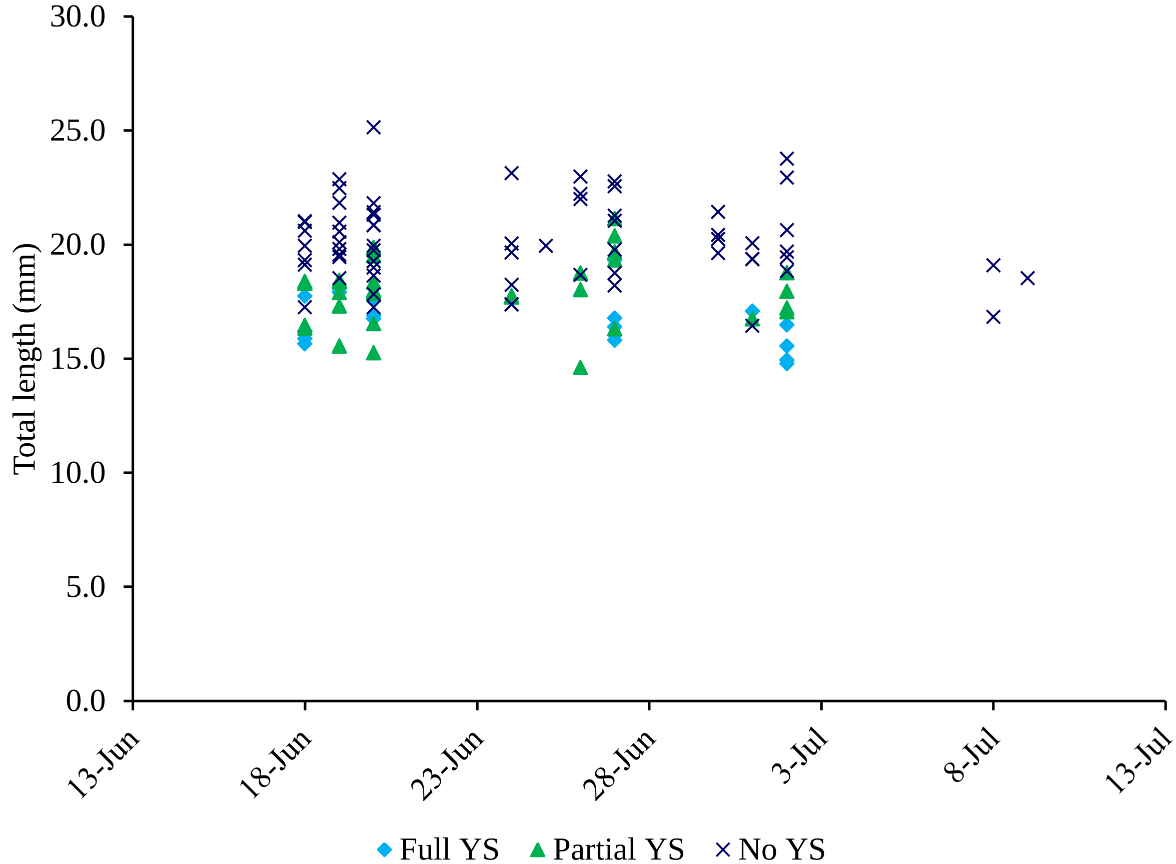


Fig. 11 – Total length values of larval lake sturgeon exhibiting full, partial, or no yolk sacs (YS), for all larvae collected from the Middle Channel of the St. Clair River in 2014

