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Assessment of Freshwater Mussel Communities of Small Stream Mouths Along Lake Erie

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ASSESSMENT OF FRESHWATER MUSSEL COMMUNITIES OF SMALL STREAM MOUTHS ALONG LAKE ERIE

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ABSTRACT

Invasion of lakes and rivers by dreissenid mussels pushed out native species, particularly freshwater mussels in the Unionidae, across the northern hemisphere, and perhaps most infamously, within the Laurentian Great Lakes. However, several coastal areas along the shallowest of these lakes, Lake Erie, may be refugia for native species, but the conditions under which native species persist are unknown. I surveyed river mouths of small streams along the Lake Erie coastline and compared species abundance to land use assessed by remote sensing techniques and to standard measures of water chemistry. Sampling focused on stream zones influenced by lake-water levels for three streams each in the western and central basins of Lake Erie and in Sandusky Bay. Eight of the nine streams possessed mussels: *Pyganodon grandis* (7 streams), *Toxolasma parvum* (5 streams), *Quadrula quadrula* (5 streams), *Lasmigona complanata* (5 streams), *Leptodea fragilis* (4 streams), and *Utterbackia imbecillus* (2 streams), while *Amblema plicata*, *Obliquaria reflexa* and *Uniomerus tetralasmus* were found each in only one stream. Distinct bathymetric features did not affect diversity levels, although water chemistry may have reduced abundance in some streams and unionid abundance was positively correlated with turbidity. Regional land use altered species dominance, as streams within physiographic regions containing higher amounts of silt were dominated by *Q. quadrula*, while more mixed habitat was dominated by *P. grandis.* Because, river mouths are refugia for unionid mussels, these areas must return to or come under

regulatory control to monitor habitat alteration, a process stopped in this region following the belief that dreissenid mussels had eradicated all species of interest.

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CHAPTER I

INTRODUCTION

Freshwater mussels in North America (Bivalvia : Unionidae) have been identified as one of the most jeopardized taxa on the continent (Williams et al. 1993). The Cumberland and Tennessee River systems in the American southeast, are historically known habitats for diverse unionid assemblages and once supported upwards of 87 species of native freshwater mussels. By the early 1990's 48 of those unionid species were considered imperiled (Williams et al. 1993). Much of the decline in diversity and abundance of freshwater biota, including mollusks, has been attributed to anthropogenically induced factors such as overexploitation, water pollution, flow modification, destruction and degradation of habitat, and the introduction of exotic species (Dudgeon et al. 2006, Haag 2012). Elsewhere in North America on the northern distributional fringe of unionids in the midwest, many of the species that formerly inhabited Lake Erie have been extirpated (Schloesser and Nalepa 1994).

The life-cycle of unionid mussels as well as their ecological niche are each critical starting points for understanding why this group of invertebrates is declining in abundance, diversity, and distribution (Haag 2012). In their larval form, unionid mussels are parasitic, while adult unionids are free-living, benthic dwelling filter feeders that ingest water through siphons. Once ingested, the water is filtered for algae, bacteria, and other organic particles. Conception of a unionid mussel begins with the release of spermatozoa by males into the water column. After freely floating, and with some luck the male gemetes will be taken in my female unionid's incurrent siphon. In the female unionid's gills the spermatozoa will fertilize eggs in the gills. When matured into glochidia, the next generation of mussels will be ejected through the excurrent siphon of a female (Haag 2012). Once in the water column, larval unionids may meet several fates: they may come into contact with a suitable host organism, be consumed by a predator, or die from the lack of host attachment. Depending on the species, glochidia can survive anywhere from hours to days before either attaching to a suitable host or perishing from lack of nutrition input (Zimmerman and Neves 2002). For example, specific glycoproteins such as fibrinogen are thought to be important macromolecules used during glochidia maturation and are suspected to trigger the metamorphosis of the glochidia into a cyst that remains attached to the host until as a juvenile mussel, it detaches from the host (Henley and Neves 2001).

Most commonly unionids are obligate parasites using fish as their host organisms. Some unionids accept a variety of fish hosts, while others are only able to use one. For example, *Toxolasma parvum* (common name: lilliput) uses *Lepomis cyanellus* (common name: green sunfish) as its only host (Graf 2002), while *Quadrula cylindrica* (common name: rabbit's foot) uses several species from the family *Cyprinidae* (Graf 2002). One species attaches to amphibians instead of fish, *Simpsonaias ambigua* uses *Necturus maculosus* (mudpuppy) as its host. To attaract these hosts, some adult unionids have elaborate lures protruding from their mantle. These lures draw host-appropriate fish close to the mussel to increase the likelihood of attachment by glochidia. Glochidia will attach to a host based on its own morphology. Typically, hooked glochidia may attach to gills, fins, or scales, while those without hooks will attach to gills (Bauer 1994). The morphology of glochidia differs by sub-family. The *Anodontinae* produce glochidia with hooks, while members of *Ambleminae* have no hooks (David and Fuller 1981).

Migration of unionids is largely, if not entirely, based on the movement of their hosts. Fish commonly move up and down streams, as well as into and out of lakes via river mouths; although movement may be limited (Borden 2009) due to lack physical connectivity from anthropogenic means such as dams or impediments, or from natural fragmentation caused by ephemeral river mouths that may be open or closed depending on water level (Zwick 1992). As a result of the migratory behavior of fish hosts, glochidia are able to "hitch a ride" against currents to later drop off of the host fish upstream, where they will complete their life cycle as adult mussels. The "drop-off" point for juvenile mussels is important for determining unionid distribution because adult unionids are functionally sedentary. Adults have a limited capability to migrate horizonitally and vertically within the benthos, but they do not cover great distances and the stimulus for moving is commonly temperature during winter and summer in some areas (Allen and Vaughn 2009). Substrate quality and nutrient availability around that point are two of many possible factors that influence the likelihood of unionid colonization. Using only a muscular foot, freshwater mussels are likely limited by the substrate. Unionids generally inhabit areas with a soft substrate, one that is primarily sand or silt.

The life histories and niches of two particular invasive species, or one exotic genus, have greatly changed the distribution of unionid mussels. In the mid 1980's, *Dreissena polymorpha* (zebra mussel), and *Dreissena bugensis* (quagga mussel) (Bivalvia : Dreissenidae) were introduced into the Great Lakes via the ballast of shipping barges (Herbert et al, 1989). Dreissenids are filter-feeders in lentic environments, and their larvae are veligers, which are free-living throughout this portion of their life-cycle. They do not attach to a fish to move upstream, nor can they move against a current. Dreissenid adult forms fit the strict definition of sedentary; they rarely move once attached to a hard substrate using their byssal threads. There are a wide variety of materials suitable for attachment. Dreissenids have been observed colonizing allochthonous input such as wood, concrete, and discarded tires. They also attach to biotic surfaces like the submerged portion of *Phragmities australis*, unionid mussels, discarded unionid shells, and other dreissenids (Lancioni and Gaino 2006). Dreissenid affinity for attaching to unionids is a leading cause for the extirpation of many native mussel species from the lake. The lattermost substrate makes it possible for these invasive mussels to colonize areas of soft substrate such as sand by stacking on top of discarded and deceased dressenids. One individual may attach to a grain of sand, and on top this one individual many more will attach.

Dreissenids have preferences for sites of attachment. Veliger larvae seem to prefer horizontal surfaces, the underside of artificial substrates as opposed to sunlit upper surface, and non-toxic elements thus avoiding copper, brass, and iron (Lancioni and Gaino 2006). Dreissenid mussels will also not colonize silt, but will readily attach to the shell of unionid mussels in a silty benthos. These exotic mussels were first detected in the Great Lakes in 1986 and their impact was pronounced by the early to mid 1990's due to studies describing the loss of unionids in Lake Erie (Table 1) (Nalepa et al. 1991, Schloesser and Nalepa 1994). As a result of these life-history qualities and substrate preferences, dreissenids rely on anthropogenic means of movement and water current to be dispersed through water bodies (Lancioni and Gaino 2006, Karatayev 1998).

At one time, Lake Erie supported millions of unionid mussels (Wood 1953) and before the mid 1980's, as many as 47 species once made this lake and its tributaries home (Strayer and Jirka 1997, Graf 2002). Lake Erie possesses several traits that make it excellent mussel habitat. This lake is eutrophic and the increased nutrient concentration, along with the warm temperature in Lake Erie's western basin may be the basis for the diverse food web within that part of the lake, which includes many types of fish and algae (Sprules 2008). Lake Erie's substrate is generally very soft and silty with scattered sand bars (Herdendorf 1987); this variation in substrates allows for suitable burrowing habitat for many lotic species of unionid (Haag 2012).

In lentic and very slowly moving lotic habitats, dreissenid mussels found a niche incorporating unionids as a substrate (Herbert et al 1989). Unionid shells provide a stable and hard location for attachment, which aided the dreissenids in becoming established in Lake Erie; much of the substrate away from the shoreline is very soft and unstable. Also, dreissenid mussels were able to enhance their filter feeding, because in close proximity to a dreissenid's point of attachment lies the incurrent siphon of unionids, which constantly draws in water. Dreissenids tap into the incurrent flow created by the “substrate unionid” using their own incurrent siphon to more easily ingest particulate matter. Commonly, many dreissenids attach to one unionid contributing to death by starvation for the unionid. This almost parasitic behavior is thought to be the main factor that eliminated many unionid species from Lake Erie (Baker and Levinton, 2003).

