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ARTICLE

Evaluation and Comparison of a Habitat Suitability Model for Postdrift Larval Lake Sturgeon in the St. Clair and Detroit Rivers

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Abstract
We evaluated composition and spatial distribution of riverine nursery habitat for larval Lake Sturgeon *Acipenser fulvescens* in the Middle Channel of the St. Clair River, Michigan, and Fighting Island Channel of the Detroit River, Ontario, using a habitat suitability model (HSM) and fish collections. Although model outputs indicated similar portions of high-quality habitat in the Middle Channel (16.9%) and Fighting Island Channel (15.7%), larval abundance and dispersal patterns varied between these systems. Analysis with Akaike's information criterion indicated that a regression model using sand–silt substrate performed best at predicting the observed water-volume-standardized CPUE (number of larvae·h^{-1}·m^{-3}) in the Middle Channel. Of 93 larvae that were collected in the Middle Channel, most were found to cluster at three distinct areas of high- and moderate-quality habitat, which was composed predominately of sand–silt substrate. Lengths of larvae varied by as much as 9 mm, and the degree of yolk sac absorption also varied, indicating that larvae in the Middle Channel remained within the channel after a short drift downstream. Of the 25 larvae that were collected in Fighting Island Channel, distribution was sporadic, and occurrence did not significantly correlate with measured habitat variables. Larvae were relatively homogeneous in size and yolk sac stage, indicating that newly emerged larvae did not utilize available habitat in Fighting Island Channel but instead drifted into the main channel of the Detroit River. Dispersal patterns indicate variability in young Lake Sturgeon ecology, which is dependent on local habitat conditions—most notably, substrate composition. Furthermore, modeled larval–habitat associations found in this study were compared to a similar study on larval Lake Sturgeon from the North Channel of the St. Clair River. Model outputs from all three systems accurately accounted for observed larval dispersal patterns among both rivers. This supports the transferability of an HSM parameterized for Lake Sturgeon from individual river reaches within two large river systems.

The Great Lakes connecting channels (upper St. Lawrence, St. Mary's, St. Clair, Niagara, and Detroit rivers) contain some of the largest populations of Lake Sturgeon *Acipenser fulvescens* in the Great Lakes basin (Thomas and Haas 2004; Bauman et al. 2011; Hayes and Caroffino 2012). Channel dredging (Bennion and

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Manny 2011), coastal development, wetland degradation and destruction, overfishing, and pollution have greatly reduced Lake Sturgeon abundance in all of these systems (Peterson et al. 2007). These actions have resulted in a moratorium on commercial fishing for Lake Sturgeon in the connecting channels, with exception of a fishery operating in the St. Lawrence River that allows an annual harvest of 80 metric tons (COSEWIC 2017).

Availability and accessibility of suitable habitat are among the greatest impediments to the recovery of Lake Sturgeon stocks in the Great Lakes (Hayes and Caroffino 2012; COSEWIC 2017). As Lake Sturgeon are prone to high rates of mortality through early development, efforts to identify the quantity and quality of spawning and nursery habitat have become a top priority for resource managers operating in the Great Lakes connecting channels (Hayes and Caroffino 2012; Great Lakes Fish and Wildlife Restoration Act of 2006). In the St. Clair and Detroit rivers, Lake Sturgeon successfully spawn on artificial reefs that were constructed to enhance fish reproduction (Read and Manny 2006; Roseman et al. 2011a; Bouckaert et al. 2014); however, there are no documented accounts of increased abundance of young of the year (age 0; 50–200 mm) or juveniles (200–500 mm) in these areas. A lack of documented increases in abundance may be attributed to poor sampling success or inefficient gear selection, but it may also reflect high mortality of larval fish.

Lake Sturgeon may experience a bottleneck early in life as a result of high predation rates or lack of suitable nursery habitat (Peterson et al. 2007; Daugherty et al. 2009); however, once larvae settle in nursery habitat and develop armored scutes along their bodies, predation pressure is greatly reduced (Peterson et al. 2007). Decreased predation pressure makes the conditions experienced prior to this developmental milestone of particular importance. Assessments evaluating dispersal patterns and habitat preferences of larval Lake Sturgeon are essential in determining early life stage survival and eventual cohort success.

Lake Sturgeon larval drift studies have occurred in several systems throughout the species' range (Auer and Baker 2002; Smith and King 2005; Benson et al. 2006). Larvae emerge from their spawning source at approximately 13–19 d posthatch, which coincides with the onset of exogenous feeding (Peterson et al. 2007). Upon entering the current, larvae may disperse throughout the full vertical extent of the water column (D'Amours et al. 2001; Verdon et al. 2013) or may drift predominately near the river bottom (Kempinger 1988; Caroffino et al. 2009; Roseman et al. 2011b). In the St. Clair River, Young (2015) used depth-stratified conical drift nets deployed at varying depths downstream of known Lake Sturgeon spawning areas in the Middle Channel and collected approximately 88% of sampled larvae within 1 m of the bottom. Differences in larval drift patterns may be attributed to variation in hydrologic and hydraulic conditions among river systems (D'Amours et al. 2001; Caroffino et al. 2009; Verdon et al. 2013), though local habitat conditions may also influence larval dispersal, especially in systems where larvae drift close to the river bottom.

In a series of flume trials, Hastings et al. (2013) observed that when gravel substrate was present close to the initial larval release point, larval drift distance was short and larvae settled in those areas. When a different substrate was offered immediately downstream of the release point, larvae drifted longer distances to find gravel. These findings suggest that larvae possess the ability not only to recognize suitable habitat when encountered but also to orient and maneuver themselves to these locations. In fast-flowing rivers, such as the St. Clair River (>1.5 m/s), larvae caught in the current could be transported out of the river in a single night of drift. Instead, Lake Sturgeon larvae are routinely collected up to several weeks after they initially begin to emerge and drift downstream (Bouckaert et al. 2014; Young 2015; Krieger and Diana 2017). If larvae are to remain in the river, they must seek refuge from the current by using available substrate (Auer and Baker 2002; Benson et al. 2005) or finding current shelters (e.g., rocks, logs, and debris). Given this, the quality and location of suitable habitat in relation to local spawning sources could also influence larval drift. Lake Sturgeon occur in dynamic systems that may differ in fluvial and ecological characteristics. This suggests that the early life ecology of Lake Sturgeon is also variable among systems and that system-specific evaluations are essential to understanding Lake Sturgeon behavior.

Two of us (Krieger and Diana 2017) developed a habitat suitability model (HSM) using benthic habitat characteristics collected from a reach of the St. Clair River, the North Channel, to identify and characterize the quality of habitat available to larval, age-0, and juvenile Lake Sturgeon. Results indicated significant associations between larval drift, the locations of age-0 fish collected from surveys, and areas of high-quality habitat predicted by the HSM. We (Krieger and Diana 2017) were the first to develop a life-stage-specific habitat model for Lake Sturgeon in the Great Lakes connecting channels, which will provide resource managers with insight into areas of likely age-0 and juvenile residence. Although 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). Assessments of the transferability of modeled species–habitat relationships across systems require information on local habitat parameters and area-specific information on animal dispersal patterns.

The purpose of this study was to parameterize and field test an HSM for larval Lake Sturgeon in the Middle Channel of the St. Clair River, Michigan, and Fighting

Island Channel of the Detroit River, Ontario. Additionally, we sought to demonstrate how an HSM developed for a particular Lake Sturgeon system—the North Channel of the St. Clair River (Krieger and Diana 2017)—could be used to accurately describe larval drift patterns in systems with novel environmental characteristics. The objectives of this study were to (1) use an HSM parameterized with local habitat information in combination with dispersal patterns of larval Lake Sturgeon to identify relationships between local habitat characteristics and larval presence; and (2) assess how HSM-modeled larval–habitat relationships translate across three reaches in the Detroit and St. Clair rivers. Given the range in environmental conditions evident in these reaches and the variability in larval Lake Sturgeon behaviors as a function of local hydrologic conditions, we hypothesized that larval Lake Sturgeon dispersal patterns in the St. Clair and Detroit rivers would vary in response to local habitat characteristics. We expected that (1) larvae collected from river reaches lacking suitable nursery habitat would drift quickly from their hatching point of origin to locations outside of the study areas; and (2) individuals collected in reaches possessing more suitable habitat would congregate in high-quality habitat areas within their respective river.

