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# The Characterization of a Vital Wisconsin Waterway: A Biological Assessment of the Lower Fox River from 2006-2014

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By Emily Lynn Kiehnau

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**Abstract**

The Lower Fox River has historically been used as a navigational crossroads, a waste disposal system, and source of hydroelectric power. Over the years, heavy use of the river has negatively affected water quality and the overall health of the system. Unhealthy rivers cannot function properly. Biological assessment based on animal surveys are often used to determine river health. I used data from the Lawrence University and Fox River Navigational System Authority invasive species-monitoring project to explore how the distribution of animals in the Fox River has changed over time and across locations. Monitoring surveys have taken place between June and August at six sites along the river from 2006 to 2014. The field data consist of a combination of presence-absence and abundance data for zooplankton, benthic invertebrate, and fish populations. There are clear trends in the community composition of animals in the river over time and across locations. Compositions of fish populations of a given site remained similar across time but varied among sites. In contrast, compositions of benthic invertebrate and zooplankton populations in a given year were fairly similar across sites but varied among years. This study provides important ecological data that can be used when making future decisions affecting the health of the river.

## Introduction

The Laurentian Great Lakes make up the largest freshwater resource in the world. With eight states and one province claiming Great Lakes shoreline and major port cities such as Chicago utilizing the Great Lakes as part of a national and international trade, the Great Lakes are a valuable resource. Biological invasions have caused some of the greatest ecological catastrophes in the Great Lakes. One of the most commonplace and devastating anthropogenic impacts on the world's ecosystems today is the introduction of invasive (nonnative) species (Mills, Leach, Carlton, & Secor, 1994). To date at least 4,500 invasive species have established successful populations and about 15% have resulted in severe negative effects on agriculture, industry, human health, or the natural environment (Mills et al., 1994). Human activities such as the construction of the Erie Canal and St. Lawrence Seaway have played a major role in the introduction of nonindigenous species to the Great Lakes ecosystem. The Great Lakes currently host at least 139 invasive fish, invertebrates, fish disease pathogens, plants, and algae and species introductions continue to pose a threat (Mills et al., 1994).

Each invasive species acts in conjunction with a variety of anthropogenic changes. Anthropogenic changes include fish stocking, point and non-point source pollution, and the introduction of other invasive species (Vanderploeg et al., 2002). The Great Lakes region is plagued by an abundance of invasive species due to the prevalence of ocean-going vessels traveling throughout the region. Rivers often assist in the dispersal of aquatic invasive species by acting as corridors from one body of water to another. A prime example of this is the Lower Fox River, which flows into the largest embayment of the Laurentian Great Lakes-Green Bay, Lake Michigan. The Lower Fox River serves as a corridor from the Great Lakes to Lake Winnebago and across a large portion of the state via the Upper Fox River and Wolf River systems. My

study provides new data on the biological conditions of the Lower Fox River, with regards to both native and invasive fish, zooplankton, and benthic invertebrate populations.

*River Ecosystems and Lotic Ecology*

Rivers provide a variety of highly dynamic and variable environments. Lotic ecology is the study of organism and environment interactions within flowing freshwater systems such as rivers and springs (Hynes, 1970). Water is a fundamental resource for all living things. Rivers provide abundant sources of water which can be utilized in a variety of ways. A single river, for instance, can be used as a navigational mechanism, a source of freshwater, and a source of hydroelectric power. It is important to maintain the health of river systems because when they are unhealthy they are not able to function properly. As the conditions of a river degrade, utility is lost, and animals, such as humans, who depend upon the system, are negatively affected. River management plans are necessary to ensure the health and proper functioning of river systems now and in the future (Townsed, 1980). One way to evaluate the condition of a body of water is to perform a biological assessment. A biological assessment employs direct methods, such as surveys, to analyze the biological residents of a river system. The biological residents of a river indicate overall river condition because one aspect of river health is the ability of the river to allow for the survival and reproduction of desirable organisms. River organisms are unique in that they are located in a dynamic environment which is in a continual stage of change.