Unionids are an indicator of water quality due to their filter feeding behavior and sensitivity to contaminants. Unionid mussels are for the most part at the mercy of their surroundings in regard to nutrition and health. Water pollution is considered to be one of the leading factors contributing to unionid decline (Strayer 2004), and although there is a gradient for pollution tolerance within Mollusca (Ortman 1917); generally speaking no unionids can survive in heavily polluted water. Living unionids are also proof of a healthy stream; more diverse and larger mussel communities are usually indicative of higher water quality in streams and lakes (Gangloff et al. 2009; Augspurger et al. 2003; Pip 2006).

Unionids display a wide range of pollution tolerance depending on the species, stage in the life-cycle, and type of pollutant. Glochidia and juvenile mussels may be more susceptible to poisoning via pollution than adults, as adults are adept at sequestering heavy metals (Waykar and Shine 2011), leading to the belief that current water quality regulations may not protect the younger life-stages of unionids (Wang 2007, 2009). A recent study in Ontario, Canada reported that chloride reaches levels that are acutely toxic to *Lampsilis faciola* glochida (Gillis 2011). Glochida may also be more sensitive towards monochloramine, a chemical formed when chloride and certain types of ammonia interact, typically downstream from wastewater flows (Goudreau et al. 1993). Metals such as lead, zinc, and copper are thought to reduce fitness of glochidia and are known to increase mortality (Kovats et al. 2010).

Unionids themselves exert feedback on their habitat. They aid in nutrient cycling (Newton at al. 2011). Many organisms rely on unionids for the release of nutrients into the water column, as the availability of nutrients often triggers production across trophic levels and increases the abundance of benthic invertebrates (Spooner 2006; Greenwood et al. 2001). Unionids cycle nutrients in two ways. They break down organic compounds filtered out from the water column as well as expel wastes that act as fertilizer (useful ammonia, organic nitrogen) for aquatic macrophytes such as algae, and as food for invertebrate scavengers (Davis, Christian and Berg 2000; Vaughn et al, 2008). Mussel waste products commonly are bacterially active and contain substantial amounts of useable carbon and phosphorus (Giles and Pilditch 2006). Unionids also physically disturb the benthos when moving, which causes nutrients (silicon, nitrogen, phosphorus) locked up in benthic sediment to be released into the water (Newton et al, 2011). Furthermore, discarded unionid shells add to the benthos because they can be used as shelter and perhaps even as a nesting area, as I observed for *Neogobius melanostomus*, the invasive round goby. The ability to cycle nutrients depends on biomass; larger mussels recycle more nutrients. The same idea applies to mussel community size; mussel beds with more individuals will cycle more nutrients than those with few individuals (Strayer 1991). If unionid abundance is declining across North America, it stands to reason that freshwater communities and ecosystems with a historical unionid component may deteriorate in diversity, and their ability to perform ecosystem services.

Land use and cover affect a stream by altering inputs and community structure (Tong and Chen 2001). Such watershed attributes can be drivers of a healthy stream ecosystem by regulating abundance and diversity of flora and fauna within that stream (Schloesser 1991). Mussels are greatly affected by the composition and temperature of surface water runoff; anthropogenic disturbance via pollution and change in land use within a watershed can greatly disturb unionid communities (Brown and Daniel, 2010). Runoff is usually warmed as it travels overland, especially in areas of low vegetation and high impervious surface. Tiled agricultural fields may also have a similar effect in warming runoff as they drain rapidly. Poole and Downing (2004) found that as the percent of agricultural land use in Iowa watersheds increased, species richness decreased. Rural areas typically add nutrients such as nitrogen and phosphorus containing compounds as well as sediment, and these areas also may harbor a fish community different than that of an urbanized area (Alexandre et al 2010; Arlinghaus et al. 2008; Lewis et al. 2007). Rural and forest watersheds will possess cyprinids (minnows) and other bethic-feeding species (Long and Shorr 2005). Urbanized areas are usually more severely impacted than rural systems (Lyons et al. 2007) and are generally characterized by the presence of centrarchids (sunfish) and other pollution tolerant taxa (Long and Shorr 2005). Urbanized areas will tend to add heavy metals, sodium, chloride and sulfate; impervious surface may also play a part in unionid distribution by allowing more of these urban pollutants direct access to streams (Tong and Chen 2001). By consequence, unionid extirpation rates in the southeastern United States (Gillis et al. 2011) as well as around Lake Erie (Krebs et al. 2010) are highest around cities and suburbs.

Land use types with vegetation coverage can modify properties of the runoff such as hydrologic cycle, chemistry and temperature. One example of a heavily vegetated land use type is the riparian zone which has the ability to moderate many aspects of a stream such as temperature, water composition and overall stream morphology (LeBlanc et al. 1997). A less vegetated land cover will decrease filtration rate and moisture retention of the soil, as well as possibly increase sediment loads in-stream and concentration of nitrogen and phosphorus based nutrients (Groffman et al. 2003). Unionids are also affected by changes in stream morphology; they commonly aggregate in area of less flooding and substrate scouring (Strayer 1999; Johnson and Brown 2000). Streams characterized by incised channels and unstable sand or unconsolidated gravel substratum will typically support few mussels (Brown and Curole 1997).

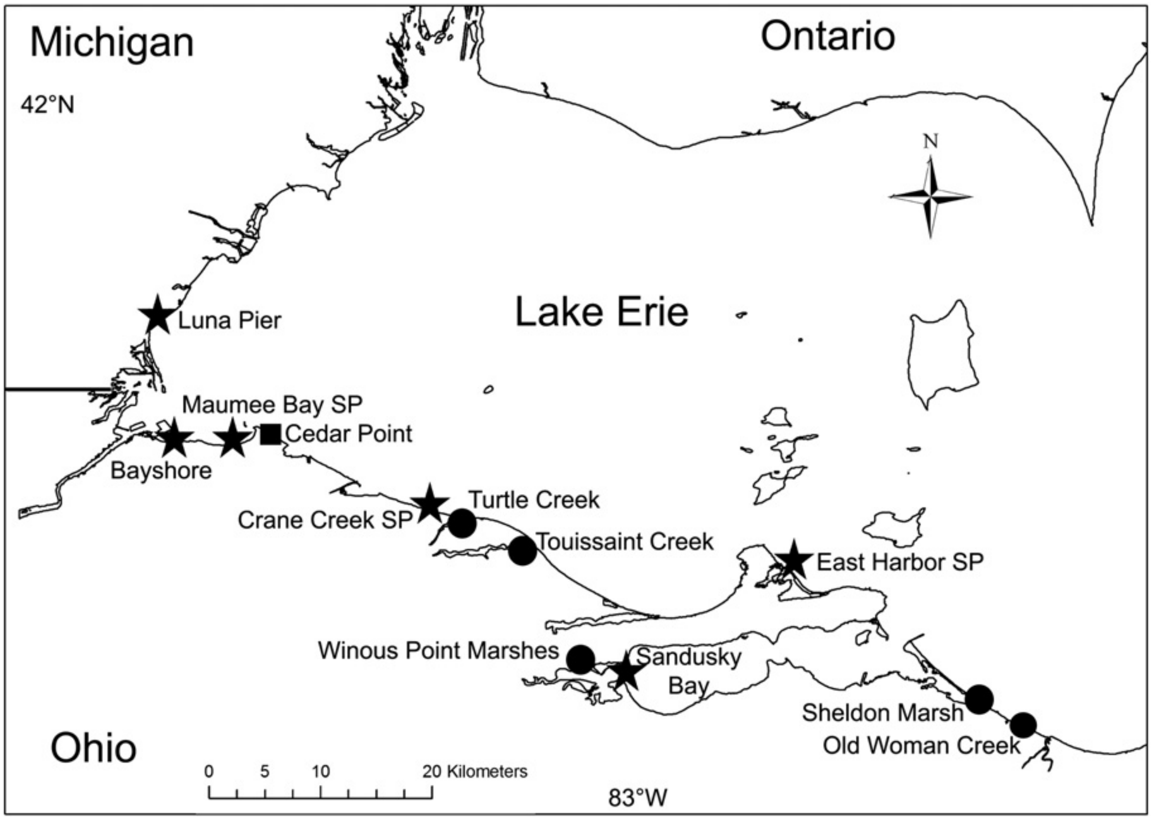


Figure 1. Locations of nearshore sampling sites in Crail et al. 2011. Squares denote sites with fresh dead found, circles represent wetland sites where live specimens were found, and Stars symbolize sites where live mussels were found in the lake.