METHODS

Study sites.— We selected segments of the Middle Channel (St. Clair River) and Fighting Island Channel (Detroit River) for assessment (Figure 1). The St. Clair River is 64 km in length and drains water from Lake Huron into Lake St. Clair. It has an average annual discharge of 5,150 m^3/s, which remains relatively constant seasonally. Flow velocities in the St. Clair River range from about 0.3 to 1.7 m/s (Schwab et al. 1989), with mid-channel depth ranging from 13 to 15 m and scattered holes deeper than 21 m. Within the St. Clair River, the Middle Channel is an 11.2-km-long reach; at its head, there is an artificial spawning reef (4,040 m^2) that was constructed in 2012 (Middle Channel Reef; Figure 1), where Lake Sturgeon eggs have been collected (Bouckaert et al. 2014). Larval fish from this reef are believed to either remain in the lower river or drift into Anchor Bay (Young 2015).

The Detroit River is 51 km long and drains water from Lake St. Clair into Lake Erie. Within the Detroit River, the Fighting Island Channel reach is located on the east side of Fighting Island in Canadian waters (Figure 1). Fighting Island Channel is 5.5 km long and has an average annual discharge of approximately 5,300 m^3/s; flow velocities range from about 0.2 to 0.9 m/s (Schwab et al. 1989), and mid-channel depth ranges from 7 to 11 m. In the channel, Lake Sturgeon eggs have been regularly collected from an artificial spawning reef (3,300 m^2) that was constructed in 2008 (Fighting Island Reef; Figure 1; Roseman et al. 2011a; Bouckaert et al. 2014).

Field data collection.— We conducted habitat assessments throughout the Middle and Fighting Island channels during summer and fall 2015 and 2016 in accordance with previously described methodologies (Krieger and Diana 2017). River habitat was characterized by following an approach based on random grids (0.1 km^2; 889 total sampling locations). Water depth, benthic invertebrate composition, substrate composition, and longitude and latitude were determined at each sampling location. Longitude and latitude were recorded using a wide-area augmentation system (estimated positional accuracy < 3 m), and water depth was measured to the nearest 0.1 m by using a boat-mounted sonar. Benthic substrate composition was determined using a Ponar grab sampling device. This device consisted of two opposing semi-circular jaws (232-cm^2 jaw opening) that were held open by a steel trigger pin. The Ponar sampler was lowered to the bottom, where the jaws penetrated the substrate, causing the trigger pin to release and the jaws to shut, thus trapping a sample of the benthos. Two to three Ponar samples were taken at each location. Substrate composition of the Ponar samples was determined by visual and tactile inspection via the Wentworth sediment classification scheme (Wentworth 1922). Samples comprising 50% or more of a single substrate type (sand, silt, clay, or cobble) were classified as that single substrate type. Samples with two substrate types, each contributing 35–50%, were categorized as a mixed substrate (e.g., sand–silt or sand–clay). All samples were washed through an elutriator, and invertebrates were separated from sediment and other river debris. Invertebrate samples were preserved in 95% ethanol, transported to the laboratory, and sorted into one of six major taxa: Ephemeroptera (*Hexagenia*), Chironomidae, Hirudinea, Gammaridae, Dreissenidae, and Gastropoda. These taxa were selected based on their abundance and inclusion in Lake Sturgeon diets (Kempinger 1996; Nilo et al. 2006; Boase et al. 2011). Invertebrates not representing one of these taxa were discarded. Benthic flow velocities were measured to the nearest 0.1 m/s using a SonTek Acoustic Doppler Profiler (ADP; Model M.78 870-58-235) during each year of study. To collect benthic flow velocities, the ADP probe was attached to our research vessel, which was driven in a zigzag pattern from bank to bank, throughout the entire study area. At each larval sampling location, a vertical velocity profile was measured while maintaining station in the river. Each profile consisted of 25–50 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 flow velocities were approximated based on the average

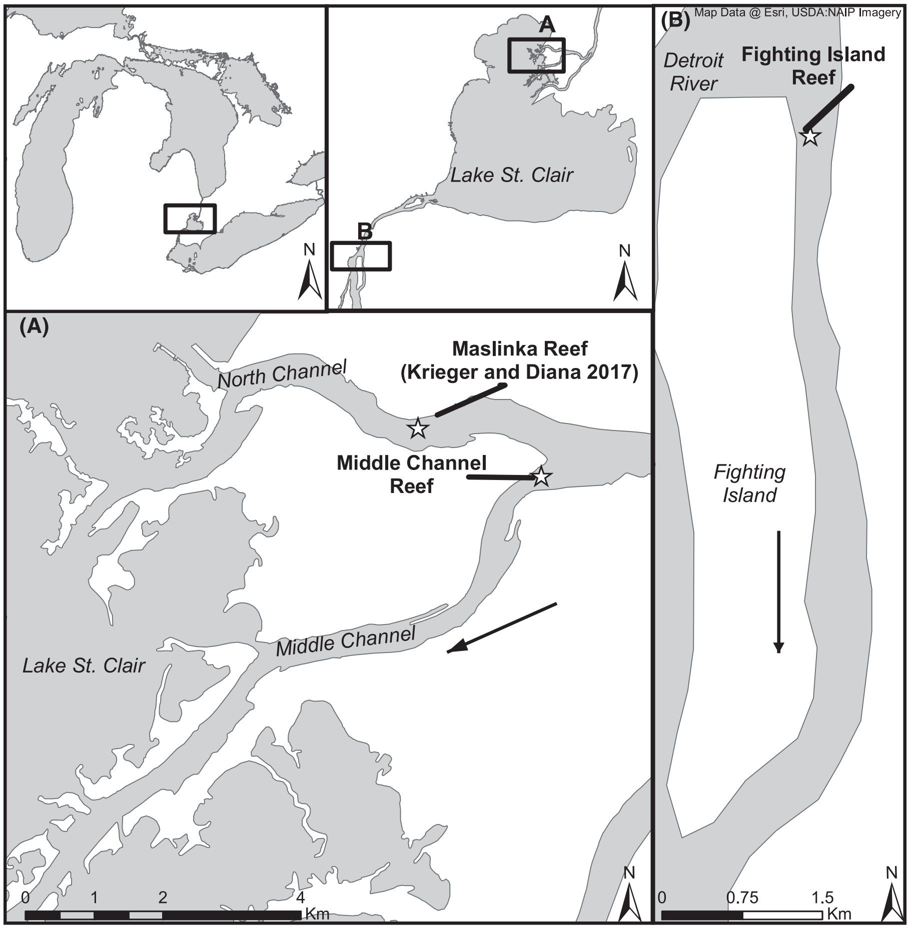

FIGURE 1. Map of study sites in the St. Clair River (Middle Channel [A]) and Detroit River (Fighting Island Channel [B]). Stars show the locations of Lake Sturgeon spawning reefs. Black arrows indicate the flow direction. A map of the North Channel site (Krieger and Diana 2017) is included for reference. The upper two left-hand maps provide a more general geographical reference as to the location of the study sites.

reading from the two bottom-most cells and represent flows at depths from 0.1 to 0.5 m off the bottom. The ADP data files containing velocity profiles were then exported into SonTek CurrentSurveyor software. 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 version 10.3 (Environmental Systems Research Institute, Redlands, California).

