Characteristics of the unionid community and habitat in a power plant thermal plume in western Lake Erie

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The University of Toledo
A Thesis

entitled

Characteristics of the Unionid Community and Habitat in a Power Plant Thermal Plume in Western Lake Erie

by

Nicholas Bryan

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in Biology

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May 2013
An Abstract of
Characterization of the Unionid Community and Habitat in a Power Plant Thermal Plume in Western Lake Erie

by
Nicholas Bryan

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in Biology
The University of Toledo
March 2013

Native unionids are endangered in the Laurentian Great Lakes due to habitat degradation and biofouling by dreissenids. However, a robust community was discovered living within the thermal discharge of a power plant at Oregon, Ohio, on the south shore of Lake Erie. Chapter 1 describes comparisons of the characteristics of this community to nearby communities outside the thermal plume, and examines habitat characteristics that may affect unionids. Unionids were sampled from the exposed lake bed at three sites during a seiche in 2011: (1) within the thermal plume, (2) at Bayshore Park (2.0km east of the plant), and (3) at the University of Toledo’s Lake Erie Center (4.0km east). In 2010, sediment samples were collected along a 2km transect extending east from the plant discharge roughly parallel to the south shore of Lake Erie. Data from other studies done in proximity to the power plant were also analyzed. Results indicated that the community within the thermal plume had higher densities, higher diversity ($H'$), more small individuals, and overall larger sizes than communities outside the plume (all $p<0.05$). Both the rate and intensity of fouling by dreissenids were lower within the plume ($p<0.05$). Both dry mass of coarse surface sediment and lakebed sediment organic
matter content were negatively correlated with distance from the plant (both $p<0.05$; $R^2 = 0.497$, and 0.479, respectively). An unexpected discovery was that the bulk of the coarse sediment was comprised of shell material from Asian clams and dreissenid mussels, suggesting a contribution of these exotic species to sediment accumulation. In total, these results suggest that several habitat characteristics close to the power plant are favorable to unionids.

Chapter 2 outlines work completed in the summer of 2012, examining habitat characteristics within the thermal plume for insights to why it is favorable to unionids: I expected warmer water temperatures, higher POM concentrations, higher organic matter in sediments, and greater coarse sediment mass in the plume. Water temperature averaged $3.8\pm1.5^\circ$C warmer (N=8) at the plant’s outflow than at the intake and decreased by $3.6\pm1.5^\circ$C by 2.0km from the outflow (N=4). The decline in temperature over distance was negatively correlated with wind speed and positively correlated with wind direction (N=4; $R^2=100\%$; $p=0.003$ and 0.005 respectively). Particulate organic matter (POM) was not consistently greater at either the intake or outflow but the difference in POM between the intake and outflow was positively correlated with wind speed (N=5; $R^2=98.3\%$ $p=0.0006$). Wind speed was also positively correlated with the change in POM concentration over distance (N=5; $R^2=86.9\%$; $p=0.01$); concentration also increased when the Maumee River discharge was increasing and decreased when discharge was falling. Differences in dreissenid veliger density between the intake and outflow were positively correlated to wind direction (N=5; $R^2=94.9\%$; $p=0.0003$). The ratio of live:dead veligers was significantly higher at the intake than at the outflow on most dates. A laboratory experiment showed that heating to levels experienced by passing through the power plant
caused significant mortality in veligers (N=20; p<0.0001). These findings show that water temperatures were higher in the plume, POM was higher in the plume on most dates, and that heating during passage through the power plant likely increases dreissenid veliger mortality. We found no significant relationships between sediment characteristics and distance from the power plant. Thus not all factors considered favorable for unionids were enhanced by proximity to the power plant.
Acknowledgements

I thank D. Moorhead and T. Crail for their guidance throughout my research. I thank C. Mayer, J. Bossenbroek, and J. Gottgens for reviewing this paper. I thank J. Gottgens, T. Fisher, and T. Bridgeman for providing laboratory support. I thank C. Florence, M. DuFour, and S. Schnapp for assistance in the field. I also thank two anonymous reviewers for suggestions that improved this work. Financial support was provided by U.S. Fish and Wildlife Service grant # 30181AG152, National Science Foundation GK-12 program grant #DGE-0742395, and Department of Education TCT program grant # P381B080006. I thank the participants of the GK-12 and TCT programs for their assistance in field collections.
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List of Abbreviations

ANCOVA………….. Analysis of covariance
ANOVA……………. Analysis of variance
CTM…………………Critical thermal maxima
POM……………………Particulate organic matter
TEBPP ....................Toledo Edison Bayshore Power Plant
List of Symbols

$H'$............................Shannon’s Index of Species Diversity

$S$...............................Bray-Curtis Similarity Index
Chapter 1

Freshwater Mussel Community Response to Warm Water Discharge in Western Lake Erie

*In review with the Journal of Great Lakes Research

Introduction

North America hosts the most diverse group of unionids (Bivalvia: Unionidae) in the world with over 300 documented species (Bogan, 1993). Historically, the western basin of Lake Erie had the largest populations of unionids within the Laurentian Great Lakes, probably due to relatively warm temperatures, shallow depths, and high flushing rates (Nalepa et al., 1991). However unionid abundances in western Lake Erie have been declining since the 1960s (Nalepa et al., 1991) due to pollution and habitat alteration (Stevens and Neilson, 1989; Nalepa et al., 1991; Morang et al., 2011). When Eurasian dreissenid mussels (Bivalvia: Dreissenidae) invaded Lake Erie in 1986 (Schloesser and Nalepa, 1994), they exacerbated unionid declines by fouling their shells and possibly competing for food and oxygen (Schloesser and Nalepa, 1996; Parker et al. 1998). Ricciardi et al. (1998) reported that all unionid species were extirpated within 4-8 years in many areas that developed high dreissenid populations.
Although habitat degradation and dreissenid mussels have reduced unionid distributions and abundances in western Lake Erie, some habitats still support abundant populations and diverse communities (Crail et al., 2011). Habitat characteristics that allow coexistence of unionids with dreissenids are unclear (Bowers and de Szalay, 2003) but understanding these characteristics may be important for the conservation and management of unionids. Recent studies suggest several reasons why certain habitats have low dreissenid fouling rates. Strong currents reduce the likelihood that dreissenid pediveligers will settle out of the water column and attach to unionids (Bowers and de Szalay, 2003). Deep layers of unconsolidated sediments allow unionids to burrow, thus escaping colonization and possibly even “shedding” attached dreissenids (Nicholas and Wilcox, 1997). Also, dreissenid predators may remove attached dreissenids from the shells of unionids (Bowers et al., 2005). The reason why dreissenid colonization rates are relatively low in some habitats is almost certainly multi-factorial, so that habitats offering a combination of key features may be most likely to allow coexistence of exotic and native mussels.

A seiche in October, 2011 along the southern shore of the western basin of Lake Erie revealed a diverse community of unionids living within the discharge plume of First Energy’s Bayshore Power Plant (BPP) at Oregon, Ohio. The plant removes water from the Maumee River as it enters the western basin and discharges it into a small bay partially separated from the larger basin by an island of sediments dredged from the Toledo shipping channel (Fig.1-1) (Ager, 2009). Herein, we present field data from unionid sampling we completed in the vicinity of the power plant’s thermal plume. We also present data from three additional studies done within and adjacent to this thermal
plume. Using these data, we elucidated the likely factors contributing to unionid success in this habitat. The goal of this study was to identify the key habitat characteristics and positive feedbacks among bivalves that allow native unionids to coexist with two exotic taxa (*Dreissena* spp. and *Corbicula* spp.). Our findings may be important for unionid conservation in western Lake Erie.