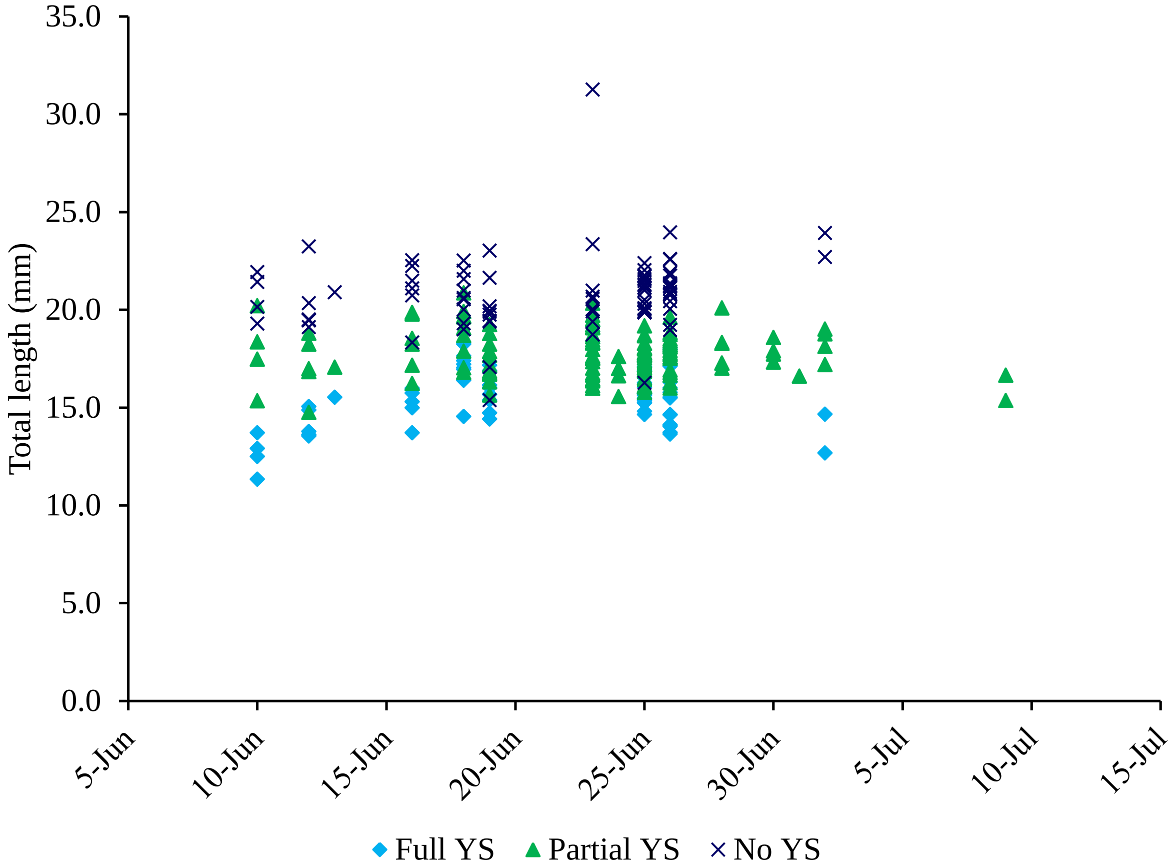


Fig. 12 – Total length values of larval lake sturgeon exhibiting full, partial, or no yolk sacs (YS), for all larvae collected from the North Channel of the St. Clair River in 2014