Information on larval Lake Sturgeon distribution was collected during the larval drift period by using D-frame drift nets (area of opening = 0.3487 m^2; 1,600-μm mesh), which sampled the bottom 0.54 m of the water column. Beginning approximately 8 d after eggs (minimum incubation time; Auer and Baker 2002) were collected on a reef by personnel from the U.S. Geological Survey, two nets were deployed approximately 50 m downstream of that reef, near mid-channel. Once larval Lake Sturgeon were collected, nets were deployed in a fixed–stratified configuration with three levels of placement consisting of two nets per level. Each level of nets was placed approximately 0.3 km apart, with the total array covering 0.6 km of the channel. Once larvae were collected in nets placed at the second level, we 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 our array. As such, collection of individuals in third-level nets was infrequent. To assess dispersal patterns of drifting larvae, nets utilized throughout each study system were moved to a total of 25–40 locations (Figure 2), beginning approximately 50 m from each reef and continuing downstream 3.0–7.5 km to where the channels emptied into Anchor Bay or the main channel of the Detroit River. We assumed that the horizontal dispersal of larval Lake Sturgeon in the St. Clair River was restricted to mid-channel depths, where flow velocities were greatest and where vegetation was limited, based on unsuccessful attempts to collect larvae closer to shore.

Larval drift surveys in the Middle Channel took place from June 10 to July 9, 2013, and from June 5 to July 29, 2014. In Fighting Island Channel, larval surveys took place from May 28 to June 16, 2016. Nets were deployed at 2000 hours each night and were retrieved at 0600 hours the following morning to capture the peak drift time of larval Lake Sturgeon (LaHaye et al. 1992; Auer and Baker 2002; Smith and King 2005).

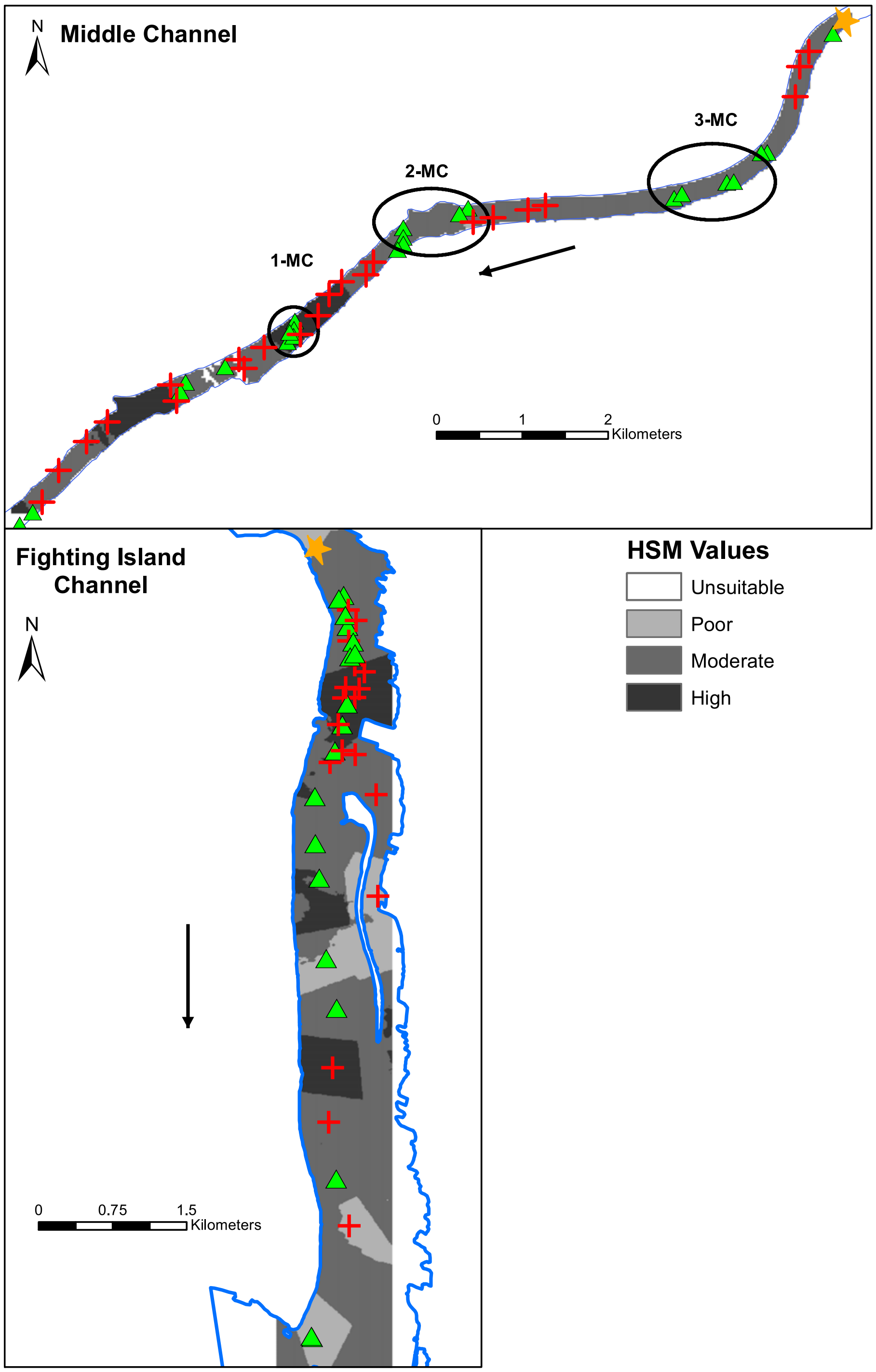

FIGURE 2. Map of net locations and habitat suitability model (HSM) output for larval Lake Sturgeon in the Middle Channel and Fighting Island Channel. Orange stars indicate locations of spawning reefs. Green triangles represent net sites where larval Lake Sturgeon were collected; red crosses represent sites where no larvae were collected. Black arrows indicate flow direction. Labeled areas of high larval Lake Sturgeon density in the Middle Channel (1-MC, 2-MC, and 3-MC) are detailed in Table 5.

Morphometric data from individual larvae were collected to assess differences in larval length and yolk sac stage. Variability in size and yolk sac absorption of Lake Sturgeon larvae collected from similar sites could indicate that larvae settled in those locations and thus would highlight probable larval nursery areas, while collections of larvae with greater uniformity in size and yolk sac stage could indicate that larvae emerged from the reef and quickly drifted out of the study system. Similarly, higher proportions of larger larvae with smaller or fully absorbed yolk sacs in individual areas could suggest that larvae settled in nursery habitat to continue development. In contrast, higher proportions of smaller individuals with larger yolk sacs could indicate that larvae were still drifting through the system (Kempinger 1988; Peterson et al. 2007). Individual larvae were photographed at 60× magnification by using a microscope with digital analysis software (Image Pro Plus version 7.0). Total length (mm) and yolk sac absorption stage (full, partial, or no yolk sac) for each larva were determined from magnified images. Lake Sturgeon larvae with full yolk sacs were identified based on 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 had fully formed mouths and possessed a prominent lateral band that 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 we detailed previously (Krieger and Diana 2017) and is summarized here. For each river reach, an extent map of the submersed channel was prepared by using base layers that delineated lake and river features (i.e., boundaries and islands) and was digitized by using available satellite image base maps of the study sites contained in ArcGIS version 10.3. A river layer shapefile was created to establish study boundaries for each habitat model. Georeferenced depths (m) and benthic flow velocities (m/s) were converted into Microsoft Excel files and imported to shapefiles. Raster layers containing values for water depths and benthic flow velocities were interpolated for each study area by 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 was converted into a raster file.