Despite the abundance of research on mussel communities in lakes and rivers, little information is available concerning the distribution of unionids within the interfaces between rivers and lakes, often called (freshwater) estuaries, or drowned river mouths. Although most species of unionids were extirpated from the open water portion of western Lake Erie, several areas of coastal refuge were identified in the late 1990's and early 2000's. In Ohio, Metzger's Marsh and Crane Creek were two well documented refuges (Nichols and Wilcox, 1997; Nichols and Amberg, 1999; Bowers and de Szalay, 2004), and coastal refuges were later discovered on Presque Isla, PA (Schloesser et. al., 1997; Schloesser and Mateller, 1999) and in the St. Clair river delta (Zanatta et al., 2002).

Coastal area like these may be refugia for the remaining mussels (Crail et al 2011), and the discovery of these coastal unionid refuges has spurred greater exploration into other areas along the shore of Lake Erie. Without more information concerning the distribution of unionids within river mouths and marshes, it is unknown whether such refuges are isolated aberrations or are part of a greater pattern of unionid distribution.

Given this question, timed haphazard (semi-quantitative) surveys were conducted in nine additional streams of northwest Ohio that had not been previously studied for mussels. These streams encompassed six watersheds, and each watershed was assessed using remote sensing software to classify and quantify land use and cover types within its borders. These results were used along with water chemistry analysis collected twice over two field seasons, in order to identify what physical features might support or limit communities of unionids in flooded river mouths.

Table 1. Unionids historically found in western Lake Erie since 1930. X's represent live unionids collected. O's represent no live specimen collected.

Species	Open Water Sites 1930-1982	Resampled Open Water Sites 1991	Nearshore Sites 1996 - Present
Amblema plicata	X	O	X
Elliptio dilatata	X	O	X
Fusconaia flava	X	O	X
Lampsilis cardium	X	O	X
Lampsilis siliquoidea	X	O	X
Lasmigona complanata	O	O	X
Leptodea fragilis	X	O	X
Ligumia nasuta	X	O	O
Obliquaria reflexa	X	O	X
Obovaria subrotunda	X	O	X
Pleurobema sintoxia	X	O	X
Potamilus alatus	X	O	X
Pyganodon grandis	X	O	X
Quadrula pustulosa	X	O	X
Quadrula quadrula	O	O	X
Strophitus undulates	X	O	X
Toxolasma parvum	O	O	X
Truncilla donaciformis	X	O	X
Truncilla truncate	X	O	X
Uniomerus tetralasmus	O	O	X
Utterbackia imbecillis	O	O	X

Records for this table were obtained from numerous past surveys of the western basin of Lake Erie; 1930 (Wright 1955), 1951-52 (Wood 1963), 1961 (Carr and Hiltunen 1965), 1972 (Roth and Mozley unpublished), 1973-74 (Wood and Fink 1984), 1982 (Manny et al. unpublished). The 1991 data derived from Schloesser and Nalepa (1994). Nearshore data are derived from more recent surveys Crane Creek in 2001 (Bowers and De Szalay 2004), and in Metger's Marsh in 1996 (Nichols and Wilcox 1997) and recent shoreline studies (Crail et al. 2011).

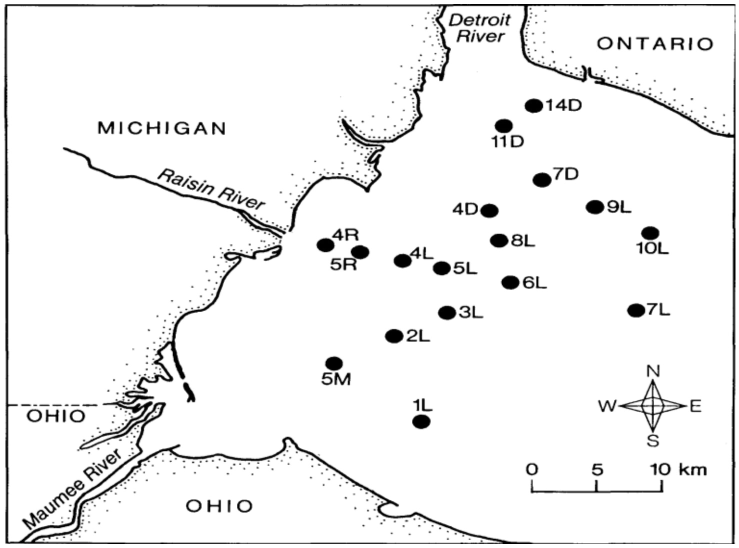


Figure 2. Locations of open water sampling sites used in 1961, 1972, 1982, and 1991(From Nalepa et al. 1991). Data from these sites were used in Table 1.

CHAPTER II

MATERIALS & METHODS

The area of study consisted of three regions of Lake Erie along northwest Ohio's coast (Figure 3). The streams surveyed that drain into Lake Erie's western basin were Cedar Creek, Turtle Creek, and Toussaint Creek. Streams that drained into Sandusky Bay were Yellow Swale, South Creek, and Raccoon Creek. Those draining into Lake Erie's central basin were Plum Brook, Cranberry Creek, and Chappel Creek. Beaches (Figure 3.) were surveyed in addition to the streams to assess whether the vouchers found on the shore were similar to specimens present in near-bye river mouths.

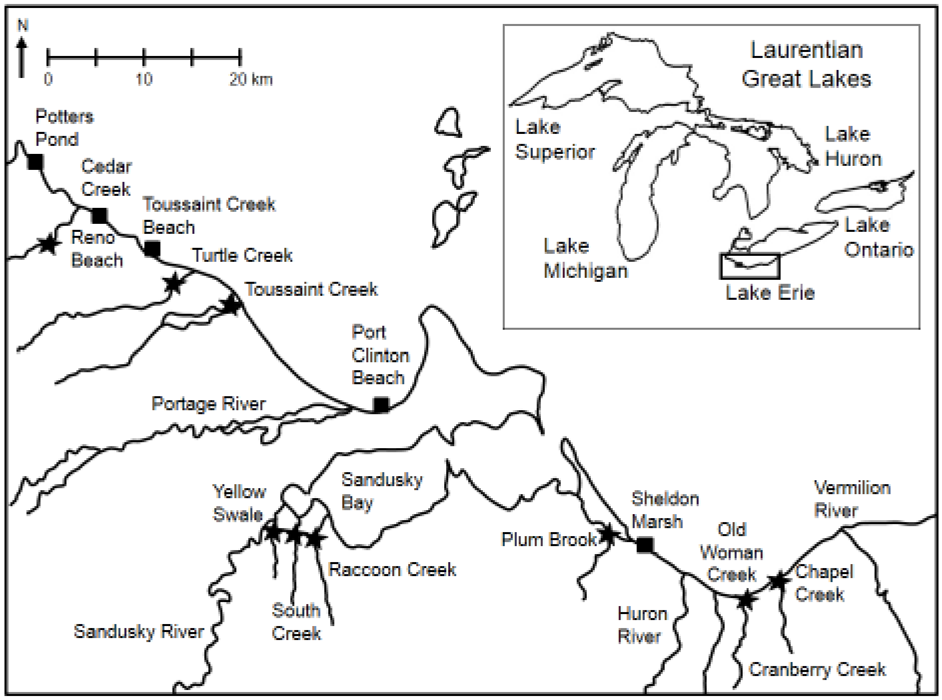


Figure 3. Illustration depicting streams surveyed and the sites examined closest to the lake. Stars signify streams while squares represent beaches surveyed.

2.1 River Mouth Survey Methods

Timed surveys were conducted between June and August of 2010 using mussel rakes (Figure 4) for a minimum of 4 person hours per stream. These surveys were semi-quantitative or “haphazard” in that individuals acting as surveyors did not follow any particular pattern when raking the benthos, but often intensified searching within an area once a live mussel was found. The haphazard technique was the most time-effective strategy due to its ability to first locate mussel patches given the patchy nature common to mussel distributions as well as the lack of any historical information concerning unionid presence in these small streams. Rakes were advantageous compared to typical tactile searches using hands and feet because they allowed for surveying in deeper water without the use of breathing equipment. Also the rakes were able to collect small individuals such as *Toxolasma parvum*, and juvenile unionids that could easily be missed when employing a traditional tactile search. All mussels were identified to species on-site. Live specimens were recorded and placed back into the stream, while voucher specimens (empty shells and valves) were collected and catalogued at Cleveland State University.

Figure 4. Mussel rakes made from standard bow rakes bought at a consumer hardware store. The basket of the rake was made from 1 cm squared galvanized steel mesh which was wrapped to form a basket. Side panels for the basket portion were cut out using metal shears and all parts were assembled to the rake using 16 gauge steel wire.

2.2 Water Sampling Methods

Each stream was sampled using an apparatus made from a 1 liter bottle with a mouth diameter of 2 centimeters attached using duct tape to a 2.5 meter segment of iron rebar. Sampling typically took place from a low hanging bridge that ran perpendicular to the stream. In cases where sampling from a bridge was not possible, the sampling apparatus was dipped from the bank of the stream. All samples were taken from the water column approximately 50 centimeters below the surface. After being filled, each sampling bottle was immediately screw-capped and stored in a cooler until they were delivered to David Klarer at the Old Woman Creek National Estuarine Reserve. Streams were sampled twice, once each in the summers of 2010 and 2011, and each sampling took place during a period of drought in the region and low flow within the streams.