**Methods**

**Study Area**

Our study area was located in the shallow (<2m depth) waters within 200m of the southern shoreline of Lake Erie, within the Maumee Bay. This included sites (1) within the power plant’s thermal plume (ca. 0.4km east of the BPP), (2) at Bayshore Park (2.0km east of BPP), and (3) at the University of Toledo’s Lake Erie Center (4.0km east of BPP) (Fig. 1-1). The BPP receives cooling water from an intake canal connected to the east side of the mouth of the Maumee River. Heated water is discharged eastward from the plant at 8 - 33m$^3$sec$^{-1}$ (Lawler et al., 2003), into a partial embayment created by a rectangular dredge-spoil island located to the north of the plant outflow. Water depths range from 0.6m to 1.5m LWD. The substratum is variable, with areas of silt-clay, silt, silty-sand, and sand. All of these substrate types include corbicula and dreissenid shells and in some areas these shells form a gravel-like substrate. The discharge water coming from the BPP ranges from 3-6°C above ambient (Tetra Tech, 2009). Water temperature at Bayshore Park is usually about 2-3°C cooler and water near the Lake Erie Center is about 3-4°C cooler than in the plume of the power plant.
**Unionid collections**

We collected unionids during two separate wind-driven seiche events. In October of 2011, they were collected by hand from the exposed lakebed from a 0.5 ha plot at each of the three sampling sites along the south shoreline of Maumee Bay (Fig. 1-1). Each plot was sampled for 2 person hours. All visible unionids on the sediment surface were identified to species, their lengths were measured, and all were examined for presence of attached dreissenids or their byssal threads. If dreissenids were present, the number attached was recorded. An additional 10×10m quadrant within the thermal plume (0.4km east of the BPP) was thoroughly searched during the seiche. All unionids at the sediment surface within the plot were identified, measured, and examined for dreissenids and their byssal threads. The purpose of this 10×10m plot was to get an estimate of unionid density within the thermal plume for comparison to densities found at Bay Shore Park during a similar seiche in 2009 (Crail et al., 2011). During the 2009 seiche, unionids were collected by hand from the exposed lakebed in four 10×10m plots. Each plot was thoroughly searched so that all visible unionids were retrieved. Unionids were identified and measured before being returned to the substrate (Crail et al, 2011).

**Dreissenid and corbiculid sampling**

We collected benthic samples in the summer of 2010 with four, 23×23cm ponar grabs at each of 23 sites located within the study area (Fig. 1-1, bottom). All living bivalves, including dreissenids and corbiculids, were removed from each sample, identified to species and returned to the site.
We also examined dreissenid and corbiculid densities reported by Ager (2009) from an environmental impact study completed during August of 2008. Ager (2009) took ponar grabs at 23 locations (4 replicates per location) within the study area: 20 within 3.0km of the BPP and three reference sites located in the more distant, open waters of Maumee Bay.

Sediments

After all bivalves were removed by hand from our benthic samples collected in 2010 (described above), the sediments were poured into a sieve bucket and rinsed with water to remove all material less than 2.0mm. Remaining material was divided into 4 size classes (2.0-6.4mm, 6.4-12.7mm, 12.7-25.4mm, >25.4mm). These fractions were then dried to a constant mass at 100°C and weighed.

One sediment core was collected from each of the same 23 sampling sites using a hand held sediment corer (7cm diameter). The corer was pushed through the loose sediments on the surface into the underlying glacial lake clay. The loose surface sediments were decanted and the remaining core contents were saved in plastic bags and taken to the lab for processing. A fine particle size fraction (0.075-0.6mm) was isolated from each sample using a wet sieve. Approximately 2cm$^3$ of each fine particle sample was placed in a crucible, dried to a constant mass at 100°C, and weighed. The crucibles were then held at 500°C for eight hours in a muffle furnace and the organic matter content of samples estimated as weight loss on combustion.
Sediment grain size data for Maumee Bay were also obtained from the Army Corps of Engineers. Their sampling was done in 2002 and reported mean sediment grain size (phi) for a wide range of locations in the area.

**Statistical Methods**

*Unionids*

The Shannon diversity index ($H'$) was calculated for each of the 0.5 ha sample plots in 2011, and the Bray-Curtis Similarity index ($S$) was calculated for each pair of plots. However, the single plot sampled at each site does not permit statistical comparisons between sites. In contrast, the 95% confidence intervals about the means for density and $H'$ of the four 10×10m plots collected at Bayshore Park in 2009 was compared to the density and diversity of the community found in the 10×10m plot within the thermal plume of the power plant in 2011. Also, the Bray-Curtis index was calculated for each pair of plots within the 2009 sampling, and between the 2011 plot and each of the 2009 plots. The population of indices from combinations of the 2009 plots was compared to the population of indices from 2009/2011 combinations, using a Mann Whitney U Test ($\alpha = 0.05$).

Only *L. fragilis* was abundant in all 0.5ha plots and size distributions suggested that two relatively distinct size groups (small and large individuals) could be distinguished (Fig. 1-2). We used a Mann Whitney U test ($\alpha = 0.05$) to compare mean shell length between sites for both age groups of this species. There were so few small individuals in the Lake Erie Center plot (N = 4), that only the power plant and Bayshore
Park plots were compared in this analysis. A Chi-Square test ($\alpha = 0.05$) evaluated differences in the ratio of small:large individuals between sites.

A Chi-Square test ($\alpha = 0.05$) was also used to compare the ratio of infested:non-infested unionids at each site. A single factor ANOVA ($\alpha = 0.05$) was then performed to determine if there was a significant difference in the mean number of attached dreissenids per unionid between sites (only infested unionids were included in this analysis). Finally, t-tests were used to compare the average length of infested and non-infested unionids in the three 0.5ha plots and the 10×10m plot from the 2011 seiche. Observations were sufficient to permit tests for differences in lengths for L. fragilis in all four plots, A. plicata in all plots except the Lake Erie Center, and T. donaciformis in only the 10×10m plot at the power plant.

**Dreissenids and corbiculids**

To determine if dreissenids and corbiculids responded to the thermal plume, we used multiple linear regressions to examine the relationships between mussel density and distance from both the power plant and south shoreline ($\alpha = 0.05$). For dreissenids, we used data from Ager (2009) and for corbiculids, we used data from both Ager (2009) and our summer 2010 study.

**Sediments**

Data from our summer, 2010 impact study were used to determine the relationship between total unconsolidated surface sediment dry mass (from ponar grabs) and distance from both the power plant and south shoreline (multiple linear regression, $\alpha$
The dry mass of each of the four, particle size classes making up the total (<6.4mm, 6.4-12.7mm, 12.7-25.4mm, >25.4mm) were analyzed using the same method. A multiple linear regression was also used to determine if a relationship existed between organic matter content of sediments and distance from both the power plant and south shoreline. Finally, the sediment grain size data (phi) from the Army Corps of Engineers (2002) were analyzed to determine the relationship between grain size and distance from both the power plant and south shoreline (multiple linear regression, α = 0.05).