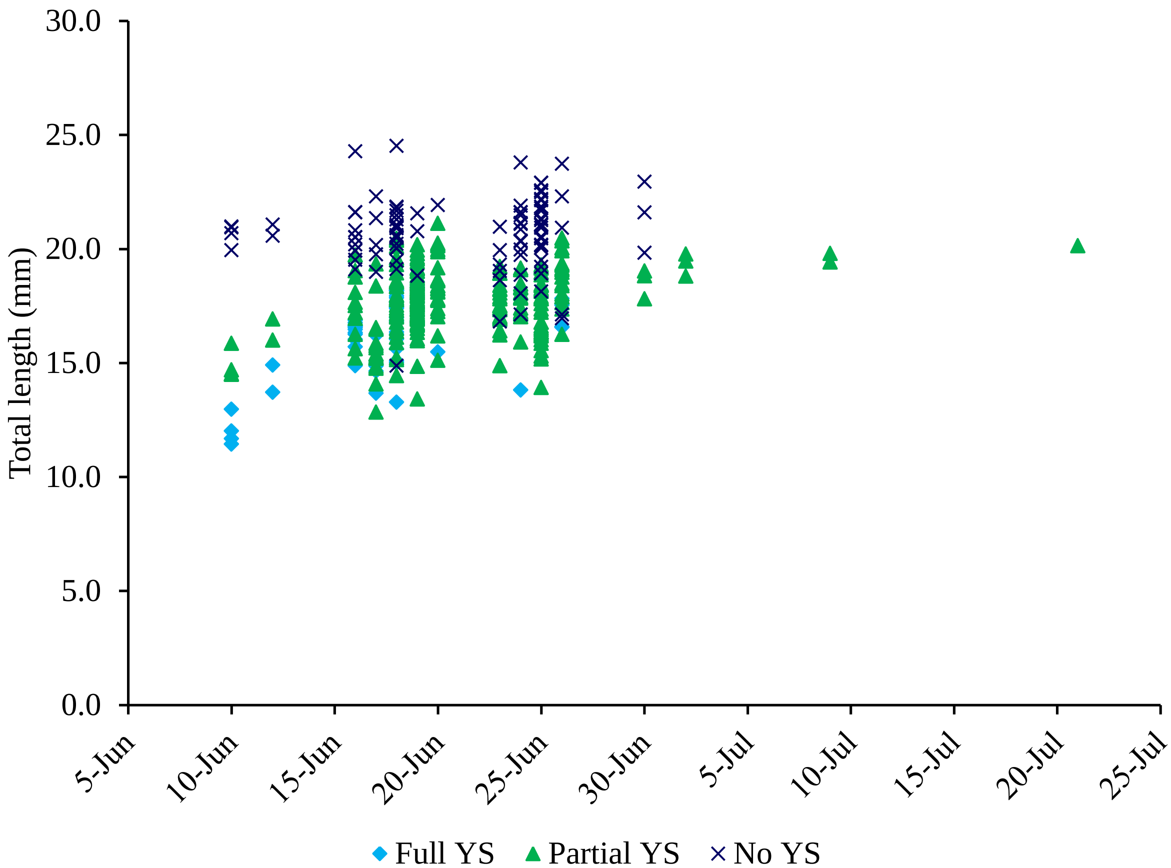


Fig. 13 – Proportion of larval lake sturgeon collected from the Middle Channel of the St. Clair River exhibiting full, partial, or no yolk sacs (YS), for each river zone sampled in 2013