For each area, a shapefile containing point values was created for locations where drift nets were placed. At each net location, the longitude/latitude, net-hours (total time of net placement at a given location), and number of Lake Sturgeon larvae collected were recorded and imported into ArcMAP version 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, Benson et al. (2005) for benthic flow velocity, and Krieger and Diana (2017) for invertebrate density and depth (Table 1). As an example, if a polygon contained sand substrate, that location was assigned an HSI value of 1 for the substrate raster layer based on Threader et al. (1998). If a point had a benthic current velocity greater than 1.0 m/s, it was assigned an HSI value of 0 based on Benson et al. (2005). In cases where substrate composition was found to include two or more substrate types, the substrate HSI values were averaged for that location. The geometric mean of each reclassified layer was then calculated with the raster calculator in ArcGIS version 10.3 using the formula:

$$(\text{Benthic Current Layer} \times \text{Depth Layer} \times \text{Substrate Layer} \times \text{Invert Layer})^{0.25}$$

to create a composite HSM throughout each system. Cells of the composite model with a value of 0 were defined as unsuitable habitat. Cells with values ranging from 0.01 to 0.60 were defined as poor-quality habitat, those with values from 0.61 to 0.80 were defined as moderate-quality habitat, and those with values from 0.81 to 1.00 were defined as high-quality habitat for larval, age-0, and juvenile Lake Sturgeon.

Data analyses.— Aside from information on habitat characteristics present in each of our study systems, we were also interested in comparing the number of Lake Sturgeon eggs that were deposited on a given reef during the study years. Egg deposition estimates provide an approximation for the number of larvae expected to enter the drift in a given year and allow for a comparison of egg and larval survival between the Middle and Fighting Island channels. To estimate the input of Lake Sturgeon larvae into our study systems, we used information on average egg deposition (number/m^2) collected from various sites at each spawning reef during years when larvae were also collected. We multiplied mean egg density by reef area to estimate the total egg deposition by Lake Sturgeon at each reef location.

For both river reaches, we examined the relationship between larval Lake Sturgeon CPUE (number of larvae/h) and combinations of habitat variables using multiple linear regressions (Table 2). To standardize CPUE between each sampling location, benthic flow velocity values were obtained for each net location from the interpolated raster layer. Since discharge in the Great Lakes connecting channels is relatively stable seasonally (Schwab et al. 1989; Hondorp et al. 2014), benthic flow velocities sampled over the course of several days during the larval drift period were assumed to represent velocity values throughout the

TABLE 1. Input values for the habitat suitability model for larval and juvenile Lake Sturgeon (from Krieger and Diana 2017).

Habitat variable	Suitability index	Source
Substrate composition		Threader et al. (1998)
Clay	0.2	
Silt	1.0	
Sand	1.0	
Gravel	1.0	
Cobble	0.8	
Boulder	0.5	
Benthic current velocity (m/s)		Benson et al. (2005)
>1.0	0.0	
0.6–1.0	1.0	
0.3–0.59	0.9	
0.0–0.29	0.5	
Water depth (m)		Krieger and Diana (2017)
<5.0	0.0	
5.1–10.2	0.8	
10.3–13.3	1.0	
>13.3	0.5	
Invertebrate density (number/m^2)		Krieger and Diana (2017)
>3,000	1.0	
701–2,999	0.7	
<700	0.4	

full drift period. Flow velocity values were multiplied by the area of the drift net opening to estimate water volume passing through each net, thus giving a volume-standardized CPUE (VCPUE) as number of larvae per hour per cubic meter of water sampled. To allow for comparisons between river systems of variable size, we standardized the VCPUE by dividing it by the total area of high-, moderate-, and poor-quality habitat in each system. As such, VCPUE was calculated per square kilometer of habitat.

Akaike's information criterion corrected for small sample sizes (AIC_c) was used to measure the relative fit of each regression and to assess the degree to which each habitat variable combination was useful in predicting VCPUE (Table 2). A one-tailed *t*-test was used to compare the relative amounts of high-quality, moderate-quality, poor-quality, and unsuitable habitat between the Middle and Fighting Island channels. We used one-way ANOVA to compare yolk sac stage and length distributions of larvae between study systems. To assess the transferability of modeled species–habitat relationships across reaches, we compared larval Lake Sturgeon–habitat relationships modeled in this study to those modeled for the North Channel (Krieger and Diana 2017). The CPUE values from Krieger and Diana (2017) were also standardized to account for differences in benthic flow velocity among net locations. All statistical analyses were performed using R version 3.1.3 (R Development Core Team 2008). Model performance based on AIC_c was tested by using the "AICcmodavg" package (Mazerolle 2017). Alpha was set at 0.05 for all comparisons.

RESULTS

Observed larval Lake Sturgeon dispersal patterns in the Middle and Fighting Island channels indicate that although relatively similar habitat exists in both systems, subtle differences in one or more individual habitat features may have a large influence on larval dispersal. Furthermore, the location of suitable habitat in relation to the individual spawning reef also influences local dispersal patterns and is an important consideration for successful recruitment of age-0 Lake Sturgeon in the St. Clair and Detroit rivers.

The Middle Channel and Fighting Island Channel study areas were 18.66 and 7.07 km^2, respectively, and contained similar proportions of high-, moderate-, and low-quality habitat (Figure 2). In the Middle Channel, 14.7% of modeled habitat ranked as high quality, while 76.8% ranked as moderate quality. Similarly, 16.8% of modeled habitat in Fighting Island Channel ranked as high quality, and 79.3% ranked as moderate quality. Areas designated as poor-quality habitat comprised less than 20% of both study areas (Table 3). Benthic current velocity, invertebrate density, and depth were similar

TABLE 2. Highest-ranked regression models using Akaike's information criterion corrected for small sample sizes (AIC_c) from the Middle Channel (MC) and Fighting Island Channel (FIC). Predictor variables are benthic current velocity (Velocity), substrate composition (Substrate), depth, and invertebrate density (Invert). Interaction terms are shown in parentheses. Relationships between the water-volume-standardized CPUE of larval Lake Sturgeon and habitat suitability model variables were modeled using simple and multiple linear regressions (K = number of model parameters; ΔAIC_c = AIC_c difference; w_i = Akaike weight). [Correction added on September 25, 2018, after first online publication: in row 25 "+Invert" was deleted and "Invert × Substrate" was replaced by "Substrate × Depth", and in row 26 "+ Depth" was deleted.]

	Model comparison summary						
River	Rank	K	AIC_c	ΔAIC_c	w_i	Cumulative w_i	Model variables
MC	1	6	23.44	0.00	0.82	0.82	CPUE × Substrate
	2	7	29.37	5.93	0.11	0.93	CPUE × Substrate + Depth
	3	9	31.86	8.42	0.05	0.98	CPUE × Substrate + Velocity + (Velocity × Substrate)
	4	2	34.67	11.23	0.05	0.99	Null
	5	3	36.28	12.84	0.01	1.00	CPUE × Velocity
	6	7	38.22	14.78	0.00	1.00	CPUE × Substrate + Invert
	7	9	39.94	16.5	0.00	1.00	CPUE × Substrate + Depth + (Substrate × Depth)
	8	11	41.33	17.89	0.00	1.00	CPUE × Substrate + Invert + Velocity + Depth (Velocity × Substrate)
	9	7	43.01	19.57	0.00	1.00	CPUE × Substrate + Velocity
	10	8	48.92	25.48	0.00	1.00	CPUE × Substrate + Invert + Depth
	11	8	49.22	25.78	0.00	1.00	CPUE × Substrate + Depth + Velocity
	12	9	51.34	27.9	0.00	1.00	CPUE × Substrate + Invert + Depth + (Invert × Substrate)
	13	9	53.41	29.97	0.00	1.00	CPUE × Substrate + Invert + Velocity + Depth
FIC	1	3	31.62	0.00	0.75	0.75	CPUE × Velocity
	2	2	33.49	1.87	0.23	0.98	Null
	3	6	34.22	2.6	0.01	1.00	CPUE × Substrate
	4	9	38.94	7.32	0.00	1.00	CPUE × Substrate + Depth
	5	9	39.43	7.81	0.00	1.00	CPUE × Substrate + Invert + Depth + (Invert × Substrate)
	6	11	42.33	10.71	0.00	1.00	CPUE × Substrate + Invert + Velocity + Depth (Velocity × Substrate)
	7	7	43.21	11.59	0.00	1.00	CPUE × Substrate + Velocity
	8	9	45.11	13.49	0.00	1.00	CPUE × Substrate + Velocity + (Velocity × Substrate)
	9	7	48.33	16.71	0.00	1.00	CPUE × Substrate + Invert
	10	8	50.36	18.74	0.00	1.00	CPUE × Substrate + Invert + Depth
	11	8	52.11	20.49	0.00	1.00	CPUE × Substrate + Depth + Velocity
	12	9	54.33	22.71	0.00	1.00	CPUE × Substrate + Depth + (Substrate × Depth)
	13	9	56.88	25.26	0.00	1.00	CPUE × Substrate + Invert + Velocity

between systems (Table 3), whereas substrate composition was quite dissimilar. The Middle Channel was composed predominately of sand and silt substrate (sand–silt; 48% of total area), followed by sand (24%) and clay (15%). In contrast, clay was the most common substrate type (53%) in Fighting Island Channel, followed by clay–silt (14%) and silt (10%).