**Results**

**Unionids**

We found 2,657 unionids representing 13 species during the 2011 seiche. There were 715 unionids in the 10×10m plot representing 11 species, and 1,942 Unionids representing 11 species in the three 0.5ha plots (Table 1.1). This includes 3 species listed in Ohio as threatened or as species of concern. For the 0.5 ha plots (2011), the thermal plume had 598 individuals, Bayshore Park had 531, and Lake Erie Center had 97. The density of unionids in the 10×10m plot within the thermal plume in 2011 (7.16 unionids/m²) was much higher than at Bayshore Park in 2009 (N=4, 0.09±0.06 unionids/m²). The 95% confidence interval from the 2009 plots (0.06-0.12 unionids/m²) suggests that unionid density was greater in the thermal plume.

Shannon’s Index for the 0.5 ha plots (2011) was highest within the thermal plume ($H'=1.51$) and declined with distance from the plant ($H'=0.96$ for Bayshore Park, $H'=0.35$ for Lake Erie Center). A regression between diversity and distance from the power plant was significant (N=3, $p<0.001$) despite there being only 3 observations. The
95% confidence interval from the 2009 plots (0.11-0.63) suggests that unionid diversity was greater in the thermal plume (1.15).

The Bray-Curtis Similarity Index ($S$) values for the 0.5 ha plots (2011) indicated that unionid communities within the plume and at Bay Shore Park were most similar ($S=0.510$), next were Bayshore Park and Lake Erie Center communities ($S=0.306$), and finally the thermal plume and Lake Erie Center communities ($S=0.276$). The average index among 10x10 m plots taken in 2009 ($N=6$ pair-wise comparisons; $S=0.582\pm0.191$) was significantly higher than the average index between the 2011 plot and the 2009 plots ($N=4$ comparisons; $S=0.023\pm0.011$) (Mann Whitney U Test, $N=10$, $p=0.013$).

The percentage of small individuals in the total population of $L.\ fragilis$ was highest within the plume (51.9%), lower at Bayshore Park (8.7%), and lowest at Lake Erie Center (2.1%). Chi-Squared tests showed that the fraction of small individuals in the population was significantly greater within the plume than outside the plume ($N=587$, $p<0.0001$), but there was no significant difference between Bayshore Park and Lake Erie Center ($p=0.170$).

Small $L.\ fragilis$ had longer shells in the thermal plume than at Bayshore Park (Mann Whitney U test, $N=94$, $p<0.0001$). Large $L.\ fragilis$ also were significantly longer within the plume than at Bayshore Park or Lake Erie Center (Single Factor ANOVA with Tukey pos-hoc, $\alpha=0.05$, $N=465$, $p<0.0001$). There was no difference in the sizes of large individuals between Bayshore Park and Lake Erie Center.

There was significantly less fouling by dreissenids on unionids at the power plant (13%) than at the other sites (71% and 79% at Bayshore Park and Lake Erie Center, respectively), but no difference in fouling between the two plots outside the plume (Chi-
Square test, N=959, p<0.0001). The mean number of attached dreissenids on infested unionids within the plume (1.76±1.73) was significantly lower than at the other sites, but the intensity of infestation at Bayshore Park (5.71±7.06) was not significantly different from the Lake Erie Center (3.50±3.56) (Single factor ANOVA with post-hoc Tukey HSD, N=297, p<0.0001).

Unionids infested with dreissenids were larger than non-infested unionids. Infested L. fragilis (97.9±12.6mm), A. plicata (73.1±22.0mm), and T. donaciformis (32.7±4.9mm) from the 10×10m plot at the power plant were all significantly larger than non-infested L. fragilis (92.6±10.5mm), A. plicata (59.2±20.7mm), and T. donaciformis (27.6±4.4mm) (N=100, 99, and 45 respectively; p=0.048, 0.003, and 0.001 respectively). No significant differences in size occurred in the 0.5ha plot at the power plant. Infested L. fragilis (70.7±16.0mm) from the 0.5ha plot at Bayshore Park were significantly larger (p=0.003, N=100) than non-infested L. fragilis (49.8±16.9mm). Finally, infested L. fragilis (74.4±10.8mm) from the 0.5 ha plot at Lake Erie Center were significantly larger (p=0.013, N=91) than non-infested L. fragilis (64.4±19.2mm).

**Dreissenids and corbiculids**

A linear regression of data reported by Ager (2009) showed a significant, positive relationship between live dreissenid density and distance from the power plant (Fig. 1-3a; N=22, p=0.0002). Conversely, data from our samples collected in 2010 showed that corbiculids (C. fluminea) had high densities close to the plant and decreased with distance (Fig. 1-3a). Also, both studies showed that almost all sites with C. fluminea densities >200/m² were within 1500m of the power plant, which roughly corresponds to a partial
embayment of the outflow area created by the island located to the north of the power plant discharge (Fig. 1-1).

**Sediments**

The mass of coarse surface sediments overlaying a compact lacustrine clay layer (Fig. 1-3b) showed a significant, negative relationship with distance from the power plant (N=85, R$^2$=0.551, p<0.0001). Of the four size fractions examined, both the 6.4-12.7mm and 12.7-25.4mm size classes also showed significant negative relationships with distance from the plant (N=85 and p<0.0001 for both analyses, R$^2$=0.286 and 0.497 respectively) (Fig. 1-3c). Shells and shell fragments of *C. fluminea* were the primary components of the 6.4-25.4mm sediment size class within 1200m of the plant, again falling within the partial embayment of the power plant discharge plume.

The organic matter content in fine sediments also showed a negative relationship with distance from the discharge (N=20, R$^2$=0.479, p=0.0007) (Fig. 1-3e). In contrast, the Army Corps of Engineers sediment data (2002) from Maumee Bay showed a significant positive relationship between mean grain size and distance from the power plant (N=76, R$^2$ = 0.1145, p=0.0028) (Fig. 1-3d).

**Discussion**

Our results indicate a larger, more diverse community of unionids living within the thermal plume of the Bayshore Power Plant than at other more exposed locations along the southwest shore of Lake Erie. Clearly unionids have not been extirpated by dreissenids, despite concerns by Ricciardi et al. (1998). The low rate of dreissenid
infestation within the discharge embayment is probably one of the factors contributing to why unionids are thriving in this habitat. Positive flow coming from power plant may reduce both the likelihood of veligers settling out of the water column (Horvath and Lamberti, 1999) and the chance of their entering the embayment from the open lake waters (Zanatta et al., 2002; McGoldrick et al., 2009). However, we found that infested unionids were larger than dreissenid-free unionids, so there was no indication that infestation inhibited growth or survival. Greater shell surface area and siphoning capacity almost certainly makes larger unionids more susceptible to infestation, and indeed, small unionids have been shown to burrow deeper than large unionids (Schwalb and Pusch, 2007), which might also reduce infestation for those living in the deeper sediments within the plume.