Organisms which inhabit lotic systems are adapted for life in a dynamic environment where characteristics such as flow, temperature, and light vary frequently. One way in which river organisms cope with this environmental variation is by varying their distribution within the river. There are a variety of mechanisms that influence the ability of organisms to distribute. Chemical and physical factors of the environment are of fundamental importance in determining

distribution of organisms because the community existing in any given location of a river is composed of species adapted to live under the prevailing abiotic conditions. Each individual species has specific ranges of temperature, pH, dissolved oxygen concentration, and other factors at which it is able to survive. Freedom of movement also affects the dispersal of organisms in a river. Some organisms, for example, have limited mobility and thus are not able to actively avoid or move out of undesirable environments. For instance, if a fish and a zooplankton are both located in an undesirable low-oxygen environment, the fish will be better able to relocate to a more desirable location than the zooplankton because it has more control over its movements. Predator-prey and competitive organism interactions can also influence whether or not a species occurs in a particular location. For example, if a predator species is abundant in a desirable environment the prey species may distribute to a less desirable environment in order to reduce predation pressure. In the end, each organism and community within a river is under a variety of pressures which control their distribution and dispersal mechanisms (Townsend, 1980). Rivers are heterogeneous at multiple scales, with a high degree of environmental variation occurring within and between river systems.

Lotic ecosystems are extremely diverse due to variations in the chemical and physical characteristics. Water flow is one physical characteristic which has implications for every aspect of a river's ecology. River flow is unidirectional and the velocity of flow is influenced by a combination of elevation, width, depth, and number of tributary inputs. Flow is important in river ecosystems because it assists in the distribution of nutrients, pollutants and organisms throughout lotic systems. The traditional way of considering ecosystems-as self-contained complexes-is not applicable to lotic ecosystems because of the water's continual and unidirectional flow. The cycling of nutrients, for example, is continually displaced downstream (Hynes, 1970). Many

other chemical and physical characteristics such as concentration of dissolved and suspended materials and temperature also have effects on aquatic ecosystems by creating diversity of environments where organisms can thrive (Townsend, 1980).

*Niches and Community Structure*

Each habitat is comprised of both conditions and resources. Habitat conditions are a set of abiotic environmental factors, such as flow and temperature, which vary with time and locations. Habitat resources are anything consumed by organisms, for example, food, light, and space. The community structures of aquatic ecosystems are sensitive to the conditions and resources available within the habitat (Loeb, 1994). The organisms that make up a given aquatic community are those that can successfully compete, reproduce, and persist in the given habitat. If a habitat provides all of the resources necessary for a given species, that species has the potential to occur in that location. Each organism has its own ecological niche space, or the "ecological space" it takes up, characterized by how the organism responds to and uses the resources of the surrounding habitat. When aquatic ecosystems are stressed, niche spaces are often disturbed. Because of the relational position of niches as pieces of the larger ecosystem, the disturbance of one niche is widely felt throughout the ecosystem (Loeb, 1994).

Stress on aquatic ecosystems can be divided into three general categories: physical, chemical, and biological. Physical stress includes changes in water flow, substrate type, or light availability. Chemical stress includes changes in toxins, changes in loading rates of bio-stimulatory nutrients, or changes in oxygen consuming materials. Biological stress includes the introduction of invasive species. Changes in any of these characteristics can lead to the distortion of an organism's niche space and potentially lead to extinction of that species (Loeb, 1994).

*Human Impact on Lotic Systems*

Human activity has had a profound impact on rivers around the world (Hynes, 1970). Most rivers have been polluted or deteriorated to a point where certain groups of organisms are unable to reproduce and survive (Vitousek, Mooney, Lubchenco, & Melillo, 1997). The reduction of diversity which results from the die-off of groups of organisms due to deteriorated river conditions is grave because it upsets the overall balance and functioning of the river systems. Pollution in lotic systems is especially difficult to control because of the many potential points of entry (long shoreline) and the unidirectional, continuous flow which enables quick contamination of a large area. When nutrients and pollutants are added to lotic systems, they are moved away from the source as water flows downstream (Hynes, 1970).

Pollution leads to a reduction in water quality which can negatively affect the survival of the organisms which inhabit the river. This is because decreased oxygen concentrations, which are associated with poor water quality, lead to a decline in survivorship of intolerant animal species. The decrease of these organisms may cause a domino-effect throughout the rest of the ecosystem, leading to an unbalanced and unstable river (Houck, 1999). When an ecosystem is unbalanced, there is a potential for the entire system to collapse, ultimately leading to the eradication of all river organisms and loss of function by the river.