Larval Lake Sturgeon abundance was considerably higher in the Middle Channel than in Fighting Island Channel. If larvae were settling in these systems, we would expect to find individuals congregated in areas of high-quality habitat, collections of individuals with variable lengths and yolk sac stages, and higher proportions of larvae with greater lengths and smaller yolk sacs. During the summers of 2013 and 2014, 93 larvae were collected from 24 different locations downstream of the Middle Channel Reef, resulting from approximately 815 net-hours of sampling. Larval TL ranged from 14.8 to 23.8 mm (18.7 ± 2.01 mm [mean ± SD]), with 79% of individuals measuring between 16 and 20 mm (Figure 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. Larvae were collected in habitats of high quality (n = 15), moderate quality (n = 76), and poor quality (n = 2; Table 4). The VCPUE was significantly higher in areas of high-quality habitat (0.15 larvae$\cdot h^{-1} \cdot m^{-3}$) compared to moderate-quality (0.11 larvae$\cdot h^{-1} \cdot m^{-3}$) and poor-quality (0.09 larvae$\cdot h^{-1} \cdot m^{-3}$) habitats ($P < 0.05$).

Larval surveys in the Middle Channel indicated that high larval concentrations occurred in three areas approximately 1.5, 3.0, and 4.5 km downstream from the Middle Channel Reef (Figure 2; Table 5). The first two areas closest in proximity to the reef contained 51 and 14 larvae, respectively, and were in moderate-quality habitat. The third area of high larval concentration occurred in high-quality habitat and contained 15 larvae. All three areas of high larval yield occurred in sand–silt substrate. In addition to these three areas, larval Lake Sturgeon were collected sporadically throughout the full extent of the system, with two individuals collected at the mouth of the channel (Figure 2).

The total VCPUE of larval Lake Sturgeon in Fighting Island Channel was significantly lower than that in the Middle Channel (one-tailed *t*-test: $P = 0.023$). Larvae ($n = 25$) were collected downstream of Fighting Island Reef during summer 2016 at 16 different locations from approximately 400 net-hours of sampling. Larval TL, which ranged from 12.5 to 19.7 mm (17.7 ± 1.9 mm; Figure 3), was similar to that in the Middle Channel; however, larvae collected in Fighting Island Channel from a single net were homogeneous in size (within 1.4 mm of each other), and a significantly higher proportion was found with no yolk sac (77.8%) compared to those in the Middle Channel (57.4%; $P = 0.041$). Six Lake Sturgeon larvae were collected in areas of high-quality habitat, 17 were captured in moderate-quality habitat, and 1 was collected in poor-quality habitat (Table 4). There was no significant difference in VCPUE measured for nets located in areas of high-, moderate-, and poor-quality habitat within Fighting Island Channel. Larvae were collected throughout the full extent of the system, beginning 0.25 km downstream from Fighting Island Reef to 5 km downstream at the mouth of Fighting Island Channel.

Unlike the Middle Channel, areas of high larval concentration were not observed in Fighting Island Channel. The VCPUE in areas of poor-quality habitat was significantly greater in Fighting Island Channel than in the Middle Channel ($P = 0.03$). No significant differences were found in VCPUE for areas of high- or moderate-quality habitat between the two channels (one-tailed *t*-test: $P > 0.05$ for both comparisons). Fighting Island Channel contained higher proportions of clay and clay–silt areas compared to the Middle Channel. Clay is a less-effective medium for larvae to settle on and received an HSI score of 0.2 (Table 1; Threader et al. 1998). In contrast, the most dominant substrate found in the Middle Channel (sand–silt) received an HSI score of 1.0.

Local habitat conditions also influenced the occurrence of larval Lake Sturgeon. The AIC_c analysis combining catch and habitat parameters was used to compare 13 different multiple linear regressions describing VCPUE–habitat relationships in the Middle and Fighting Island channels (Table 2). The 13 different linear regression models were identical to those tested in our earlier study of larval Lake Sturgeon dispersal in the North Channel (Krieger and Diana 2017) to allow for comparisons between all three systems. For both the Middle and Fighting Island channels, only the top model is discussed because no other model was within 2 units of the lowest AIC_c value, with the exception of the null model for Fighting Island Channel, suggesting that there was a low probably of other models having the best fit (Burnham and Anderson 2002). For the Middle Channel, the highest ranked linear regression model predicted VCPUE by using substrate—specifically the locations composed of sand–silt substrate ($F = 2.38$, df = 14, $P = 0.046$; $R^2 = 0.21$). For Fighting Island Channel, the highest ranked linear regression model predicted VCPUE by using benthic flow velocity, but this model was not statistically significant ($F = 4.33$, df = 12, $P = 0.072$; $R^2 = 0.11$), indicating that local habitat characteristics surveyed in this study did not significantly correlate with larval VCPUE in Fighting Island Channel.

Although larval abundance was low in Fighting Island Channel, estimated Lake Sturgeon egg density was considerably higher than in the Middle Channel. Lake Sturgeon egg sampling in the Middle Channel yielded 243 eggs/m^2 from egg mat gangs deployed immediately around the Middle Channel Reef during 2013–2014 (Prichard et al. 2017), whereas 1,367 eggs/m^2 were collected from gangs around Fighting Island Reef during 2016 surveys (Craig et al. 2017). Total estimated egg deposition was 9.8×10^5 for Middle Channel Reef and 7.8×10^6 for Fighting Island Reef.

DISCUSSION

Variation in dispersal of larval Lake Sturgeon in relation to composition and spatial distribution of suitable habitat found in the Middle and Fighting Island channels supports our hypotheses on Lake Sturgeon–habitat interactions in the St. Clair and Detroit rivers. In the Middle Channel, high-quality habitat consisted of areas with sand–silt substrate, and HSM output indicated the presence of high-quality habitat at variable distances downstream of the Middle Channel Reef where larval VCPUE was significantly greater compared to areas of moderate- or poor-quality habitat. In contrast, Fighting Island Channel was composed predominately of clay and clay–silt substrate, larvae were found in low abundance, and there was no distinction in larval VCPUE among high-, moderate-, and poor-quality habitat areas.

Given that high-quality habitat in the Middle Channel did not occur until 4.5 km downstream from the Middle Channel Reef, we would expect low larval

TABLE 3. Medians (range in parentheses) for environmental variables measured in the Middle Channel (MC) and Fighting Island Channel (FIC) by habitat quality. Substrate composition is excluded from this table because it is a categorical variable.