We found a higher number of small unionids living within the plume. Our data suggest that for at least two of the most common species (A. plicata and L. fragilis), the thermal plume may support breeding populations or perhaps is a gathering area for species of host fish that may drop glochidia in this location. However, we have no data to relate age to size. Finally, elevated temperature has been shown to increase growth rates of marine bivalves (Shpigel et al., 1992; Gangnery et al., 2003) and our results showed that unionids within the thermal plume were larger than their counterparts outside the plume. In particular, both small and large individuals of L. fragilis were significantly larger within the plume.

We found a dense corbicula population within about 1500m of the BPP (Fig. 1-3a), largely within the embayment created by the dredge-spoil island. Scott-Wasilk et al. (1983) also showed that C. fluminea develop dense populations in thermal effluents along
the western Lake Erie coast. These populations can generate large volumes of shell material, which we found contributed to the development of a deeper substrate inside the embayment. Finally, temperature may also help explain why dreissenid densities and fouling rates are low close to the plant. Dreissenid veligers may be killed by heat shock as they pass through the cooling system, creating a veliger shadow and effluent temperatures may approach the upper limits of adult dreissenid thermal tolerance (McMahon and Ussery, 1995).

Sediments within the thermal plume provided a greater volume of potential unionid habitat. Sediment composition and distribution is reported to be extremely important to the distribution and abundance of unionids (Box and Mossa, 1999). We found that unconsolidated sediment mass declined with distance from the power plant and almost all of the gravel-size sediment consisted of spent C. fluminea shell. We speculate that the shell material acted as a gravel bed, which trapped fine particles. The result was a substrate comprised of coarse and fine particles that is both friable enough for unionids and stable enough to resist erosion. Asiatic clams are a common component of the benthic community in thermally impacted waters of western Lake Erie (Scot-Wasilk et al., 1983), so it’s likely they have engineered substrates that are beneficial to unionids in other thermal plumes. In western Lake Erie refuges, Nichols and Wilcox (1997) and Bowers et al. (2005) also report that unionids in deeper substrate tend to have a lower infestation rate of dreissenids.

Sediments within the plume also had higher organic matter content than sediments outside the plume. Unionids pedal feed on organic material in sediment (Yeager and Cherry, 1994; Raikow and Hamilton, 2001), although the relative
importance of pedal feeding is uncertain. Nonetheless, mussels close to the power plant had both more habitat (sediment) and potentially access to more organic matter in sediments than at the other sites. Further study would be needed to determine the source of the sediment organic matter, however, we observed high concentrations of fish and birds near the BPP (personal observations), which probably contribute fecal input. Also, the lower Maumee River, from which water is drawn to cool the power plant, is very productive (Bridgeman et al., 2011) and has a high sediment load (Richards et al., 2010), so that it is likely an organic matter source.

The south shore of Lake Erie is the most altered shoreline segment of the Great Lakes. The shoreline is 83% armored, so the lakebed is severely sand starved compared with conditions that existed 200 years ago (Morgan et al., 2011). The decline in unionids that was already occurring before the dreissenid mussel invasion (Nalepa et al., 1991) was due in part to shoreline alteration (which reduced land/lake sediment exchange) and pollution. When dreissenids invaded, they exacerbated the negative effect that habitat degradation was already causing. Increasing sources of coarse sediment (sand/gravel) may be important to the conservation of unionids in western Lake Erie.

**Conclusion**

The thermal plume at the Bayshore Power Plant provided favorable habitat for unionids due to a combination of interacting factors. Dreissenid density was low, sediment and potential food availability (sediment organic matter) was high, and temperature and flow (plant discharge = 8 - 33m³/sec⁻¹) were elevated within the embayment. All of these factors may individually and synergistically contribute to the
greater sizes, density, and diversity of the unionid community in the thermal plume. Despite concerns of extirpation from the Great Lakes, robust communities continue to persist in protected nearshore habitats that accumulate sediments.
Table 1.1. Numbers (N) and shell length (mm) of unionids sampled in 10x10m and 0.5ha plots at Maumee bay, Ohio.

<table>
<thead>
<tr>
<th>Species</th>
<th>Power Plant (10x10m)</th>
<th></th>
<th>Power Plant (0.5 ha)</th>
<th></th>
<th>Bay Shore Park (0.5 ha)</th>
<th></th>
<th>Lake Erie Center (0.5 ha)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Length ± 1SD</td>
<td>N</td>
<td>Length ± 1SD</td>
<td>N</td>
<td>Length ± 1SD</td>
<td>N</td>
<td>Length ± 1SD</td>
</tr>
<tr>
<td><em>Amblema plicata</em></td>
<td>374</td>
<td>56.4±23.2</td>
<td>273</td>
<td>26.4±15.6</td>
<td>127</td>
<td>21.0±4.8</td>
<td>3</td>
<td>15.0±1.0</td>
</tr>
<tr>
<td><em>Fusconaia flava</em></td>
<td>1</td>
<td>46</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td><em>Lasmigona complanata</em></td>
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<td><em>Lampsilis siliqudia</em></td>
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<tr>
<td><em>Leptodea fragilis</em></td>
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<td>87.1±18.5</td>
<td>129</td>
<td>65.3±26.1</td>
<td>367</td>
<td>69.3±16.0</td>
<td>91</td>
<td>71.2±14.7</td>
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<td><em>Obliquaria reflexa</em>*</td>
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<td>31</td>
<td></td>
<td></td>
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<tr>
<td><em>Potamilus alatus</em></td>
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<td>13.9±15.9</td>
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<td><em>Toxolasma parvus</em></td>
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<td>N</td>
<td>Mean ± SD</td>
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<td><em>Truncilla donaciformis</em></td>
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<td>29.6±5.2</td>
<td>52</td>
<td>14.7±6.7</td>
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<td>24.6±3.1</td>
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<tr>
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<td></td>
<td>3</td>
<td>31.0±7.9</td>
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</tbody>
</table>

* Ohio Species of Concern
** Ohio Threatened Species
Figure Legends

Fig. 1-1. Location of study area within the United States and Great Lakes region. The lower panel shows the location of the three 0.5ha plots (black squares) and sampling sites (bullseyes).

Fig. 1-2. *L. fragilis* size distributions adjacent to the power plant (top), Bayshore Park (middle), and the Lake Erie Center (bottom).

Fig. 1-3. Gradients of environmental variables (a) corbiculid (open circles) and dreissenid (filled circles) densities (Ager 2009), (b) total sediment mass (mg), (c) coarse sediment (12.7-25.0mm) mass (mg), (d) mean phi grain-size value, (e) percent organic matter in fine sediments (0.075- 0.60mm).
Fig. 1-1.
Fig. 1-2.
Fig. 1-3.
Chapter 2

Habitat Characteristics of a Unionid Refuge in the Thermal Plume of a Power Plant in Western Lake Erie

Introduction

Historically, western Lake Erie supported abundant populations of unionids (Nalepa et al., 1991), however, their abundance has decreased by 99% since 1960 (Nichols and Smith, 2009). Pollution, habitat alteration, and invasive dreissenid mussels have all contributed to this decline (Stevens and Neilson, 1989; Schloesser and Nalepa 1994; Morang et al., 2011), although the dreissenid invasion (mid 1980s) was the most catastrophic and well-documented impact (Schloesser and Nalepa, 1994; Nalepa et al., 1996; Schloesser et al., 2006). Despite the negative impacts dreissenids have on unionids, robust unionid communities are able to coexist with dreissenids in several shallow (<2m) refuge habitats (Nichols and Wilcox 1997; Nichols and Amberg, 1998; Zanatta et al., 2002; Bowers and deSzalay, 2003; Bowers et al., 2005, McGoldrick et al., 2009; Crail et al., 2011; Chapter 1). Conservation of unionids is a priority to many in the Great Lakes community, thus the study of these refuges has been a major focus of research since the dreissenid invasion. If the critical characteristics of refuges that allow for
unionid/dreissenid coexistence can be determined, then managers could focus on conserving and even creating habitats with these characteristics.