2.3 Statistical Methods

Shannon diversity (H) between regions among streams was assessed using PAST ver 1.96 (Hammer et al. 2001) to conduct a pairwise t-test as well an ANOVA. Water chemistry results were analyzed in SAS using both Pearson and Spearman rank Correlation Coefficient tests as well as general linear regression models (GLM).

2.4 Imaging Methods

Data Sources & Software: Aerial orthophotographs (1 meter/pixel, CIR, MrSid format) and LIDAR (1 meter/pixel, LAS format) tiles were derived in 2006 and supplied by the Ohio Geographically References Information Program (OGRIP) and its Ohio Statewide Imagery Program (OSIP). Shapefiles produced by the United State Department of Agriculture's (USDA) Natural Resource Conservation Service (NRCS) were used to derive watershed maps. Software packages used during image processing included ERDAS Imagine 2011 (Intergraph), eCognition 8 Developer (Trimble), and Quick Terrain Modeler (Applied Imagery).

Orthophotos for all counties containing a portion of the watershed(s) of interest were processed into a mosaic using the Mosaic Pro tool in ERDAS Imagine. A state-wide shapefile of Ohio's watersheds was then placed as the top layer over the mosaic aerial image. Next, watersheds were subset from the mosaic aerial image. Watershed polygons in a shapefile containing streams surveyed were selected within Imagine's viewer and copied. This process saved the shape (perimeter) of the watershed, and then using the "paste from selected object" option created an area of interest (AOI). Each AOI represented the outline of a watershed. Aerial photos of each watershed were clipped from the mosaic aerial image by using the "subset" dialogue under the raster tab of Imagine.

Lidar data were processed for all counties that contained a portion of any stream surveyed in Quick Terrain Modeler (QT modeler.) This processing consisted of deriving digital elevation models (DEM) and digital surface models (DSM). Subtracting the DEM from the DSM created a normalized digital surface model (NDSM), as this can give the height of an object above ground elevation. The NDSMs for each county were subset with the previously mentioned aerial photograph watershed AOIs in order to yield NDSM for each watershed. Using Imagine, the 3-band aerial orthophotograph, and the LIDAR data for each watershed was loaded and layer-stacked in order to form one final image per watershed (4 bands: near infrared, blue, green, and LIDAR).

Finally, each watershed image was classified using eCognition. This was done by using the multispectral segmentation protocol, and classifications were based on samples chosen for each type of land-use category. Image layers were weighted as follows: near infrared 1, blue 1, green 1, and LiDAR 2. This action enabled LIDAR to be a greater influence on the classifications than near infrared, blue, and green. Furthermore, the scale parameter was set to 20, shape to 0.3, and compactness to 0.7. These settings allowed for pixels of similar shape and color to be grouped together into objects, which allowed classification to be less time consuming. Then, a spectral difference segmentation (set to 2) was run to group chromatically similar image objects.

CHAPTER III

RESULTS

Nine unionid species were identified as living in eight streams (Table 2). In order of abundance these species were *Pyganodon grandis, Quadrula quadrula*, *Toxolasma parvum*, *Leptodea fragilis*, *Lasmigona complanta*, *Utterbackia imbecillis*, *Obliquaria reflexa*, *Uniomerus tetralasmus,* and *Amblema plicata*. An additional five species were only identified from shells: *Lampsilis siliquoidea*, *Lasmigona compressa*, *Ligumia nasuta*, *Potamilus alatus,* and *Strophitus undulatus*.

Table 2. Mussels found (live/shells) within the survey region from West to East.

Species (Live/ Voucher)	CPUE	*Amblema plicata*	*Lampsilis siliquoidea*	*Lasmigona complanata*	*Lasmigona compressa*	*Leptodea fragilis*	*Ligumia nasuta*	*Obliquaria reflexa*	*Potamilus alatus*	*Pyganodon grandis*	*Quadrula pustulosa*	*Quadrula quadrula*	*Strophitus undulatus*	*Toxolasma parvum*	*Uniomerus tetralasmus*	*Utterbackia imbecillis*	Shannon #
Cedar Creek	0.4	0	0	2/1	0/1	1/1	0/5	0	0	0/12	0	0	0	0/3	0	0	0.7
Turtle Creek	4.9	0	0	0	0	2/9	0	0	0/2	14/18	0/1	42/10	0	1/0	0	0	0.8
Toussaint Creek	4.5	1/2	0	0	0	1/1	0	6/5	0/2	3/12	0	32/13	0/1	2/2	0	9/1	1.3
Yellow Swale	2.9	0	0	1/4	0	0	0	0	0	27/77	0	1/0	0	5/19	1/3	0/2	0.8
South Creek	4.8	0	0/1	3/2	0	12/5	0	0	0	37/31	0	5/0	0	0/5	0	0/7	1.0
Raccoon Creek	3.3	0	0	10/2	0	0	0	0	0	3/3	0	0	0/3	0	0	0	0.6
Plum Brook	4.1	0	0	0	0	7/0	0	0	0	11/0	0	0	0	13/3	0	2/0	1.2
Cranberry Creek	4.0	0	0	5/1	0	0	0	0	0	9/2	0/0	1/0	0	1/1	0	0	1.0
Chappel Creek	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total		1/2	0/1	21/10	0/1	23/16	0/5	6/5	0/4	104/145	0/1	80/25	0/4	22/33	1/3	11/10	

Table 3. Averaged water chemistry results taken during the summers of 2010 and 2011.

Site	Chloride	Turbidity	ALK	NH_3-N	NO_2-N	NITRATE	Silicate	Sulfate	SR - P	Ca	Mg	Na	K	Fe
	ppm	JTU	ppm	ppm	ppb	ppm	ppm	ppm	ppb	ppm	ppm	ppm	ppm	ppm
Cedar Creek	100.7	13.5	197.8	0.01	2.3	0.57	6.4	62.5	54.4	72.3	21.7	59.5	4.0	0.3
Turtle Creek	26.2	76.4	158.0	0.05	4.8	0.76	3.7	50.3	86.6	56.2	19.3	13.7	3.9	1.7
Toussaint Creek	62.1	55.23	200.9	0.03	4.2	0.68	3.0	89.7	105.5	77.6	27.2	30.2	7.1	1.1
Yellow Swale	43.0	44.8	227.6	0.07	2.6	1.3	5.3	51.3	60.9	77.8	23.9	25.1	4.7	1.2
South Creek	44.1	37.5	208.8	0.0	0.97	1.5	3.9	688.1	30.9	257.9	53.2	27.9	4.9	2.6
Raccoon Creek	86.6	12.4	197.8	0.01	12.45	5.5	2.9	498.1	73.9	209.8	28.3	109.4	14.3	0.4
Plum Brook	66.9	13.12	160.3	0.01	71.70	1.3	1.9	72.9	32.6	65.5	18.2	44.1	3.5	0.4
Cranberry Creek	40.4	14.6	147.7	0.01	25.38	5.9	2.7	42.9	635.0	59.4	17.0	24.6	10.8	0.5
Chappel Creek	47.8	19.2	132.4	0.0	1.65	3.8	2.8	41.0	25.4	52.3	12.7	27.2	5.3	22.5
Average	57.5	31.9	181.3	0.0	14.0	2.4	3.6	177.4	122.8	103.2	24.6	40.2	6.5	3.4

3.1 Western Basin of Lake Erie

The streams in this region all had a thin riparian zone and were most often adjacent to farmland. Toussaint Creek and the Turtle Creek both had a similar substrate, mainly comprised of silt. *Quadrula quadrula* was the most abundant species in this region accounting for 65% of the live specimens. Each of these streams drained directly into Lake Erie; the Cedar and the Turtle have marinas at their mouths.

Cedar Creek (41.6333, -83.3106)

The riparian zone around Cedar Creek was small. Generally a riparian zone would stretch from about only 3 to 10 meters away from the banks of the Creek, which were incised. This stream was also narrow, at approximately 4 meters bankfull width. Outside of the small riparian zone lay agricultural fields. Within the stream, there were plenty of examples of coarse particulate organic matter (CPOM) and much allochthonous input, such as downed trees and garbage. The substrate mainly consisted of hard packed clay and mud, along with cobble. Cedar Creek's depth when surveyed ranged from 0.66 m to 1.5 m deep.

Few mussels were present and the stream seemed degraded by erosion of the banks. A couple of White Heelsplitters (*L. complanata*) and one Fragile Papershell (*Leptodea fragilis*) were found well upstream from the mouth; each species is pollution tolerant, especially the White Heelsplitter. Also 12 voucher specimens of Giant Floaters (*Pyganodon grandis*) were found. The collection of 5 *Ligumia nasuta* shells, representing an endangered species, led to an increased search effort, but no live individuals were found.

Turtle Creek (41.6054, -83.1512)

The area surveyed was a typical flooded river mouth. This stream's surroundings were categorized mainly as agricultural. Any riparian zone present was very thin, made up of mostly shrubs and a few trees. However, the stream channel was very wide, much more so than other streams surveyed, except Toussaint Creek, and the flow was slow. The substrate was very soft and unstable.