Site	Habitat quality	Area (km²)	Benthic current velocity (m/s)	Invertebrate density (number/m²)	Depth (m)
MC	High	2.74	0.43 (0.36–0.47)	927 (905–1,125)	13.26 (12.6–14.03)
	Moderate	14.14	0.38 (0.24–0.41)	1,336 (129–4,181)	12.19 (10.95–15.5)
	Poor	1.18	0.25 (0.12–0.56)	450 (124–2,253)	4.7 (2.3–7.8)
	Unsuitable	0.00	0.00	0.0	0.0
FIC	High	1.19	0.42 (0.34–0.43)	882 (794–3,312)	11.5 (8.9–11.86)
	Moderate	5.61	0.37 (0.33–0.47)	794 (18–1,588)	10.7 (8.9–11.28)
	Poor	0.27	0.34 (0.29–0.51)	176 (0–265)	7.85 (8.93–9.24)
	Unsuitable	0.00	0.00	0.0	0.0

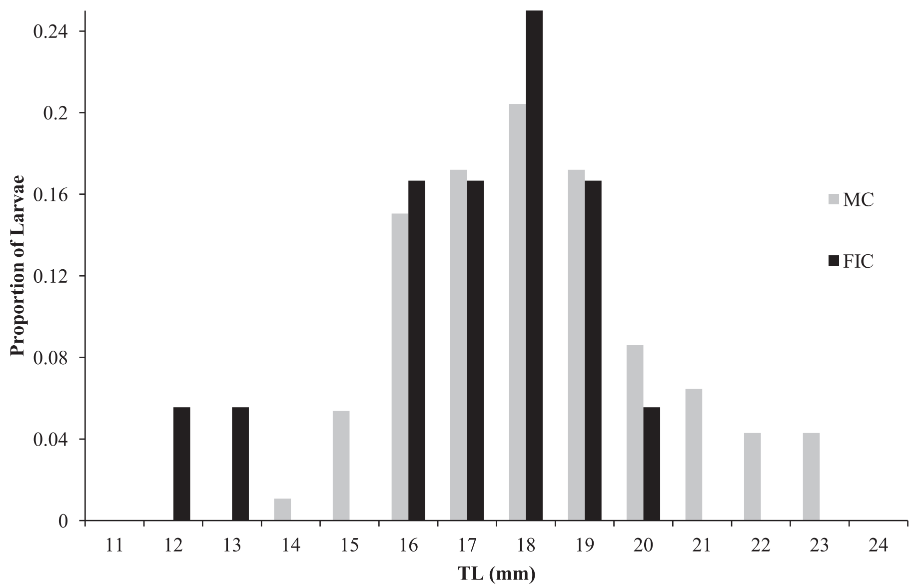

FIGURE 3. Length frequency histogram of larval Lake Sturgeon collected from the Middle Channel (MC) and Fighting Island Channel (FIC) in 2013–2016.

TABLE 4. Summary statistics describing larval Lake Sturgeon catch from drift nets in each habitat quality type by river system (MC = Middle Channel; FIC = Fighting Island Channel; VCPUE = water-volume-standardized CPUE).

Site	Habitat quality	Larvae collected	Net-hours	CPUE (larvae/h)	VCPUE (larvae·h^{-1}·m^{-3})
MC	High	15	221	0.068	0.15
	Moderate	76	481	0.158	0.11
	Poor	2	112	0.018	0.09
	Unsuitable	0	0	0.000	0.00
FIC	High	6	105	0.057	0.048
	Moderate	17	272	0.063	0.011
	Poor	1	25.5	0.039	0.140
	Unsuitable	0	0	0.000	0.000

abundance immediately downstream from the reef and higher abundance closer to areas of high-quality habitat further downstream. Our survey of larval Lake Sturgeon in the Middle Channel identified three areas of high larval concentration where 86% of larvae were collected: at 1.5, 3.0, and 4.5 km downstream from

TABLE 5. Summary catch statistics for six locations (within three clusters) that had high densities of larval Lake Sturgeon within the Middle Channel (MC). The area of each high-density location is given along with the percent area relative to the total study area (in parentheses). Cluster ID corresponds to the point locations depicted in Figure 2 (VCPUE = water-volume-standardized CPUE). The percent contribution of each high-density location to total larval yield from the MC is also given.

Cluster ID	Habitat quality	Area (km²)	Larvae collected	Net-hours	VCPUE (larvae·h^{-1}·m^{-3})	Percent of total
1-MC	High	0.041 (0.22%)	15	220.33	0.12	16
2-MC	Moderate	0.094 (0.52%)	14	270.57	0.103	15
3-MC	Moderate	0.098 (0.53%)	51	120.13	0.59	54

the Middle Channel Reef. Only three larvae were collected within 1.5 km downstream of the reef, and only five larvae were captured further than 4.5 km downstream. Furthermore, our AIC_c analysis indicated that the presence of sand–silt substrate best described the observed VCPUE values in the Middle Channel. Although only one area of high larval concentration overlapped with high-quality habitat in the Middle Channel, all three areas occurred at locations possessing sand–silt substrate.

These findings for the Middle Channel match well with and are supported by our prior study of larval Lake Sturgeon–habitat associations in the nearby North Channel (Krieger and Diana 2017). The HSM output from that study indicated an abundance of high-quality habitat for larvae located in distinct patches approximately 0.25, 0.75, 1.25, and 2.00 km downstream of the Maslinka Reef, and 81% of larvae (n = 283) were collected in those patches. Using analogous AIC_c analysis methods, we (Krieger and Diana 2017) found that the presence of sand substrate was the best predictor of larval CPUE in the North Channel and that larvae occurred at high densities in areas comprised of sand.

In contrast, no significant association between VCPUE and habitat quality was found for larval Lake Sturgeon in Fighting Island Channel. In the North and Middle channels, larvae congregated in areas comprised of sand and sand–silt, which can provide refuge from high current velocities and potential predators (Auer and Baker 2002; Benson et al. 2005). However, Fighting Island Channel possessed higher proportions of clay and clay–silt, each of which is a less-suitable medium for larval settlement (Benson et al. 2005; Krieger and Diana 2017). Indeed, of the four habitat parameters assessed in this study, substrate composition was the lone variable included in the best multiple linear regressions predicting larval VCPUE for both the North and Middle channels. As such, it is reasonable to assume that substrate would also influence larval dispersal in Fighting Island Channel. While our model identified suitable larval habitat in Fighting Island Channel, high HSI scores from non-substrate habitat parameters likely influenced HSM rankings. For instance, an area in Fighting Island Channel composed of the median habitat values for depth, invertebrate density, velocity (Table 3), and clay–silt substrate would still receive a composite HSM score of 0.78, close to a ranking of "high-quality" habitat in our study. Although depth, invertebrate density, and velocity values are quite similar for the North, Middle, and Fighting Island channels, the substrate composition of Fighting Island Channel is markedly different. Since we gave equal weighting to all variables in our model, the similarities in some habitat characteristics could have underestimated the importance of substrate composition in our HSM prediction. Given that larval Lake Sturgeon have been shown to drift greater distances when suitable substrate was not readily encountered (Hastings et al. 2013), prolonged time spent drifting could result in increased risks of predation and starvation (Auer and Baker 2002; Peterson et al. 2007), corresponding to high larval mortality rates and the relatively low abundance observed in our study.

In addition, even though estimated egg densities on Fighting Island Reef were much higher than densities from the Middle Channel Reef, larval sampling in Fighting Island Channel yielded far fewer individuals than were collected in the Middle Channel. This may indicate that few larvae enter Fighting Island Channel due to high egg mortality or that larvae emerge from the reef and quickly drift through the channel. However, larval yield was low even in nets placed immediately downstream of the reef. Furthermore, if larvae were drifting quickly out of Fighting Island Channel immediately after emergence, we would expect higher catch rates during peak drift and a shorter overall drift period compared to the Middle Channel—neither of which was observed. As such, although we believe that egg deposition on Fighting Island Reef is sufficient to produce similar numbers of drifting larvae as found in the North Channel (n = 283; Krieger and Diana 2017) and Middle Channel (n = 93; present study), high rates of egg and larval mortality are likely responsible for low larval VCPUE in Fighting Island Channel.