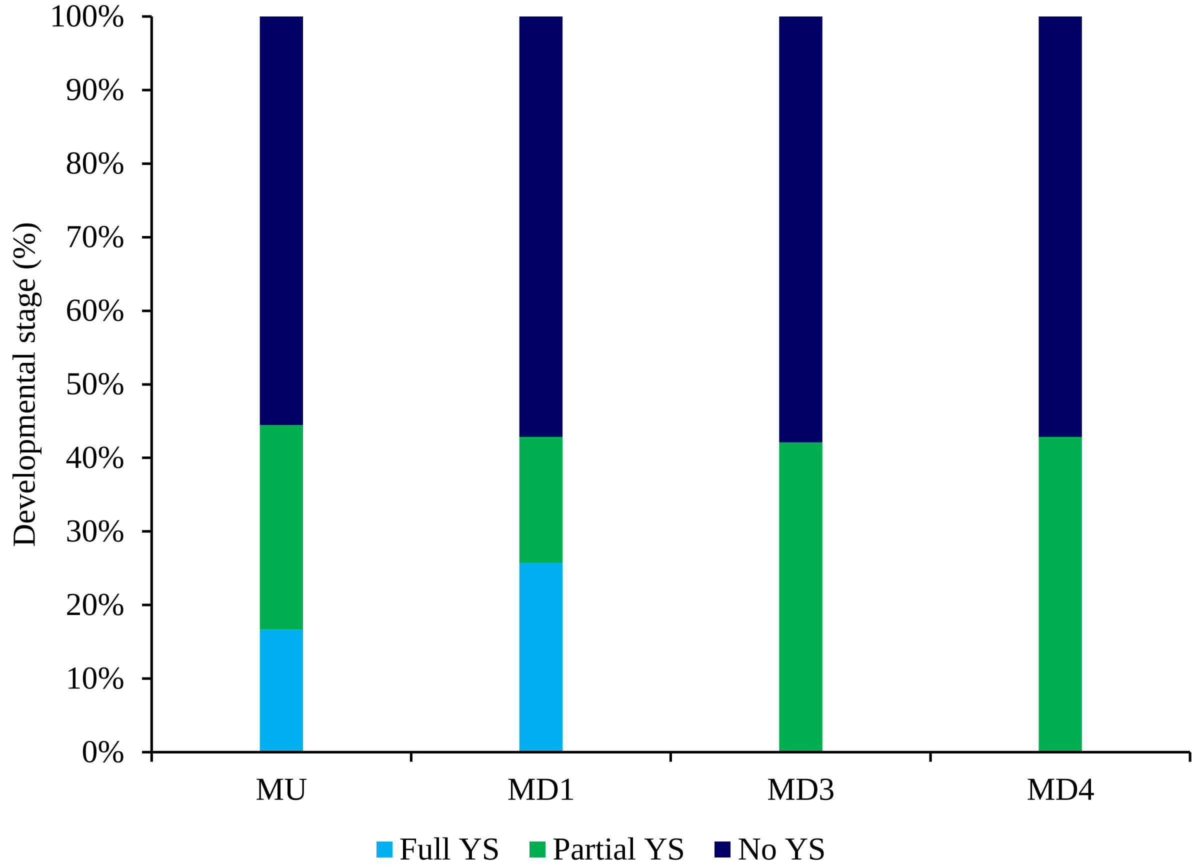


Fig. 14 – Proportion of larval lake sturgeon collected from the Middle Channel of the St. Clair River exhibiting full, partial, or no yolk sacs (YS), for each river zone sampled in 2014