The habitat supported a low diversity community near Lake Erie despite human impacts. *Quadrula quadrula* (42) was common, followed by *Pyganodon grandis* (14). *Leptodea fragilis* (2) and *Toxolasma parvum* (1) were also found.

Toussaint Creek (upstream site: 41.5783, -83.1485. downstream site: 41.5851, -83.0681)

Surrounding land use varied from recovering riparian zone to residential and agricultural. This river was wider than all others surveyed and the current was very slow making the Toussaint appear like a classical flooded river mouth for several miles upstream. Within the stream, patches of aquatic vegetation such as water lotus were present. Different sites along this river had substrates that varied in degree of stability and softness, and ranged from a very soft, mostly silt benthos that was approximately 30 cm deep, to a much more stable mix consisting of less silt, but still soft with occasional patches of sand mixed with gravel. The water depth ranged from 0.6 to 2m.

A diverse community was found in the Toussaint; seven species were found alive and nine were found as shells. The dominant species found in soft substrates included *Quadrula quadrula* (32) and *Utterbackia inbecillis* (9); *Obliquaria reflexa* (6) occurred in one area of mixed sand and gravel.

3.2 Sandusky Bay Region

Several small streams enter Muddy Creek Bay which composes the western portion of Sandusky Bay. Each is inhabited by mussels. As such, these streams near their mouths fall within the lands protected by the Winous Point Marsh Conservancy, but the areas surveyed which were upstream, were dominated by farmland and thin riparian zones that may restrict habitat quality.

Yellow Swale (41.4231, -83.0338)

This stream had a wide established riparian zone consisting of older, large trees and diverse vegetation. Outside the riparian zone were agricultural fields, wild low laying vegetation such as wildflower fields, and residential properties. Yellow Swale's bankfull width was less than that of Turtle Creek or Toussaint Creek, but was not incised. Flow in this river was also slow where surveyed, 3-5 kilometers from the Sandusky River, which then drains into Muddy Creek Bay. Yellow Swale looked like a typical flooded river mouth influenced by lake water levels, despite entering the larger Sandusky River. This stream has been dredged upstream of the original mouth to join the Sandusky River, and further downstream there is a wetland which comprised the original mouth. The substrate was soft, but not as soft as Toussaint Creek or Turtle Creek, as more sand was present in the substrate. The water depth ranged from 0.67 m to 1.5 m where we surveyed. Yellow Swale also possessed thick in-stream vegetation downstream.

Pyganodon grandis (27) was by far the most prevalent species found. Notably, one live *Uniomerus tetralasmus* (Pondhorn) was found, along with several voucher specimens (shells of fresh dead) of that species. One individual each of *Lasmigona* *complanata* and *Quadrula quadrula* were found along with several *Toxolasma parvum* (5).

South Creek (41.4147, -83.0083)

Despite appearing like a wide, shallow ditch, this stream had an established healthy riparian zone downstream with residential areas outside of the riparian zone. The substrate in-stream was muddy and soft, with perhaps a 50/50 sand/silt mix. Upstream (south of the bridge used for access) the stream was surrounded with herbaceous vegetation, cattails, reeds, and tall grass.

Pyganodon grandis was the prevalent species (37 live, 31 fresh dead), followed by *Leptodea fragilis* (12 live, 5 dead), particularly in the upstream sandy portion of the stream. Some *Quadrula quadrula* (5) were found downstream in the softer, more unstable sediment along with *Lasmigona complanata* (3).

Raccoon Creek (41.4079, -82.9815)

This stream was similar to Cedar Creek in possessing incised banks, thick canopy cover, a narrow bankful width, a substrate filled with decaying vegetation, cobble and hard packed mud, and also abundant allochthonous input in the form of CPOM and anthropogenic waste. This creek was surrounded by a riparian zone of varying width ranging from several to tens of meters, to residential areas, and eventually to marsh land towards the mouth. Unionids were found in only one spot near the route 6 bridge, in a sandy area of deposition (70/30 mud/sand): *Lasmigona complanata* (10), *Pyganodon grandis* (3), and as fresh dead, *Strophitus undulatus*.

Like Cedar Creek, the most prevalent species found was the pollution tolerant *Lasmigona complanata*. Although the water in each of the areas where unionids were found in Cedar and Raccoon was shallow, it appears that the larger *L. complanata* can survive if the substrate is soft enough to allow burrowing and movement within sites.

3.3 Central Basin

In this region fewer unionid communities of any kind are known. Nearby, Old Woman Creek, which is a protected preserve, has up to six species, but only *Pyganodon grandis* and *Utterbackia imbecillis* were ever reported in many numbers. Another protected area, Sheldon Marsh likewise has four species in low abundance (Crail et al., 2011).

Plum Brook (41.4244, -82.6400)

Surveys in lower Plum Brook encompassed areas that are part of the Erie Co. Metroparks. Plum Brook was wide and slow moving, much like South Creek and Yellow Swale. Lower Plum Brook was surrounded by a large, thick, gradually sloping riparian zone with residential properties outside of it. Plum Brook appeared to be a healthy flooded river mouth or estuary possessing an abundant amount of aquatic vegetation throughout the stream, and this vegetation became increasingly thicker downstream. Plum Brook varied in substrate types: hard compact mud, soft vegetation covered mud, and soft mud free of vegetation.

Plum Brook's most abundant species was *Toxolasma parvum* (13 live individuals and 40% of all live specimens found), followed by *Pyganodon grandis* (11), *Leptodea fragilis* (7), and a pair of *Utterbackia imbecillis*. Shells were rare, and 96% of the animals found in this stream were alive when collected. Most of these individuals, excluding *T. parvum*, were juveniles.

Cranberry Creek (41.3813, -82.4730)

This stream was surveyed close to the lake, but on the south side of route 6 before the stream is culverted and runs through a marina at the mouth. Surrounding types of land use were residential and agricultural fields further upstream of the survey site and route 6. Land fill was observed being dumped. Perhaps as a result, this stream's substrate was partially compact mud. The bankfull width was narrow, but wider than Raccoon or Cedar Creeks, and the banks were slightly eroded but vegetated, mainly by small herbaceous plants along with sparse adult trees.

Much of the collected fauna from Cranberry Creek was very young specimens of *Pyganodon grandis*, *Lasmigona complanata,* and perhaps *Leptodea fragilis*. Due to the small size of the juvenile individuals collected, identification was not conclusive.

Chappel Creek (41.3921, -82.4399)

Chappel Creek was the only stream where no unionids were found. The riparian zone, when present, was very thin. Residential property lined the banks of the creek. Upstream of the mouth, Chappel Creek ran adjacent to a parking lot and recreation area, and generally, there was very little to no buffer zone to absorb and process run-off.

In-stream, Chappel Creek was unique in terms of depth and substrate, varying greatly from several centimeters to 2 meters within a small distance (15 meters), suggesting that this stream had been heavily altered by people in the past. The substrate was a mixture of hard packed cobble, mud and a flaky orange silty deposition that did not appear natural.

Table 4. Summary of shells found on beach sites.

Species	Latitude & Longitude	*Amblema plicata*	*Elliptio dilatata*	*Fusconaia flava*	*Lampsilis siliquoidea*	*Leptodea fragilis*	*Ligumia nasuta*	*Obliquaria reflexa*	*Potamilus alatus*	*Pyganodon grandis*	*Quadrula quadrula*	*Truncilla truncata*	*Utterbackia imbecillis*
Reno Beach	41.6667, -83.2684	1	1	10	54	15	0	1	1	0	5	1	0
Potter's Pond	41.6781, -83.3078	0	0	0	0	190	0	0	0	6	0	0	0
Turtle Creek	41.6152, -83.1314	0	0	0	0	48	0	0	0	1	1	0	1
Port Clinton	41.5152, -82.9344	3	4	0	3	98	1	1	1	0	5	1	0
Sheldon Marsh	41.4197, -82.6051	0	0	0	1	1	0	0	0	25	0	0	1
Total		4	5	10	58	352	1	2	2	32	11	2	2

3.4 Beach Surveys

Shells of 12 species were found during the beach surveys (Table 4): *A. plicata*, *Elliptio dilatata*, *Fuscanaia flava*, *L. siliquoidea*, *L. fragilis*, *L. nasuta*, *Obliquaria reflexa*, *Potamilus alatus*, *P. grandis*, *Q. quadrula*, *Truncilla truncata*, *U imbecillis*. Beach results were mainly comprised of *Leptodea fragilis* (73% of fresh shells collected), which is believed to still be in Lake Erie proper (Bryan et al. 2013). Other species were found infrequently, and most often age could not be accurately determined due to weathering. When a specimen was exposed to wind and surf the shell's appearance can degrade rapidly. Conversely, if a specimen was found buried in the sand, wind and physical erosion of the periostracum could be hindered (Krebs and Begley 2013).