A few mechanisms that allow unionids and dreissenids to coexist are understood. For unionid infestation to be low, the habitat must either have a low influx of dreissenid veligers or conditions that allow unionids to shed their attached dreissenids. A combination of these two factors is ideal. Deep, soft surface sediments in marshes and bays allow unionids to burrow and shed their dreissenids through suffocation and dislodgement (Nichols and Wilcox 1997; Bowers et al., 2005). Predators may remove dreissenids directly from the shells of infested unionids (Bowers et al., 2005). Bowers and deSzalay (2003) found that dreissenid settlement can be relatively high in a coastal marsh (>3000/m²), so that dreissenid removal appeared to be the primary mechanism allowing unionids to survive in these habitats. Water level fluctuations, caused by wind-driven seiches, can expose dreissenids to dessication and temperature extremes, causing them to die or release from unionids (Schloesser and Masteller 1999, Bowers et al., 2005). Water currents can also keep veliger-laden water from entering habitats and reduce the likelihood of settlement (Bowers and deSzalay, 2003; McGoldrick et al., 2009; Bryan et al., in press).

Although low dreissenid infestation of unionids is one of the most important characteristics of refuges, unionids must also have access to suitable substrate (Allen and Vaughn, 2010; Yeager and Cherry, 1994). There must be enough food for unionids to grow and reproduce, and an adequate supply of fish hosts for reproduction (Strayer, 2008). Ultimately, habitats with low dreissenid fouling, plenty of stable surface sediments, and ample food and fish hosts will likely be the most favorable (Strayer,
A previously unknown unionid refuge was recently discovered in the thermal plume of the Bayshore Power Plant, located on the south shore of Maumee Bay in Oregon, Ohio (Crail et al., 2011; Chapter 1). This habitat hosts a diverse community of unionids with much higher densities (7.16 m\(^{-2}\)) than has been reported for other refuges (0.01-0.09 m\(^{-2}\); Bowers and deSzalay, 2003; McGoldrick et al., 2009; Crail et al., 2011). Chapter 1 compared unionid densities from plots sampled within the plume in 2011 to plots sampled outside the plume in both 2009 and 2011, and concluded that densities inside the plume were greater. Similarly, Moorhead et al. (unpublished) found unionids (9.57 ± 6.45 m\(^{-2}\)) in ponar grabs taken within 1150 m of the power plant (N=12) but found none beyond that distance (N=14). Based on these data, we speculated in Chapter 1 that unionid densities were negatively correlated with distance from the power plant and unionid diversity and average individual size were higher within thermal plume. For all of these reasons, Chapter 1 concluded that the thermal plume provides a favorable habitat for unionids.

The goal of the present study was to evaluate some likely characteristics of this habitat that make it favorable to unionids. We expected warmer water temperatures, higher particulate organic matter (POM) concentrations in water (potential food source; Nichols and Garling, 1999), higher organic matter content in sediments (potential food source; Raikow and Hamilton, 2001), and greater coarse sediment mass in the plume. We also expected live dreissenid veliger densities to be low, either because there are relatively few in the water column of the lower Maumee River (source of cooling water) or because they are killed when they pass through the power plant. Also, the large
dredge-spoil island to the north of the plant’s discharge (Fig. 2-1) affords shelter and embayment to the habitat, reducing water input to the bay from the lake.

**Methods**

**Study Area**

Our study was conducted in Maumee Bay, within 500m of the southern shoreline of Lake Erie. Water samples were taken from the intake canal of First Energy’s Bayshore Power Plant and within the thermal plume exiting the plant. The plant removes water from the Maumee River as it enters Lake Erie and discharges it into a small bay created by an island built of sediments dredged from the Toledo shipping channel (Fig. 2-1) (Ager, 2009). Sediment samples were also taken along a transect extending 2.5km east from the plant outflow.

**Temperature and suspended particulate organic matter**

Water temperature was recorded at the power plant intake and outflow on eight dates in the summer of 2012 (18 June-26 September). On four dates (27 June-26 September), temperature was also measured at 11 locations along a transect extending 3km east from the plant intake (Fig. 2-1).

Three, whole water samples (0.5L) were taken at the same 11 locations along the same transect on five dates (13 June-26 September); a 200ml subsample from each was filtered through a 0.1µm glass fiber filter. Filters were oven-dried at 60°C to a constant weight, fired at 550°C for two hours, and particulate organic matter (POM) was estimated as weight loss on ignition.
**Dreissenid veligers**

Four, 1L water samples were collected at the plant intake and outflow, and at the Bayshore Park (2.0km east of the plant) on five dates (6 June-15 August). Each sample was poured through a plankton net (60µm mesh) and concentrated to 140ml. Three subsamples (1-4ml depending on veliger density) from each concentrated sample were then completely counted for dreissenid veligers using a dissecting microscope with cross-polarized light. Four, 10m plankton tows (60µ mesh, 0.2m diameter, ca. 1260L water filtered) were taken from shore at the same three locations on four dates (6 June-26 July). Concentrated samples (140ml) were held at 25°C in a laboratory for 24 hours. Three, 3.0ml subsamples were then taken from each sample and the first 30 pedeveligers in each subsample were identified as being alive or dead by visual assessment using a dissecting microscope with cross-polarized light (Horvath and Crane, 2010).

On June 24 we simulated the heating and turbulence experienced by veligers passing through the power plant in a laboratory experiment. Plankton tows were taken at Bayshore Park (2km east of the plant) to obtain 2L of concentrated veligers that were unaffected by heat. Veligers were allowed one hour to adjust to room temperature (25°C) and 70ml samples were transferred to conical (250ml) flasks. Each flask was then subjected to either 1) heat 2) turbulence 3) heat with turbulence, or 4) control (N=5 for each treatment).

The heat treatment raised samples from 25°C to 36°C on a hot plate over 10 minutes, approximately the time it takes for water to flow through the power plant (Bob Smothers, head engineer; personal correspondence). The turbulence treatment was stirred at 250rpm for 10 minutes with a stir bar in the flask. The heat with turbulence treatment...
combined stirring and heat treatments. Finally, the control treatment was left at 25°C with no heating or stirring. After treatment, samples were left at 25°C for 24 hours. The first 30 pedeveligers counted in each sample were then identified as being alive or dead through visual assessment using a dissecting microscope with cross-polarized light.

Wind speed, wind direction, and Maumee River discharge

We anticipated effects of weather conditions on patterns in temperature, POM, and veliger density because the study area is very shallow and subject to both seiches and suspension of particulates by wind. Therefore, wind speed, wind direction, and Maumee River discharge (source of water entering the power plant) were obtained from NOAA (http://tidesandcurrents.noaa.gov/) and the USGS (http://waterdata.usgs.gov/oh/nwis/). We calculated the 4, 24, and 48-hour averages for each parameter prior to each sampling event.