Differences in the physical characteristics of collected larvae further support our assertion on variable drift patterns in larval Lake Sturgeon. In the Middle Channel, the majority of larvae collected were over 19 mm in length and were found with either a partial yolk sac (62%) or a fully absorbed yolk sac (33%), indicating that they were ending the yolk sac stage and initiating consumption of food. Peterson et al. (2007) noted that larval Lake Sturgeon remain on the natal reef for periods of 2–4 weeks after hatch as they absorb their yolk sacs and then emerge from the reef with relatively similar lengths and partially or fully absorbed yolk sacs as they begin to drift downstream (LaHaye et al. 1992; Auer and Baker 2002). However, larvae that were collected downstream of Middle Channel Reef ranged in size by as much as 9 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 that 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 the majority of larvae were dislodged, downstream collections should contain higher proportions of small (12–16 mm) individuals with full yolk sacs, and more consistent numbers of larvae should be collected throughout the channel (as described by Smith and King 2005; Peterson et al. 2007). Instead, variability in size and developmental stage observed in larvae collected from the Middle Channel suggests that individuals were residing in the river in areas of favorable habitat after drifting variable distances downstream from their spawning source.

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). Although larvae in the Middle Channel were more dispersed than those collected in the North Channel, we found that larval VCPUE in the Middle Channel was also significantly correlated with high-quality habitat and was concentrated in three distinct areas. For Fighting Island Channel, we found a low abundance of larvae in high-quality habitat and the lack of a significant relationship between habitat parameters and larval VCPUE. Based on this, we conclude that larvae exited the channel and dispersed into the Detroit River. Although variation in patterns of larval dispersal occurred across these river reaches, such variation was consistent with our predictions of larval dispersal in response to local habitat conditions in each system. Drifting larvae made use of and congregated around suitable habitat—most notably sand and sand–silt substrate in deep water with moderate currents—when it was available to them. If such habitat was not available, larvae remained in the water column and quickly drifted out of the study system. This is an important first step in linking HSI relationships across different reaches of river that support Lake Sturgeon and other species of interest and emphasizes the importance of local habitat conditions in determining dispersal and habitat use by early life stage fishes. The Middle and Fighting Island channels are similar in many ways, but there are dissimilarities that result in different patterns of larval Lake Sturgeon occurrence. System-specific models incorporating a range of local habitat characteristics allow us to evaluate and compare habitat features between seemingly similar systems and to determine subtle yet important differences that exert a profound influence on the distribution of local species.

Limitations and Biases

Although the findings and interpretations generated from this study are supported by available data and existing literature, some limitations and assumptions resulted from a lack of available data. First, while predation on larval Lake Sturgeon has not been documented in the St. Clair River or Detroit River, predators undoubtedly influence larval survival and subsequent dispersal to nursery habitat. Given that larvae were found to concentrate in areas at variable distances downstream of their spawning source rather than continually decreasing with downstream distance in the North and Middle channels, the observed dispersal patterns in these systems cannot be explained by predator effects alone but are instead the result of preferential habitat selection by larvae as well.

Additionally, there is a lack of knowledge regarding sources of larval Lake Sturgeon from locations upstream of our study sites. Young (2015) collected 54 larvae just upstream from the Middle Channel Reef; however, those larvae showed proportions of stages with full, partial, and no yolk sacs that were nearly identical to the proportions among larvae collected from downstream in our study. In addition, the lengths of larvae collected upstream and downstream from the Middle Channel Reef in our study were not statistically discernible. Given the distinct concentrations of larvae in areas of high- and moderate-quality habitat downstream of the Middle Channel Reef and the similarities in morphometric characteristics for upstream versus downstream collections, we believe that larvae from upstream sources drifted past the Middle Channel Reef, mixed with larvae emerging from this reef, and used similar habitat downstream. Thus, the input of upstream larvae is not influencing the larval distribution patterns found downstream.

CONCLUSION

Observed larval Lake Sturgeon dispersal and associations with local habitat quality support two main conclusions. First, larval dispersal in the St. Clair and Detroit rivers varies in response to local habitat conditions, and system-specific evaluation is required in order to understand local larval–habitat associations. This conclusion is supported by the variable patterns of larval dispersal in individual reaches of the St. Clair and Detroit rivers. Our second conclusion is that substrate is the most significant predictor of likely nursery areas for larval Lake Sturgeon in our study rivers and possibly for Lake Sturgeon in other Great Lakes connecting channels.

Although the North, Middle, and Fighting Island channels possess similar hydrological and ecological characteristics, they are still quite distinguishable. All three reaches have experienced varying levels of anthropogenic modification, harvest and overfishing pressures, and impacts from contaminants and invasive species, and they exhibit differences in specific habitat conditions. Subtle differences like these are what distinguishes the three channels as unique systems and in part drives the variation in larval Lake Sturgeon behavior highlighted in this study. Given this variation, we believe the mere presence of suitable habitat within a system is not sufficient for utility as nursery habitat. Rather, we believe the amount and location of this habitat in relation to sources of young Lake Sturgeon shape early behavior and distribution by influencing larval drift and subsequent survival. Given the importance of early life stage success in the recovery of Lake Sturgeon, future work should focus on linking available HSMs that are designed to identify candidate sites for spawning habitat in multiple rivers (such as the one developed for our study system by Bennion and Manny 2014) to models that have been developed for identifying nursery areas. By understanding the connectivity between stages of early life development, we can better understand the effects of proposed restoration activities and identify ongoing impediments to stock recovery.

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REFERENCES

Auer, N. A., and E. A. Baker. 2002. Duration and drift of larval Lake Sturgeon in the Sturgeon River, Michigan. Journal of Applied Ichthyology 22:557–564.

Bauman, J. M., A. Moerke, R. Greil, B. Gerig, E. Baker, and J. Chiotti. 2011. Population status and demographics of Lake Sturgeon (*Acipenser fulvescens*) in the St. Mary's River, from 2000 to 2007. Journal of Great Lakes Research 37:47–53.

Bennion, D. H., and B. A. Manny. 2011. Construction of shipping channels in the Detroit River: history and environmental consequences. U.S. Geological Survey, Scientific Investigations Report 2011-5122, Ann Arbor, Michigan.

Bennion, D. H., and B. A. Manny. 2014. A model to locate potential areas for Lake Sturgeon spawning habitat construction in the St. Clair-Detroit River system. Journal of Great Lakes Research 40: 43–51.

Benson, A. C., T. M. Sutton, R. F. Elliot, and T. G. Meronek. 2005. Seasonal movement patterns and habitat preferences of age-0 Lake Sturgeon in the lower Peshtigo River, Wisconsin. Transactions of the American Fisheries Society 134:1400–1409.

Benson, A. C., T. M. Sutton, R. F. Elliot, and T. G. Meronek. 2006. Biological attributes of age-0 Lake Sturgeon in the lower Peshtigo River, Wisconsin. Journal of Applied Ichthyology 22:103–108.

Boase, J. C., J. S. Diana, M. V. Thomas, and J. A. Chiotti. 2011. Movements and distribution of adult Lake Sturgeon from their spawning site in the St. Clair River, Michigan. Journal of Applied Ichthyology 27:58–65.

Bouckaert, E. K., N. A. Auer, E. F. Roseman, and J. Boase. 2014. Verifying success of artificial spawning reefs in the St. Clair-Detroit River system for Lake Sturgeon (*Acipenser fulvescens* Rafinesque, 1817). Journal of Applied Ichthyology 30:1393–1401.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach, 2nd edition. Springer, New York.

Caroffino, D. C., T. M. Sutton, and D. J. Daugherty. 2009. Assessment of the vertical distribution of larval Lake Sturgeon drift in the Peshtigo River, Wisconsin, USA. Journal of Applied Ichthyology 25:14–17.

COSEWIC (Committee on the Status of Endangered Wildlife in Canada). 2017. COSEWIC assessment and status report on the Lake Sturgeon *Acipenser fulvescens*, western Hudson Bay populations, Saskatchewan–Nelson River populations, southern Hudson Bay–James Bay populations and Great Lakes–Upper St. Lawrence populations in Canada. COSEWIC, Gatineau, Quebec.