3.5 Watershed Land Use/Cover Analysis

The total area for all watersheds combined was 208,340 hectares and the land use/cover percentages across these watersheds were as follows: 72% agricultural use, 5.7% impervious surface, 14.6% natural vegetation, 0.8% water, and 7.0% of the total area was unclassified. While all were similar, variation in land use/cover patterns existed among watersheds (Figure 5). In comparison to the entire region, the land use and cover for the western most watersheds (Cedar & Turtle Creeks, Toussaint Creek, Yellow Swale, and South & Raccoon Creeks) were similar in terms of agricultural use and naturally vegetated cover. These watersheds were composed of agricultural land use ranging from 71% to 77%, and natural vegetation covering 9% - 14%. The two watersheds east of Sandusky Bay that contain Plum Brook, Chappel Creek, and Cranberry Creeks differed in their percentages of agricultural land use and naturally vegetated cover: Plum Brook's watershed was 69% farmland and 21% was naturally vegetated, while the watershed containing Chappel Creek and Cranberry Creek used the smallest percentage of land for agriculture (53%) and was covered by the highest percentage natural vegetation (32%).

3.6 Water Chemistry

Water chemistry among all streams surveyed was similar with relatively few outliers (Table 3). These observed may have impacted unionid diversity or abundance. Cranberry Creek had an unusually high amount of soluble reactive phosphorus that was over five times the average among all Creeks (635 ppb compared to 123 ppb). Surveys here yielded juvenile unionids but a distinct lack of adult specimens. Several streams were more turbid than average (31.9 JTU). These streams were Turtle Creek (76.4), Toussaint Creek (55.23), Yellow Swale (44.8), and South Creek (37.5). Higher than average amounts of sulfate and calcium were measured in South Creek (688.1 ppm, 257.9 ppm) and Raccoon Creek (498.1 ppm, 209.8 ppm). Chappel Creek, which yieled no unionids during surveys, did not yield abnormal chemical results.

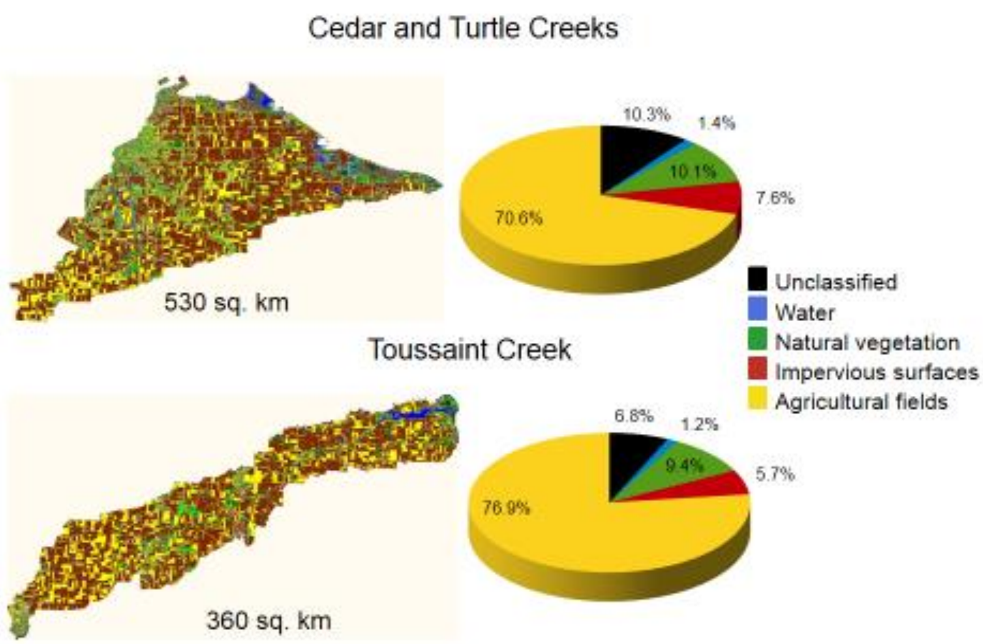
3.7 Statistical Results

The total number of live, whole individuals found alive in the the bethos during surveys correlated significantly with turbidity ($r=0.83$, $P<0.01$), while other chemicals such as nitrate could possibly have more subtle effects. A stepwise model produced an equation as follows: $Y(live) = -59.6 + 1.16\,Turb + 1.14\,Mg + 1.23\,Fe + 0.58\,NO2N + 0.21\,Cl$. (See table 5)

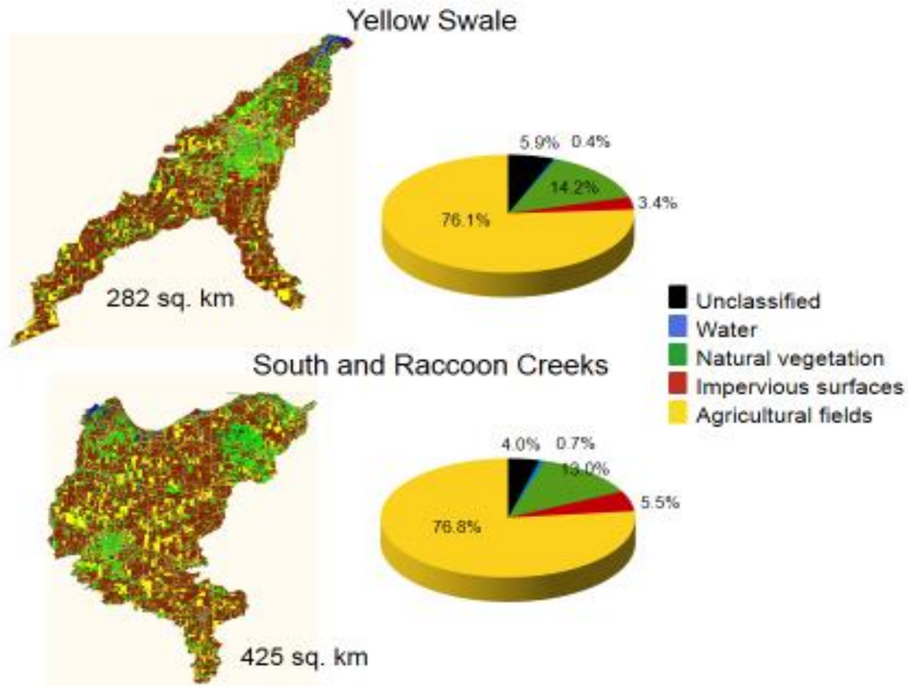
Table 5. Results from ANOVA

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-59.58245	6.60227	540.31099	81.44	0.0029
Chrloride	0.21469	0.05600	97.49372	14.70	0.0313
Turbidity	1.15785	0.06442	2143.12132	323.04	0.0004
NO2-N	0.57832	0.05387	764.52781	115.24	0.0017
Magnesium	1.13927	0.08918	1082.69537	163.20	0.0010
Total Iron	1.22967	0.17049	345.11497	52.02	0.0055

A. Western Basin



B. Sandusky Bay



C. Central Basin

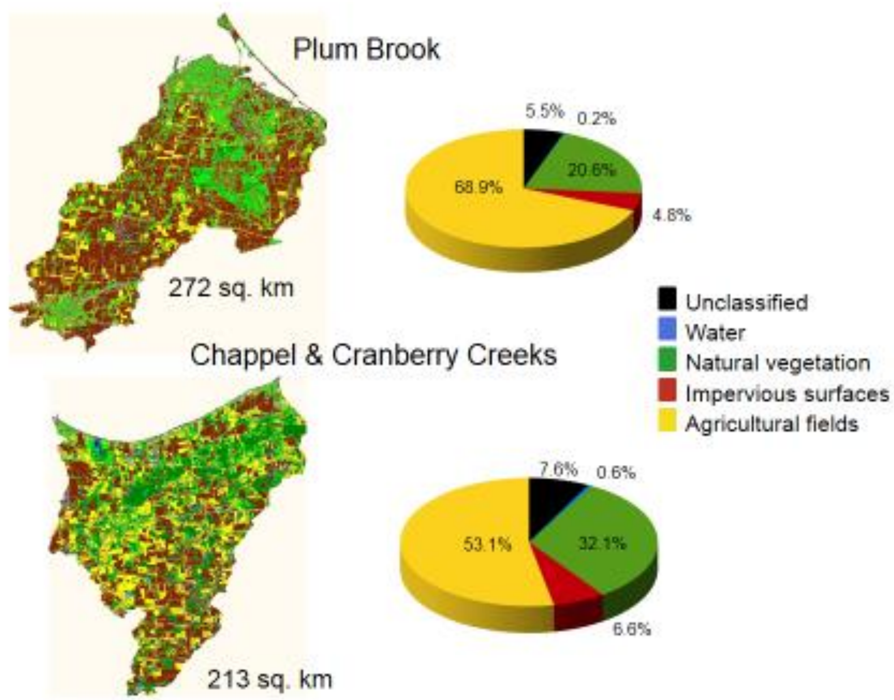


Figure 5. A-C. Color coded watershed maps and pie charts depicting land use from west to east. Brown and Yellow were combined to form the yellow slice of each chart; each color represents types of agricultural fields, barren and vegetated respectively. Gray roads were also grouped with buildings to indicate impervious surface in red on the charts.