Sediments

Sediment cores (N=9; 30.5cm length x 38mm diameter) were taken along a transect extending 2500m from the power plant outflow (N=9), which roughly bisected the bay into which the power plant discharges water (Fig. 2-1). The corer was pushed through the loose surface sediment into the underlying clay layer, which was left as a plug in the bottom of each core. Each core was capped and stored at 4°C.

In the lab, each core was pushed out of its PVC sleeve onto a tray. Loose surface sediments were separated from the clay and sieved into three grain-size fractions (<2mm, >2<10mm, >10mm). The three surface fractions and clay plug from each core were oven-
dried at 100°C to a constant weight; the surface fractions were weighed. Fine sediment samples (<2mm) were homogenized and a 10g subsample was weighed, fired at 550°C for eight hours and organic matter content estimated as weight loss on ignition. The top 1.0cm of the clay plug was also weighed and fired to estimate organic matter content.

Statistics

We used simple linear regressions to analyze the relationships between temperature and POM to distance from the power plant. One-way analyses of variance were used to test for differences in veliger densities and live:dead ratios between the power plant intake, outflow, and the nearby Bayshore Park. Multiple linear regressions were used to analyze the relationships between sediment characteristics and both distance from the power plant and distance from the southern shoreline.

The slopes and $R^2$ values from the temperature and POM transects, as well as the differences in veliger density and water temperature between the intake and outflow were compared to the wind speed, wind direction, and Maumee River discharge at the time of sampling. Wind direction was represented such that directions west of north were negative (-1 to -179 degrees) and directions east of north were positive (1 to 179 degrees). Stepwise linear regressions determined the best-fit models explaining slope, $R^2$, veliger density and temperature differences from these environmental factors. We considered the $R^2$ values from regression analyses to represent a measure of the variability in observations over distance.
Results

Temperature

Water temperature averaged 3.8±1.5°C (N=8) warmer at the power plant outflow than at the intake (Table 1) and decreased with distance from the outflow (Fig. 2-2). For example, water temperature at 2.0km from the plant averaged 3.5±1.5°C (N=4) cooler than at the outflow. Wind speed (48-hour average) and wind direction (48-hour average) explained nearly 100% of the differences in the slope of the temperature regression lines (N=4; \( R^2 = 100\% ; p=0.0007 \)). The slope was negatively correlated with wind speed and positively correlated with wind direction.

Particulate Organic Matter

The relationship between POM and distance from the power plant outflow was highly variable among sampling dates (Fig. 2-3, Table 2.2). The sampling location at 3000m was outside of the thermal plume, so those data were not used in statistical analyses. Simple linear regressions found no significant relationship with distance on June 6 and September 26, significant negative relationships on June 26 and August 6 (\( p<0.0001 \) and \( p=0.002 \), respectively), and a significant positive relationship on 16-July (\( p<0.0001 \)).

ANCOVA found that wind speed (4 hour average) and status of river discharge (increasing or decreasing at the time of observation) explained 86.9% of the variability in the slope of POM with distance (N=5; \( p=0.01 \)). Wind speed was positively correlated with slope (r=0.18), but the direction of the slope was positive when the Maumee River discharge was increasing, and negative when discharge was decreasing. The \( R^2 \) values of
the POM regressions over distance were negatively correlated (N=5; \( p=0.003 \)) with wind speed (48-hour average).

Differences in POM at the intake were also explained by wind speed (48-hour average) and status of river discharge (N=5; \( R^2=91.3\%; \ p=0.007 \)). POM was negatively correlated with wind speed and was greater than 6.25mgL\(^{-1}\) when river discharge was increasing, and less than 6.25mgL\(^{-1}\) when decreasing. The concentration of POM at the outflow was also explained by wind speed (24-hour average) and status of river discharge (N=5; \( R^2=95\%; \ p=0.008 \)). Output POM was positively correlated to wind speed and was high when the river was rising and low when it was falling. Finally, the difference between POM at the intake and outflow was positively related to wind speed (48-hour average) alone (N=5; \( R^2=98\%; \ p=0.0006 \)).

\textit{Dreissenid veligers}

Dreissenid veliger densities were greatest on the first sampling day at all locations and decreased with time (Table 2.3). Wind direction (24-hour average) explained the differences in veliger density between the intake and outflow (N=5; \( R^2=94.9\%; \ p=0.003 \)). Densities were highest at the intake when winds were from the west; intake and outflow densities were similar when winds were from the north; and densities were highest at the outflow when winds were from the northeast.

The ratio of live:dead veligers was significantly higher at the intake than at the outflow on three of the four veliger sampling days (Table 2.3), but significantly greater at the outflow on July 9 (N=4 for each date). The laboratory experiment showed that the heat treatment produced the lowest live:dead ratio (Table 2.4). Heat with turbulence had a
higher ratio than heat-only, but was lower than the control and turbulence-only treatments (N=20, \( p<0.0001 \)).

**Sediments**

No significant relationship to distance from the shore or power plant was found for surface sediment mass, organic matter in surface sediments, or organic matter in lakebed clay of the offshore transect. The coarse (>10mm) sediment fraction was not significantly correlated with distance (\( p=0.091 \)) from the power plant despite a decline in maximum values seen with distance (Fig. 2-4).

**Discussion**

The unionid community within the power plant’s thermal plume exhibits larger sizes and lower dreissenid infestation as well as higher abundance and diversity than at other nearby locations along the southern shore of Maumee Bay (Chapter 1). The data reported in Chapter 1 and Moorhead et al. (unpublished) suggest that unionid density is negatively correlated with distance from the power plant. We speculated that this site was favorable because of warmer water temperature, a possible food source supplied by POM in discharge water, increased veliger mortality by traveling through the power plant cooling system, and accumulations of loose surface sediments and sediment organic matter due to partial protection from winds and currents afforded by the dredge-spoil island located north of the power plant outflow.

Results of this study showed that temperatures in the thermal plume within 700m of the power plant were 2.4°C to 6.1°C higher than outside it. The water temperature at
the plant’s output was consistently greater than at the intake, ranging between 1.6°C and 6.5°C warmer. Exposure to warmer temperatures has implications to several aspects of unionid biology. Versteegh et al. (2010) showed that onset and cessation of growth in unionids depend on water temperature. Huebner (1982) showed that oxygen consumption by *Anodonta grandis* increased linearly with temperature, and Galbraith et al. (2009) found that the onset of reproduction was correlated with cumulative degree-days for three *Quadrula* species. Thus, unionids living at higher temperatures in the thermal plume are likely to have longer growing seasons, increased metabolic rates, and earlier reproduction than those living outside the plume. This may explain why *Leptodea fragilis* living within the plume are larger than those living outside it (Chapter 1), of course, they may also live longer with lower rates of dresseinid infestation, but Chapter 1 included no data on unionid ages.