Rivers are especially susceptible to human impact due to their utility as waste disposal systems, sources of fresh water and food, and sources of hydroelectric power. The heavy use of river systems by humans has made pollution and reduced water quality prevalent problems in rivers today. River pollutants can come from a variety of point and non-point sources. Point source pollution is directly attributable to one influence, while non-point source pollution is diffuse and not easily identifiable. Common non-point source pollutants include runoff from

agricultural areas, while chemicals released from a paper mill are considered point source pollution. Sources of pollution today are numerous, ranging from industry waste and farming runoff to runoff from residential areas. Pollution and the associated decrease in water quality negatively affect the communities of organisms which reside in the rivers by reducing diversity and causing an unbalanced ecosystem.

One of the most prominent problems in river systems today is the excessive addition of nutrients from outside sources. The addition of excessive amounts of nutrients from sources such as sewage runoff and fertilizers leads to a process termed cultural eutrophication. Under normal circumstances, eutrophication is a natural and slowly occurring process characterized by increased fertility and primary production and decreased levels of dissolved oxygen. However, when it is accelerated by human activity and pollution, eutrophication leads to premature aging and death of the aquatic system. Initially, cultural eutrophication leads to shifts in species composition and decreased biodiversity, with only pollution-tolerant organisms able to survive. However, as conditions worsen and primary production continues to intensify, anoxic conditions are created and even the most pollution-tolerant species die, leaving behind a river teeming with nutrients and devoid of life (Wetzel, 2001).

*Studying Lotic Ecology*

River ecosystems are undergoing dramatic changes in response to human development and population growth. The structure and function of these systems are being affected and their resources are being jeopardized. A healthy river ecosystem is a self-regulating, self-sustaining unit composed of biotic communities and abiotic characteristics. The health of a river ecosystem is degraded when its capacity to "clean" itself and absorb stress has been exceeded. An unhealthy river cannot sustain or regulate itself. It is important that rivers are evaluated so that disturbances

can be predicted and controlled. The community structure of an aquatic ecosystem is sensitive to and determined by the conditions and resources available within a habitat, and thus community structure is an indicator of abiotic environmental factors such as temperature, dissolved oxygen concentration, and flow (Loeb, 1994). Water quality can either be determined by using a biotic index such as the Hilsenhoff biotic index, which assigns tolerance values to river arthropods, or by measuring chemical characteristics such as dissolved oxygen, pH, and biological oxygen demand from water samples (Hilsenhoff, 1982). It is important to monitor the condition of rivers because when they are unhealthy, they are not able to function properly and thus are more susceptible to wide-scale ecosystem collapse. The conservation of rivers is essential because they are integral to the survival of humans and numerous other groups of organisms.

*Biological Monitoring and Management Concerns*

There are five main factors that influence the biological integrity of an aquatic ecosystem: water quality, habitat structure, energy source, flow regime, and biotic interactions. In order to protect the biological integrity of water resources, a broad approach for water pollution control needs to be adopted, not one that focuses only on water quality (Karr, 1994). Biological monitoring is essential to assess the health of aquatic ecosystems because of the concept of niche space. The organisms that inhabit aquatic ecosystems are the fundamental sensors that respond to any stress affecting the system. In other words, the health of aquatic ecosystems is reflected in the health of the aquatic organisms that inhabit them (Loeb, 1994).

It is important to study all the organisms in the food web of a given area because organisms differ greatly in their physiological sensitivity to various chemicals, and in the assortment of chemicals they need for growth. Shifts in the relative number of species belonging to different groups indicate changes before they become severe and the greater the number of

affected organisms observed, the stronger the evidence for an environmental change becomes. (Patrick, 1994).

Biological monitoring can make contributions to increasing the understanding of the ecological effects of contaminants and aquatic ecosystems in general. It can also enhance the ability to make accurate predictions about relationships between contaminants and ecological risk, assess the success of implementing cost-effective changes to improve environmental quality, and communicate the value of improved water quality to the public. In order to be successful, biological monitoring programs must fulfill scientific, economic, and social objectives. (Stewart & Loar, 1994).

The goal of biological monitoring of running water has both monitoring and management aspects. The monitoring component is to assess the present and continuing condition of a given lotic system with regard to measured or implied standards, and to itself over time. The management aspect is to make predictions about future conditions so as to permit implementation of appropriate changes (Cummins, 1994).