CHAPTER IV

DISCUSSION

Unionids use river mouths as refugia from dreissenid mussels. *Quadrula quadrula* (common name : Mapleleaf) was the dominant species in Turtle Creek and Toussaint Creek (Western basin). Each of these streams had a soft substrate mainly comprised of silt, and were the most turbid streams sampled. *Quadrula quadrula* is more tolerant of suspended solids than other unionids such as *Lampsilis teres* (Ellis 1936), further enabling it to become established in a turbid, silty habitat. This type of lotic environment is partially caused by the high proportion of agricultural land use now present to naturally vegetated land cover in each stream’s watershed in the western basin region (Peacock et al. 2005). Geologically, the streams that harbored greater numbers of *Q. quadrula* are part of the Maumee Lake Plain, which consists mainly of silt, clay, and carbonate rock; these three components combined with a shift to agricultural land use have helped to create an ideal substrate for the Mapleleaf by increasing water turbidity, adding to the unstable silt-based benthos, and buffering the pH.

In the Sandusky Bay and Central basin regions, *Pyganodon grandis* (common name : Giant Floater) was the most commonly found species. Although the streams in the Sandusky Bay's region are still within the Maumee Lake Plains, the substrate in Raccoon Creek, South Creek, and Yellow Swale contained less silt and more sand. These streams are close to the Castalia Karst Plain (Brockman 1998) which consists of thinner layers of silt and clay along with a greater amount of sandy deposits. This observed change in substrate could possibly be due to a physiographic gradient between the Maumee plains and the Castalian karst; physiographic gradients are known to affect soil properties and vegetation (Campo-Bescós 2013) which affect stream morphology and chemistry (LeBlanc et al. 1997). Perhaps the change in benthic composition is also partially due to these watersheds having a higher proportion of land covered by natural vegetation. *P. grandis* is a habitat generalist (Haag 2012) known to prefer small streams, lakes, soft substrate, and also possesses a tolerance to pollution and sedimentation (Parmalee & Bogan 1998). These traits enable Giant floaters to persist in Yellow Swale and South Creek (third and fourth most turbid streams surveyed) because of their turbidity, sandier benthos, and increased proportion of naturally vegetated area in their watersheds.

Pyganodon grandis was also found in Raccoon Creek (Sandusky Bay region), which was high in chloride, magnesium, sodium, and several nitrogen containing components. This stream contained ten *Lasmigona complanataI.* This species was also found alive in other chemically disturbed streams across the survey area (Cedar Creek and Cranberry Creek). All of the live individuals of either species were found in an area of sandy deposition. Raccoon Creek is known to be chemically unstable and unhealthy which may account for the low species diversity and abundance.

The Central Basin streams surveyed were split between two physiographic regions, each with similar numbers of live *Pyganodon grandis*: Castalia Karst Plain and Erie Lake Plain. Plum Brook lies in the karst plain, while Cranberry Creek and Chappel Creek were part of the Erie Lake Plain region, which is comprised of silt, clay, sandstone, and shale (Brockman 1998). Plum Brook can also be separated from the other two streams in this region by amount of anthropogenic disturbance. Plum Brook is part of the Erie County Metroparks and thus is surrounded by a comparably larger riparian zone; this stream was habitat for *P. grandis* and a slightly greater number of *Toxolasma parvum*. Cranberry Creek was channelized and culverted near the mouth, while the mouth of Chappel Creek is now surrounded by anthropogenically sculptured land use such as housing developments, a summer camp, and a popular public beach accompanied by buildings. While all of the Central Basin creeks were within watersheds that consisted of a lesser proportion of farmland to natural vegetation, chemically Plum Brook was healthy. Cranberry Creek possessed a very large amount of soluble reactive phosphorus (SRP), which is suspected to be the result of a manure pile upstream, and construction equipment seen dumping landfill into the stream. Still it harbored *P. grandis* and *L. complanata*. Oddly, no large adults of any species were found in Cranberry Creek and no mussels were found in Chappel Creek at all, perhaps due to the disturbed stream morphology, the high iron content of the water, hard gravel substrate, or a combination of all three.

Furthermore, while there are no historical results for Chappel Creek to use as comparison it is assumed that its nutrient loading is similar to near-bye Old Woman Creek, which typically has high nutrient and sediment loads (OEPA 2005). Unlike Old

Woman Creek, Chappel Creek has been anthropogenically disturbed, including movement of the mouth (David Klarer personal communication). This stream has been impacted by crop production within the vicinity (OEPA 2005). Cedar and Raccoon Creeks had substantially higher chloride levels than the other creeks surveyed. Raccoon Creek has been known to harbor elevated nutrient levels downstream of Clyde, Ohio (OEPA 2009) that would have impacted survey results. South Creek has also been historically known for excess nutrient loading due to the access of livestock to the stream as well as run-off from adjacent residential and agricultural areas (OEPA 2009), yet it harbored a healthy mussel population.

Watershed geology plays a major part in composing a steam's benthos and water chemistry. Substrate composition relates to current velocity; a watershed showing rapid change in elevation may face benthic scouring (Gordon et al. 1992). Physiography can affect the composition of riparian zones near a stream, which in turn influences the stability of the stream's channel (Stalnaker et al. 1995). Together these features may determine water chemistry (Web and Walling 1992; Allan 1995). Sedimentary rock such as limestone, which is common around Lake Erie, will help to buffer the stream from radical changes in pH. Conversely, streams upon metamorphic rock generally have poorly buffered water and low pH. A stream can become more acidic by decaying vegetation and other allochthonous input. As acidity rises, mussel diversity and abundance decrease (Allan 1995). Extremely low pH is especially harmful for freshwater bivalves. Calcium can bond with anions, and it is important for unionids to uptake calcium ions in order to for shell growth and repair (Bogan 2001). For unionids, basic pH along with moderately hard, to hard water is preferred if not essential (Zanatta et al. unpublished)

Vegetation together with watershed size and annual rainfall will determine the physical and hydrological stability of streams (Church 1992, Gordon et al. 1992). Some species such as *Quadrula quadrula* were found in unstable sediment described as silty, in a larger steam, with very little riparian zone area in either the Western Basin or in part of a stream where particulate matter size is less. *Toxolasma parvum* was mostly found in a stream with a stable substrate and a large riparian zone. Lowland rivers, or river mouths containing silt and clay are usually more stable due to the bonding properties of these two components, as oppose to sand (Krebs et al. 2010), and this may enable river mouths to be a good habitat for generalist unionids (Church 1992; Allan 1995). However, some sand may be beneficial to certain species like *Pyganodon grandis*, as it may allow for easier burrowing; parts South Creek where many *P. grandis* were found exemplified the positive aspect of sand in a mixed benthic environment.

Due to overland run-off, in addition to ground water, river mouths may exhibit variability in flow and may be flashy. However an area with a low gradient elevation, such as in northwest Ohio can slow run-off and become lentic. Historically, such streams with turbid water were thought to harbor a lower abundance and diversity of mussels (Coker 1915). However, rivers with high amounts of sediment can also harbor numerous mussels as in Turtle Creek, Toussaint Creek, Yellow Swale, and South Creek. Size of streams may matter less in terms of quality of mussel habitat due to the extensive influence from the lake and watershed size (Krebs et al 2010, Crail et al. 2011).

Although, larger streams in agricultural areas may deposit more silt and that change coulf shift species dominance from *Pyganodon grandis* to *Quadrula quadrula*.

There are a variety of tributaries draining into Lake Erie and the river mouths and their connectivity to the lake has long been assumed to be providing corridors between adjacent communities (patches) of mussels. However, thick wetlands (Yellow Swale, Raccoon Creek, Plum Brook) or even marinas (Cedar, Turtle, Chappel, Cranberry) may act as barriers to reduce or block dispersal for fish (Krebs et al. 2010). Even in small streams, not all stream mouths are open all year round. Mouths can be open ephemerally, such as at Old Woman Creek. This known mussel refuge, has a mouth that is periodically closed off by sediment deposition until this river's flow is strong enough to break through. Other streams such as Plum Brook and Yellow Swale have mouths that become highly vegetated, similar to wetlands, and fish movement may depend on periods of high lake water levels. The mouth of South Creek leads to Muddy Creek Bay and was less than 1 meter deep in 2011, a high-water year, but perhaps that is open enough. An undisturbed, wide, non-vegetated, and slowly moving river mouth (South Creek, Toussaint Creek) could allow for a greater amount of fish to enter and exit, bringing with them more mussels.

At the shallowest levels, river mouths (in northwest Ohio) flow slowly and this enabled lentic and riverine (lotic) species to be present in small river mouths of northwest Ohio; *Pyganodon grandis*, *Toxolasma parvum, and Utterbackia imbecillis* were found, as well as lotic species such as *Unionmerus tetralasmus*, which typically live in ponds and slow moving streams, and *Quadrula quadrula* which is found in slow moving streams with silty substrate. River mouths also make poor habitat for dreissenids: water level fluctuation, ice scour, reed beds/wetlands (Bodamer and Bossenbrook 2008), and predation by fish, crayfish, and turtles (Bowers and de Szalay 2005), can combine with flow to oppose travel of veligers upstream.