We also speculated that POM concentrations might be higher in the water output from the plant than lake water because cooling water is drawn from the highly productive Maumee River. Also, small organisms in the water may be killed by passing through the plant and become a food source to unionids. Large concentrations of fish and birds feed in the outflow channel (personal observation) so they too may add to the suspended POM in the output water. Versteegh et al. (2010) showed that the rate of growth in unionids depends on food availability so that high concentrations of POM in the effluent could be a reason why there are larger, denser, and more diverse unionid communities present. However, we found no significant difference in POM between the intake and outflow from the plant, but it is possible that the power plant changes the quality of POM as we found increased mortality of veliger larvae after passing through the plant (see below). It
is likely that other organisms in the water column may be affected as well. Nichols and Garling (1999) showed that unionids use bacteria as their main dietary source of carbon, so it’s possible that the plant could increase the availability of food for unionids by killing live organisms in POM and stimulating bacterial growth on these now-dead organisms.

Wind speed had significant effects on both the rate of change in POM concentration with distance from the power plant and variability in POM (R$^2$ of regressions) over distance. These effects are partly a result of water movements because we also found that temperature decreased linearly with distance from the output at a rate dependent on wind speed and wind direction. In essence, water exits the small embayment more rapidly when winds are from the west and more slowly when they’re from the east; wind speed enhances the effect of wind direction. However, Demers and Therriault (1987) also found that wind velocities greater than 4ms$^{-1}$ suspended POM in shallow estuaries, so that winds during our study likely suspended organic matter and increased POM concentrations in Maumee Bay. Surface water close to the power plant is partly protected from wind by the dredge-spoil island located to the north of the plant outflow (Fig. 2-1) and stays relatively calmer than water further from the plant. This may be part of the reason why POM concentrations were lower close to the plant on dates with high winds and a rising river (July 16 and September 26).

The pattern of discharge from the Maumee River also affected POM concentrations in our study. Concentrations of suspended solids in the Maumee River in 2011-2012 ranged from 10.1-689.6mgL$^{-1}$ and were positively correlated (r=0.8) with river discharge (Heidelberg water quality laboratory). Thus when the river is rising, it
provides Maumee Bay with sediment-rich water (Richards et al. 2010). At these times, we found a positive slope in POM concentration with distance from the plant (July 16 and September 26). This may be because the amount of water passing through the power plant is not dependent on river discharge, so that the water entering the intake channel of the plant may be slower than the main river channel during high flow, allowing some sediment to settle out of the water before it enters the plant’s cooling system. In addition, the sediment carried into Maumee Bay may remain at a higher concentration beyond the dredge-spoil island, and backflow into the embayment created by the island. Indeed, POM concentrations at 3000m were not consistent with values between 160-2050m, indicating that they were independent of the plume. Thus POM concentration declines over distance from the outflow when river discharge is decreasing and wind speed is low. River discharge tends to increase rapidly and then decrease slowly, so POM concentration is probably higher near the plant more often than it is lower. Thus, higher POM in water close to the power plant may contribute to the robust population of unionids that lives in this habitat.

The proportion of unionids infested by dreissenids and the average number of dreissenids on an infested unionid are lower inside than outside the thermal plume (Chapter 1) and we speculated that the power plant causes significant mortality to dreissenid veligers. We found that water temperature at the outflow on July 17 was 34.8°C, which McMahon (1996) reported caused 100% mortality in adult zebra mussels in less than 15 hours in laboratory experiments. Unionids almost certainly have a higher thermal tolerance than dreissenids, as Galbraith et al. (2012) found that the critical thermal maxima (CTM) for three unionid species ranged from 39.1°C to 42.3°C and that
greater acclimation temperatures resulted in higher CTMs. Our experiment also showed that heating similar to that of water passing through the power plant significantly increased veliger mortality. Lower densities of veligers in the water column have been shown to result in lower settlement rates (Martel et al. 1994), thus the thermal plume may have lower numbers of both dreissenid adults and veligers thereby reducing infestation rates on unionids, as observed in Chapter 1.

In Chapter 1 we found that the amounts of coarse surface sediments and organic matter concentrations in fine sediments were greater inside the thermal plume, and speculated that these factors contributed to the success of the unionid communities. Others have also found that surface sediment is a predictor of unionid distribution. For example, Cyr et al. (2012) showed that sediment accumulation predicted the distribution of *Elliptio complanata* in nearshore areas of a Canadian Shield lake, noting a unimodal relationship between total mussel density and sediment depth, with highest densities at sites with 30cm of sediments. Sediment depths in our cores ranged from 4-20cm (not shown). Raikow and Hamilton (2001) demonstrated pedal feeding was a substantial source of food for unionids in a southern Michigan stream, which derived 80% their carbon from sediment-derived material and only 20% from suspended material. However, we found that neither the amounts of surface sediments nor the organic matter content in surface sediments were significantly related to distance from the power plant. Our results suggest that surface sediments may not be as important to the unionids in this location as anticipated in Chapter 1.
Conclusions

The habitat within the thermal plume of the Bayshore Power Plant is dynamic and affected by several environmental factors that have implications to unionids. The power plant heats water to temperatures that increases mortality in dreissenids and the warmer temperatures in the plume may stimulate unionid growth and reproduction. POM concentrations vary with river discharge, wind speed and direction, but variations in quality are unknown. We did not find that surface sediment characteristics varied consistently with distance from the power plant. Thus it appears that higher water temperatures and lower dreissenid infestation are the two factors correlated with the higher sizes, densities, and species diversity of unionids in this thermal plume.
Table 2.1. Water temperature at the power plant intake and outflow. Regression equations, *p* values, and *R*^2^ values are shown for dates on which water temperature transects were done.