Craig, J., G. Kennedy, and E. Roseman. 2017. Fish eggs collected in the St. Clair and Detroit rivers, 2005–2016. U.S. Geological Survey, Great Lakes Science Center, Ann Arbor, Michigan.

D'Amours, J. D., S. Thibodeau, and R. Fortin. 2001. Comparison of Lake Sturgeon (*Acipenser fulvescens*), *Stizostedion* spp., *Catostomus* spp., *Moxostoma* spp., Quillback (*Carpiodes cyprinus*), and Mooneye (*Hiodon tergisus*) larval drift in Des Prairies River, Quebec. Canadian Journal of Zoology 79:1472–1489.

Daugherty, D. J., T. M. Sutton, and R. F. Elliott. 2009. Suitability modeling for Lake Sturgeon habitat in five northern Lake Michigan tributaries: implications for population rehabilitation. Restoration Ecology 17:245–257.

Great Lakes Fish and Wildlife Restoration Act of 2006. U.S. Code, volume 16, section 941.

Hastings, R. P., J. M. Bauman, E. A. Baker, and K. T. Scribner. 2013. Post-hatch dispersal of Lake Sturgeon (*Acipenser fulvescens*, Rafinesque, 1817) yolk-sac larvae in relation to substrate in an artificial stream. Journal of Applied Ichthyology 29:1208–1213.

Haxton, T. J., C. S. Findlay, and R. W. Threader. 2008. Predictive value of a Lake Sturgeon habitat suitability model. North American Journal of Fisheries Management 28:1373–1383.

Hayes, J., and D. C. Caroffino. 2012. Michigan's Lake Sturgeon rehabilitation strategy. Michigan Department of Natural Resources, Fisheries Special Report 62, Lansing.

Hirzel, A. H., G. L. Lay, V. Helfer, C. Randin, and A. Guisan. 2006. Evaluating the ability of habitat suitability models to predict species presence. Ecological Modelling 199:142–152.

Hondorp, D. W., E. F. Roseman, and B. A. Manny. 2014. An ecological basis for future fish habitat restoration efforts in the Huron–Erie Corridor. Journal of Great Lakes Research 40:23–30.

Kempinger, J. J. 1988. Spawning and early life history of Lake Sturgeon in the Lake Winnebago system, Wisconsin. Pages 110–122 *in* R. D. Hoyt, editor. Eleventh annual larval fish conference. American Fisheries Society, Symposium 5, Bethesda, Maryland.

Kempinger, J. J. 1996. Habitat, growth, and food of young Lake Sturgeons in the Lake Winnebago system, Wisconsin. North American Journal of Fisheries Management 16:102–114.

Krieger, J. R., and J. S. Diana. 2017. Development and evaluation of a habitat suitability model for young Lake Sturgeon (*Acipenser fulvescens*) in the North Channel of the St. Clair River, Michigan. Canadian Journal of Fisheries and Aquatic Sciences 74:1000–1008.

LaHaye, M., A. Branchaud, M. Gendron, R. Verdon, and R. Fortin. 1992. Reproduction, early life history, and characteristics of the spawning grounds of the Lake Sturgeon (*Acipenser fulvescens*) in Des Prairies and L'Assomption rivers, near Montreal, Quebec. Canadian Journal of Zoology 70:1681–1689.

Larson, M. A., F. R. Thompson III, J. J. Millspaugh, W. D. Dijak, and S. R. Shifley. 2004. Linking population viability, habitat suitability, and landscape simulation models for conservation planning. Ecological Modelling 180:103–118.

Mazerolle, M. J. 2017. AICcmodavg: model selection and multimodel inference based on (*Q*)AIC(*c*). R package version 2.1-1. Available: https://cran.r-project.org/package=AICcmodavg. (August 2018).

Morris, L., and D. Ball. 2006. Habitat suitability modeling of economically important fish species with commercial fisheries data. ICES Journal of Marine Science 63:1590–1603.

Nilo, P., S. Tremblay, A. Bolon, J. Dodson, P. Dumont, and R. Fortin. 2006. Feeding ecology of juvenile Lake Sturgeon in the St. Lawrence River system. Transactions of the American Fisheries Society 135:1044–1055.

Peterson, D. L., P. Vecsei, and C. A. Jennings. 2007. Ecology and biology of the Lake Sturgeon: a synthesis of current knowledge of a threatened North American Acipenseridae. Review of Fish Biology and Fisheries 17:59–76.

Prichard, C. G., J. M. Craig, E. F. Roseman, J. L. Fischer, B. A. Manny, and G. W. Kennedy. 2017. Egg deposition by lithophilic-spawning fishes in the Detroit and Saint Clair rivers, 2005–2014. U.S. Geological Survey, Great Lakes Science Center, Scientific Investigations Report 2017-5003, Ann Arbor, Michigan.

R Development Core Team. 2008. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. Available: http://www.R-project.org. (August 2018).

Read, J., and B. A. Manny. 2006. Monitoring element of the Belle Isle/Detroit River sturgeon habitat restoration, monitoring, and education program. Research Completion Report submitted to the Michigan Sea Grant program, University of Michigan, Ann Arbor.

Roseman, E. F., J. Boase, G. Kennedy, J. Craig, and K. Soper. 2011b. Adaption of egg and larvae sampling techniques for Lake Sturgeon and broadcast spawning fishes in a deep river. Journal of Applied Ichthyology 27:89–92.

Roseman, E. F., B. Manny, J. Boase, M. Child, G. Kennedy, J. Craig, K. Soper, and R. Drouin. 2011a. Lake Sturgeon response to a spawning reef constructed in the Detroit River. Journal of Applied Ichthyology 27:66–76.

Schwab, D. J., A. H. Clites, C. R. Murthy, J. E. Sandall, L. A. Meadows, and G. A. Meadows. 1989. The effect of wind in transport and circulation in Lake St. Clair. Journal of Geophysical Research 94:4947–4958.

Smith, K. M., and D. K. King. 2005. Dynamics and extent of larval Lake Sturgeon *Acipenser fulvescens* drift in the Upper Black River, Michigan. Journal of Applied Ichthyology 21:161–168.

Thomas, M. V., and R. C. Haas. 2004. Abundance, age structure, and spatial distribution of Lake Sturgeon *Acipenser fulvescens* in the St. Clair system. Michigan Department of Natural Resources, Fisheries Research Report 2076, Ann Arbor.

Threader, R. W., R. J. Pope, and P. R. H. Schaap. 1998. Development of a habitat suitability index for Lake Sturgeon. Ontario Hydro, Report H-07015.01-0012, Toronto.

Verdon, R., J. C. Guay, M. La Haye, M. Simoneau, A. Cote-Bherer, N. Ouellet, and M. Gendron. 2013. Assessment of spatio-temporal variation in larval abundance of Lake Sturgeon (*Acipenser fulvescens*) in the Rupert River (Quebec, Canada), using drift nets. Journal of Applied Ichthyology 29:15–25.

Vinagre, C., V. Fonseca, H. Cabral, and M. J. Costa. 2006. Habitat suitability index models for the juvenile soles, *Solea solea* and *Solea senegalensis*, in the Tagus estuary: defining variables for species management. Fisheries Restoration 82:140–149.

Wang, Y. L., F. P. Binkowski, and S. I. Doroshov. 1985. Effect of temperature on the early development of White and Lake sturgeon, *Acipenser transmontanus* and *A. fulvescens*. Environmental Biology of Fishes 14:43–50.

Wentworth, C. K. 1922. A scale of grade and class terms for clastic sediments. Journal of Geology 30:377–392.

Young, R. T. 2015. Assessing the spatiotemporal distribution of larval Lake Sturgeon (*Acipenser fulvescens*) within the St. Clair River delta, Michigan. Master's thesis. University of Michigan, Ann Arbor.