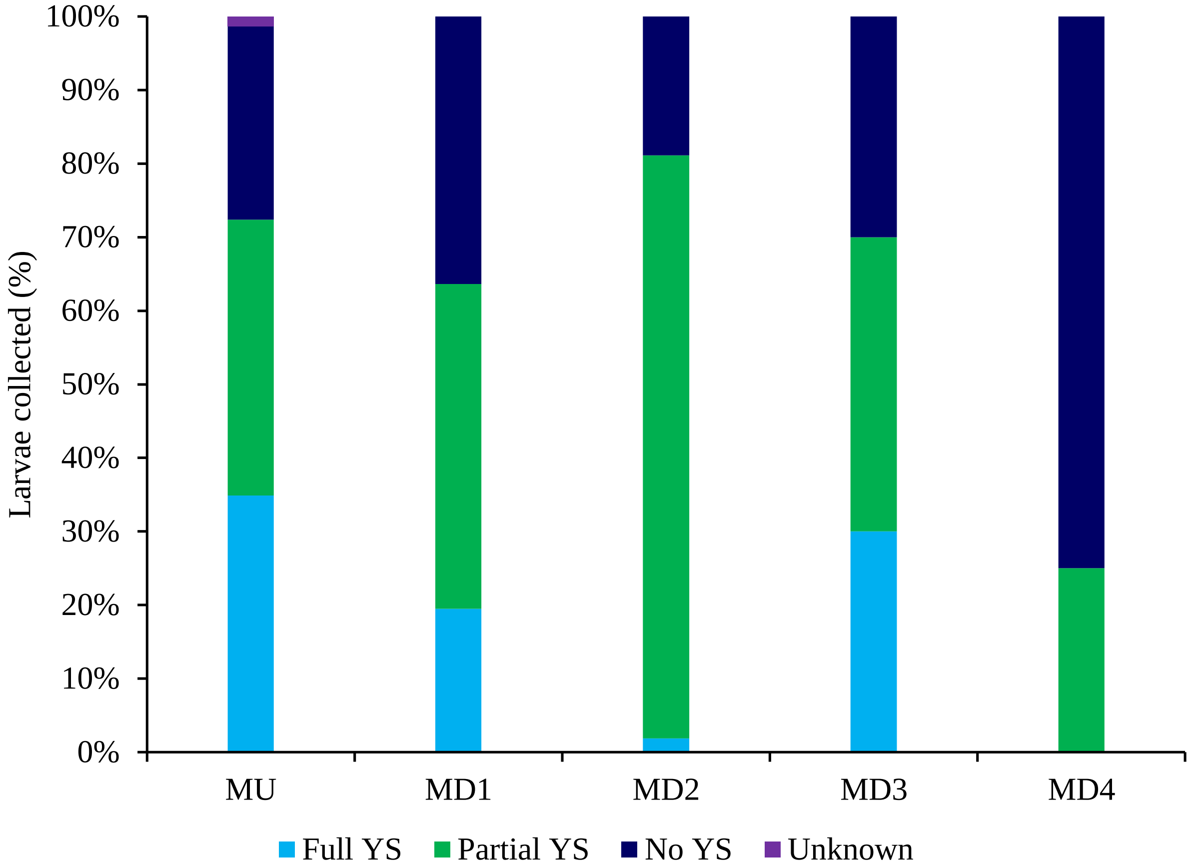
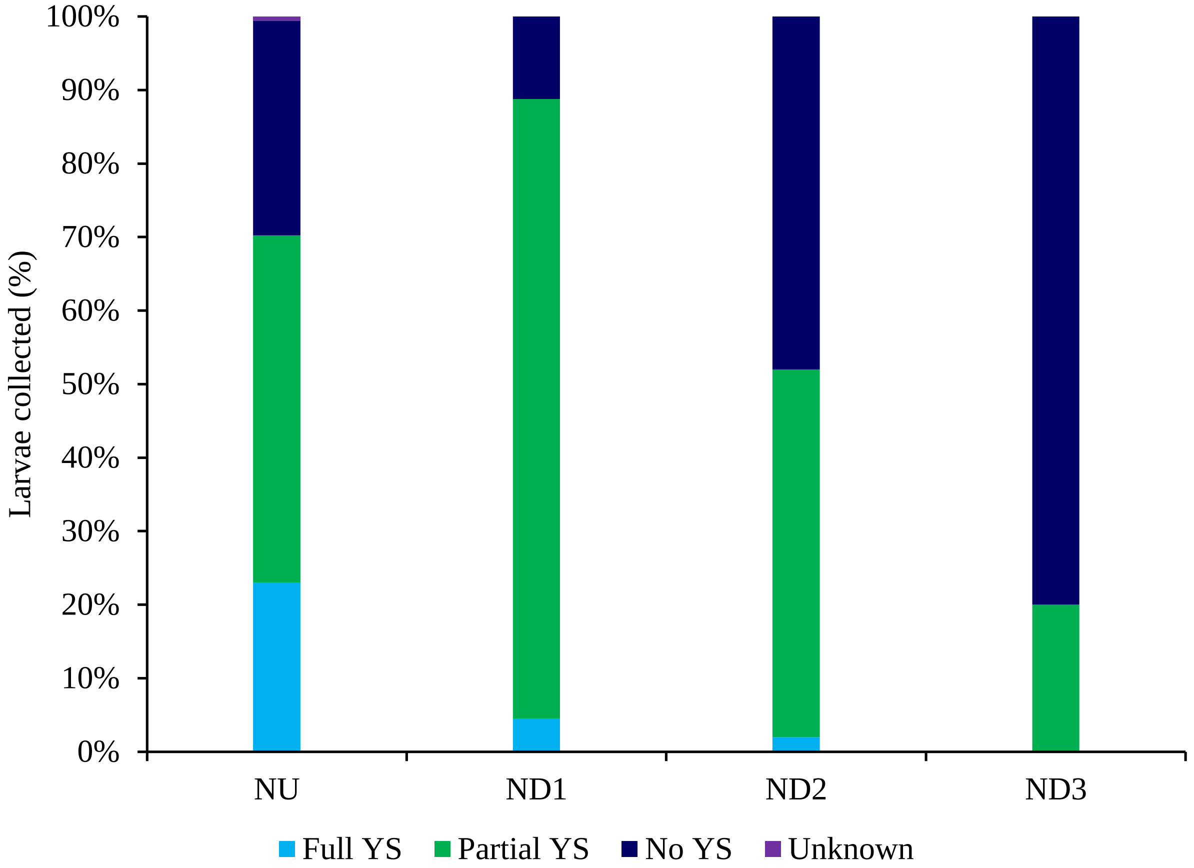


Fig. 15 – Proportion of larval lake sturgeon collected from the North Channel of the St. Clair River exhibiting full, partial, or no yolk sacs (YS), for each river zone sampled in 2014



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