*Lower Fox River, Wisconsin*

The Lower Fox River is a large, non-wadable, low-visibility river located in northeastern Wisconsin (Santy, 2001). It extends northeast from Lake Winnebago to Green Bay for a total of 62 kilometers (39 miles) (Santy, 2001). The river has an average daily flow of 122 cubic meters (4320 cubic feet) of water per second, and travels at a steep gradient (Santy, 2001). It is interrupted by a series of 17 locks and 12 dams, and has an overall elevation drop of 50 meters (United States Army Corps of Engineers [USACE], 2010; Santy, 2001). The Lower Fox River serves as a waste treatment system and drainage system and for a large portion of the state

(Wiley, Lueck, Scott, & Wisniewski, 1957). The Lower Fox River Basin is comprised of the following six watersheds: the Fox River, Duck Creek, East River Apple Creek, Plum Creek, Mud Creek, Dutchman Creek, and Ashwaubenon Creek (Santy, 2001). In total, the Lower Fox River empties a drainage basin of 10,217.7 square kilometers (6,349 square miles) and carries water from approximately six percent of the watershed at any given moment towards Green Bay and the Laurentian Great Lakes (Santy, 2001).

The Fox River Valley is the second largest urbanized area in Wisconsin, and most of the basin's urban areas are near the Lower Fox River (Santy, 2001). The habitat of the Lower Fox River watershed is 53 percent agricultural and 35 percent forested (Robertson, 1996). The land which directly surrounds the Lower Fox River is primarily agricultural land comprised mostly of cropland, but also including some orchards, pastures, and meadows (Figure 1; Santy, 2001). The most prominent urban and developed areas of the Fox Valley are located at each end of the river, near Green Bay and Lake Winnebago (Figure 1).