Lake Erie exhibits great variation in terms of biotic and abiotic features, both in the lake's benthic and surrounding environments, possibly because it is the smallest of the Laurentian Great Lakes in terms of maximum depth and volume (Lake Erie Lakewide Management Plan: Annual Report 2011). Lake Erie offers a gradient in bathymetry. The western basin is shallow, averaging approximately 10-15 meters deep, while the central basin is slightly deeper at an average of 30 meters. The eastern basin of the lake is the deepest portion ranging from 45 to 65 meter deep (NOAA publically available bathymetric data: http://www.ngdc.noaa.gov/mgg/greatlakes/erie.html). This variety may allow for a multitude of fauna, such as freshwater mussels and fish to inhabit different depths, or underwater topography that may better suit the needs of individual species and diverse communities.

The western basin of Lake Erie is unique in that it can be called a "riverine lake", meaning that it is shallow, very productive, and receives enough input from the Detroit and Maumee Rivers to generate a slow flow (Fuller et al. 1995; Ludsin et al. 2001). The Maumee River delivers silty substrate, which may be good habitat for some unionids, where areas of substrate composed of a higher amount of gravel, cobble, or sand may serve as habitat for different species. Dreissenids are also well adapted to temperatures similar to those in Lake Erie. *Dreissena polymorpha* spawning and gamete development are triggered by temperatures ranging from 4.3 degrees C (39 degrees F) to 13.4 degrees C (57.7 degrees F) (Lancioni & Gaino 2006). Based on data collected by the Great Lakes

Forcasting System, from 2006 to 2011 (Table 6) Lake Erie's western basin water temperature at 3.3 meters below surface is usually within that temperature range for about 6 months of the year. Also, the presence of unionids within some of the deeper parts of the lake may have provide substrate for dreissenids in cooler areas of the lake that would normally have been barren mud flats; unionids deceased or living make an excellent substrate for dreissenids.

Many species of unionids exhibit a variety of tolerance to both cooler and warmer temperatures, and may possess different behaviors to cope with change in temperature (Pandolfo et al. 2010). Adults of some species such as *Pyganodon grandis*, *Toxolasma parvum,* and *Unionmerus tetralasmus*, all species found in northwest Ohio in small streams, may move to deeper water, or burrow deeper into the substrate to avoid overheating (Holland 1991; Johnson 2001). Certain glochidia species may be limited in their ability to disperse due to water temperature; some species are more cold tolerant such a *P. grandis* (Clark 1973), while the range of other species like *Elliptio complanata* (a species native to the Northeast Atlantic slope) is more defined by a lack of tolerance to warmer temperatures (Matteson 1955). Outside of the Lake Erie watershed, unionids have become rare as they reach their northern range in Canada (Graf 2002).

Table 6. Average Water Temperature of Lake Erie's Western Basin by Month.

Month	Temperature (C)
January	0.7
February	0.3
March	2.56
April	7.6
May	14
June	20.5
July	24.1
August	25.1
September	21.8
October	15.4
November	9.11
December	2.5

(Data gathered National Oceanic and Atmospheric Administration's Coastal Forecasting System, specifically using the Great Lakes Observing System's point query tool. http://www.glerl.noaa.gov/res/glcfs/ and http://www.data.glos.us/glcfs/)

Therefore, nearshore refuges may harbor remnant populations of unionids for several reasons. *Dreissena polymorpha* and *Dreissena bugensis* apparently rarely colonize river mouths or become established in large numbers at the lake/river interface. Current exists, even if slow, and substrata in flooded small river mouths are soft, unstable, and silt-based, which is a substrate that dreissenids cannot colonize easily. In small river mouths, water temperatures can be too warm for dreissenid maturation because of their shallow depths and high temperature of runoff which can warm these small streams.

CHAPTER V

CONCLUSIONS

5.1 Western Basin Streams

The presence of shells of the Eastern Pondmussel (*Ligumia nasuta*) suggested better conditions in the past in Cedar Creek. No access was available near the mouth due to a narrow channelized portion of the stream seemingly used for irrigation and agricultural runoff as well as a very active marina present at the mouth. Although Cedar Creek may have once been more suitable habitat for unionids, that is no longer true as a result of anthropogenic disturbance.

Turtle Creek also possessed an active marina at the mouth, but only a hundred yards downstream, the flooded area opens into a wide wetland with emergent vegetation. The substrate was amorphous, which as noted favors *Quadrula quadrula*, and the water is deeper in mid-channel. The increased depth may be due to observed dredging as well as natural scouring from storm events. This stream harbored many native mussels upstream of the marina and areas of dredging, and possesses a habitat very well suited for *Q. quadrula*.

Toussaint Creek possessed a diverse and abundant mussel community. The mouth is regulated by the David Bessie Nuclear Powerplant, and numerous small marinas line the shores. In some localities, the Ottawa National Wildlife Refuge has obtained property, for example the marsh at Gaeth-Kurdy (Crail et al., 2011). The lower reaches appear to be filling in as we surveyed in 1.5 to 2 meters of water within sight of the entrance to the lake, which may lead to requests for dredging in the near future. The course substrates composed a bar in the center of the river which is the habitat and collection locality for the state threatened Threehorn Wartyback (*Obliquaria reflexa*) that were found. A relatively diverse community of unionids were found in Toussaint Creek and this stream should be treated as a known refuge for native mussels.

5.2 Sandusky Bay Streams

Yellow Swale possessed a state threatened *Uniomerus tetralasmus*, a true lentic specialist. This stream, like others in the area, tends to fill in near the mouth, creating a wetland blocking boat navigation with the lake, or in this case the flooded mouth of the Sandusky River. Yellow Swale has not been greatly disturbed by human activity and as a result, this stream is a good example of a small stream acting as a refuge for unionids.

South Creek is very shallow where it enters Muddy Creek Bay, but is possibly open all the way upstream to survey sites. *Pyganodon grandis* was the most commonly found species; almost 2/3 (65%) of the all live specimens found were Giant Floaters. However, 12 *Leptodea fragilis* were found live (5 shells) and this is further evidence of continuous connection to the lake. Here a *Neogobius melanostomus* or Round Goby, was found, using a discarded mussel shell to brood its young. Connectivity with the lake likely sustains community diversity of mussels. Much like Yellow Swale, South Creek exemplified small creeks acting as refugia for native mussels, and should be protected as such before anthropogenic disturbance renders this stream less suitable for mussels.

Although Raccoon Creek enters the Pickering State Bird Refuge Downstream, degradation from farm runoff seems to have severely impacted the stream above this preserve. The benthos for much of this creek is not suitable mussel habitat as it is hard clay and mud, along with debris and a variety of allochthonous input. Further upstream from the access point the creek narrows to approximately 1.5 meters where it serves as drainage for surrounding agricultural fields. Most of Raccoon Creek is morphologically not suited for unionids; the substrate is too hard and water chemistry may be another limiting factor.

5.3 Central Basin Streams

Cranberry Creek and Chappel Creeks may typify human destruction of habitat. All of the specimens found were either small adults, or juveniles which would further suggest that this stream's community is a sink population within water chemistry not conducive for growth of mussels to adulthood. Neither of these streams represent acceptable habitat for a sustainable assemblage of unionids as they both been heavily modified for human use rather than that of native mussels.

Plum Brook was the site of a cesium spill about 30 years ago and seems to be a recovering mussel habitat. More live specimens were found than voucher specimens, suggesting that Plum Brook's unionid community may be young and increasing in abundance. The data collected for this study provides further evidence that flooded river mouths and estuaries act as refugia for unionid mussels given the absence of anthropogenic disturbance, and that physiographic data along with land use/cover data may help to determine why some species are using river mouths as refugia. Plum Brook is another site that exhibits characteristics of unionid refugia; the native mussel community included individuals in a range of ages, from juvenile to adults. The water chemistry and land use in the watershed were among the most conducive for mussels out of all streams surveyed.

Regarding all streams, most unionids were found in the soft, vegetation-free areas of the stream. Areas of very thick vegetation were not surveyed as they restricted use of the mussel rakes and the rakes easily damaged aquatic vegetation. Species found more often included three habitat generalists: *Pyganodon grandis*, *Toxolasma parvum*, and *Lasmigona complanata*. These species utilize a diverse set of host fish (Watters et al. 2009). *Quadrula quadrula* was found commonly in areas with fine sediment. Other species such as *Obliquaria reflexa* and *Uniomerus tetralasmus* were found in one site; each are state threatened and the latter has a great tolerance for ponds with poor water quality (Haag 2012). Shells of *Leptodea fragilis* were found in large numbers. It should be noted that it's believed that *L. fragilis* can survive in Lake Erie because of its opportunistic life cycle, justified by a high rate of fercundity and rapid growth (Haag 2012); it may simply be able to out-pace dreissenids and reproduce before the invasive mussels can attach and starve them. *L. fragilis* was more common in larger streams closer to the lake as its host fish is freshwater drum, a common lake fish (Lyons et al 2007).

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