<table>
<thead>
<tr>
<th>Date</th>
<th>Intake (°C)</th>
<th>Outflow (°C)</th>
<th>Equation</th>
<th><em>p</em> value and <em>R</em>^2^</th>
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<td>6/18/12</td>
<td>25.6</td>
<td>27.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6/27/12</td>
<td>25.4</td>
<td>27.6</td>
<td>-0.0013x + 27.78</td>
<td><em>p</em>=0.0007, <em>R</em>^2^=0.824</td>
</tr>
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<td>7/9/12</td>
<td>28.7</td>
<td>32.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/17/12</td>
<td>28.3</td>
<td>34.8</td>
<td>-0.0014 + 34.91</td>
<td><em>p</em>=0.0006, <em>R</em>^2^=0.832</td>
</tr>
<tr>
<td>7/26/12</td>
<td>26.9</td>
<td>30.4</td>
<td></td>
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</tr>
<tr>
<td>8/7/12</td>
<td>27.1</td>
<td>30.9</td>
<td>-0.0018 + 31.46</td>
<td><em>p</em>&lt;0.0001, <em>R</em>^2^=0.927</td>
</tr>
<tr>
<td>8/15/12</td>
<td>23.6</td>
<td>28.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/26/12</td>
<td>17.3</td>
<td>21.5</td>
<td>-0.0030 + 21.71</td>
<td><em>p</em>&lt;0.0001, <em>R</em>^2^=0.922</td>
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<tr>
<td>Mean±1SD</td>
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<td>29.1±4.0</td>
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Table 2.2. POM concentrations (mgL$^{-1}$) with distance (m) from the power plant outflow for five sampling days. An “NA” indicates that samples were not collected.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>June 13</th>
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<th>July 17</th>
<th>August 7</th>
<th>Sept.26</th>
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<td>160</td>
<td>8.00±2.00</td>
<td>4.17±1.89</td>
<td>8.67±1.76</td>
<td>7.67±2.02</td>
<td>9.67±1.53</td>
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<tr>
<td>310</td>
<td>7.67±0.76</td>
<td>4.83±2.36</td>
<td>9.83±0.76</td>
<td>8.17±0.29</td>
<td>7.33±1.76</td>
</tr>
<tr>
<td>460</td>
<td>8.67±1.26</td>
<td>4.67±1.04</td>
<td>7.83±0.76</td>
<td>7.50±1.50</td>
<td>6.67±1.26</td>
</tr>
<tr>
<td>660</td>
<td>7.00±0.87</td>
<td>3.83±1.61</td>
<td>7.50±0.50</td>
<td>7.50±1.32</td>
<td>7.83±1.04</td>
</tr>
<tr>
<td>860</td>
<td>6.00±2.65</td>
<td>2.33±1.89</td>
<td>9.83±0.58</td>
<td>7.17±1.04</td>
<td>8.83±0.76</td>
</tr>
<tr>
<td>1100</td>
<td>10.17±3.06</td>
<td>1.83±0.76</td>
<td>9.33±1.04</td>
<td>7.67±1.61</td>
<td>7.33±0.58</td>
</tr>
<tr>
<td>1350</td>
<td>6.83±1.89</td>
<td>2.50±0.50</td>
<td>9.17±1.26</td>
<td>5.17±0.58</td>
<td>9.17±0.76</td>
</tr>
<tr>
<td>1700</td>
<td>6.50±1.00</td>
<td>1.17±0.29</td>
<td>13.67±2.93</td>
<td>6.50±2.00</td>
<td>9.00±0.50</td>
</tr>
<tr>
<td>2050</td>
<td>NA</td>
<td>0.83±0.76</td>
<td>14.67±1.04</td>
<td>4.67±1.76</td>
<td>9.67±1.26</td>
</tr>
</tbody>
</table>

Mean±1SD 7.23±1.68 3.00±1.79 10.21±2.38 7.46±2.09 8.12±1.16
<table>
<thead>
<tr>
<th>Regression</th>
<th>(-0.0007x + 8.146)</th>
<th>(-0.0022x + 4.996)</th>
<th>(0.0031x + 7.043)</th>
<th>(-0.0016x + 8.406)</th>
<th>(0.0008x + 7.622)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R^2)</td>
<td>0.028</td>
<td>0.520</td>
<td>0.539</td>
<td>0.340</td>
<td>0.120</td>
</tr>
<tr>
<td>(p) value</td>
<td>0.4382</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.0015</td>
<td>0.0763</td>
</tr>
</tbody>
</table>
Table 2.3. Wind direction, veliger densities, and live:dead ratios (±1SD). Means within dates that have different letters are significantly different ($p \leq 0.05$). An “NA” indicates that no data was collected on that day.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wind Direction</th>
<th>Veliger Density (#L$^{-1}$)</th>
<th>Live:Dead Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24hr mean</td>
<td>Intake</td>
<td>Outflow</td>
</tr>
<tr>
<td>June 6</td>
<td>41±126</td>
<td>1155±504 a</td>
<td>1260±241 a</td>
</tr>
<tr>
<td>June 18</td>
<td>-83±82</td>
<td>253±89 b</td>
<td>175±64 a</td>
</tr>
<tr>
<td>July 9</td>
<td>35±39</td>
<td>43±20 a</td>
<td>111±38 b</td>
</tr>
<tr>
<td>July 26</td>
<td>-6±159</td>
<td>76±30 b</td>
<td>119±36 b</td>
</tr>
<tr>
<td>August 15</td>
<td>1±90</td>
<td>6±7 a</td>
<td>33±12 b</td>
</tr>
</tbody>
</table>
Table 2.4. Live:dead ratios for the veligers subjected to heat, turbulence, heat + turbulence, and controls. Means with different letters are significantly different ($p<0.05$).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Live:Dead±1SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>2.12±0.46 c</td>
</tr>
<tr>
<td>Heat</td>
<td>0.37±0.10 a</td>
</tr>
<tr>
<td>Turbulence</td>
<td>2.35±0.65 c</td>
</tr>
<tr>
<td>Heat with Turbulence</td>
<td>1.12±0.30 b</td>
</tr>
</tbody>
</table>
Figure Legends

Fig. 2-1. Sampling locations for POM, temperature, and sediment cores

Fig. 2-2. Variation in water temperature with distance from the plant outflow on four dates in 2012.

Fig. 2-3. Variation in POM concentrations with distance from power plant for two sampling dates in 2012: June 26 (closed circles) and July 16 (open circles)

Fig. 2-4. Variation in dry mass of coarse sediment (>10mm) with distance from the power plant outflow.
Fig. 2-1.
Fig. 2-2.
Fig. 3.
Fig. 4.
Chapter 3

Summary

In Chapter 1 we synthesized data from several studies to show that a robust unionid community lives in the thermal plume of the Bayshore Power Plant. Unionid size, density, and diversity decreased with distance from the power plant, as did infestation of unionids by dreissenid mussels. Coarse sediment volumes decreased with distance from the plant, and the bulk of this coarse material was comprised of corbiculid and dreissenid shells. We speculated that the power plant provides favorable habitat for unionids because: 1) warm water temperatures in the thermal plume stimulate unionid growth, 2) the power plant causes significant mortality to dreissenid veligers that pass through the cooling system thereby reducing infestation of unionids by dreissenids within the plume, 3) aquatic organisms are killed as they pass through the plant’s cooling system, which increases particulate organic matter (POM) in water and organic matter content in sediments (both are a potential food source to unionids) in the plume, 4) the dense corbiculid population contributes large volumes of spent shells, which increases coarse sediment mass and thus provides more potential unionid habitat within the plume, and 5) the large dredge-spoil island to the north of the plant’s outflow provides partial protection from wind and wave energy, which favors sediment accumulation and allows
the positive water flow coming from the plant discharge to prevent veliger laden water from the offshore lake waters moving into the bay.

We tested some of these speculations with field and laboratory studies detailed in Chapter 2. We expected water temperature, POM, surface sediment mass, and sediment organic matter content to be negatively correlated with distance from the power plant’s outflow. We also expected the ratio of live to dead dreissenid veligers to be lower in the outflow water than in the intake, and that heating veligers to temperature regimes comparable to a trip through the power plant would cause significant mortality. We found that the power plant caused significant mortality to dreissenid veligers, temperature was negatively correlated with distance from the power plant, and that wind speed and direction affected the relationship between temperature and distance. We also found that the relationship between POM and distance from the plant was most often negative, and that neither surface sediment mass nor surface sediment organic matter content were correlated with distance from the power plant.

Overall, our results indicate that heat from the power plant appears to be the primary reason why this habitat is so favorable to unionids, because it kills dreissenid veligers that pass through the plant, raises water temperatures within the plume to exceed the thermal limits of adult dreissenids, and likely stimulates unionid growth. An increased flux of POM from the plant and protection afforded by the dredge spoil island also likely contribute to the favorability of the habitat. However, surface sediment accumulation does not appear to be an important variable because it showed no consistent pattern within the study area.
References


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