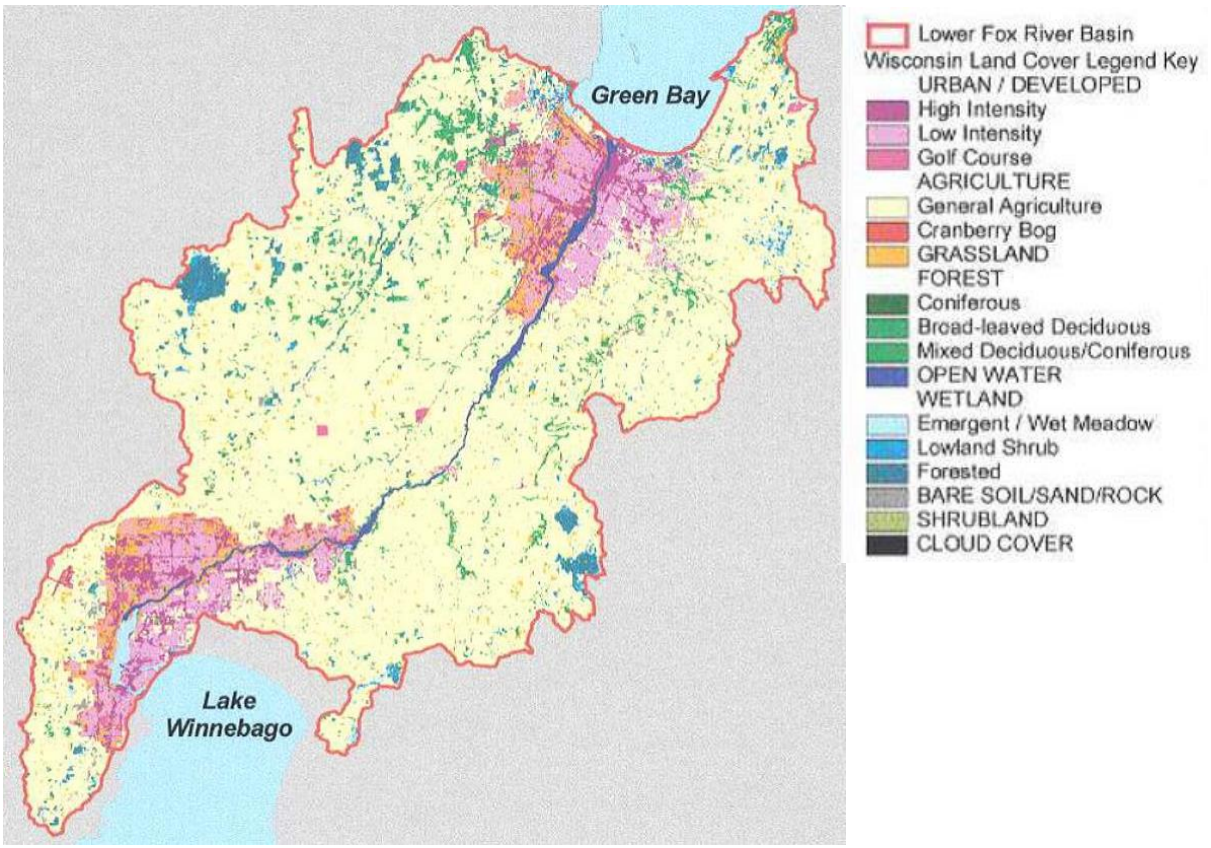



**Figure 1**: Land Cover in the Lower Fox River Basin. Modified from Santy, 2001.

Human activity has had varying and profound effects on the Lower Fox River since early settlement in the 1800s (Wiley et al., 1957). Initially, logging and forestry dominated the Fox River Valley, causing the river to be a major site of sawmills. At that time, sawmills, which released large amounts of sawdust into the river, were responsible for the majority of human waste being released into the river. Farm-related nutrient loading has also been a major source of pollution for the river due to the dominance of agricultural land surrounding the Fox River (Figure 1; Robertson, 1996). The pulp and paper industry, which has historically dominated in the Fox River valley, is also responsible for contributing vast amounts of waste to the river (Balch, Mackenthun, Van Horn, & Wisniewski, 1956; Quirk & Engineers, 1969). Pollution from paper mills most often entered the river in the form of sawdust and lightly treated water (Balch et al., 1956; Quirk & Engineers, 1969). In the end, as industry continues to progress, municipal and

industrial developments continue to introduce pollutants from a variety of point and non-point sources, leading to further deterioration of the river (Conley, 1983).

The Lower Fox River has a long history of anthropogenic pollution and in the 1950s the Fox River was labeled as one of the ten most polluted rivers in the United States (Markert, 1981). Over the years, the Lower Fox River has had to endure conditions of heavy stream employment due to municipal and industrial disposal and water supply, hydroelectric power development, navigation, and recreation (Wiley et al., 1957). Overall, industrial activities and land use have been the primary sources of pollution (Wiley et al., 1957).

The Lower Fox River is classified by the Wisconsin Department of Natural Resources as "impaired," with insufficient water quality for fishery and recreational use (Wisconsin DNR TMDL, 2007; Clayton, 2009). The condition of the river is important today because it is a vital freshwater source and a biologically and economically significant system. Although management efforts have been implemented to address the water quality problems of the Lower Fox River, initial action has resulted in insufficient improvements. Essentially, although the health of the river has improved, there is still vast room for further progress.

The Lower Fox River has also been a historically important navigational crossroads, a way of getting to and from more central areas of the state (Wiley et al., 1957). Navigation of this steep river is made possible by the control of many dams and locks (Wiley et al., 1957). A series of 12 dams and 17 locks were put in place during the 1800s to increase navigability of the river and produce hydroelectric power (Santy, 2001). Increased navigability was thought to be desirable not only because of the river's ideal location as a navigational crossroads, but also because it made the river more accessible to industrial and municipal development (Balch et al., 1956). In addition to impacting transportation and development, the navigation system and

power dams have also greatly affected the physical and biological characteristics of the river (Wiley et al., 1957).

The water flow characteristics of the Lower Fox River are greatly affected by the power dams. The power dams back up the flow of water in the river, leading to changing water levels and water flow which ultimately result in unnatural pooling (Wiley et al., 1957). The locks and dams drastically alter the water level and impede the movement of fish and other organisms in the river (Santy, 2001). Habitat along the river has also been affected, with the river changing from hard, rocky-bottom areas, scoured free of silt and organic debris by fast flowing water, to series of soft, silt-bottomed pools (Wiley et al., 1957). These environmental changes have led to wide-scale ecological shifts which have affected the animal communities within the river (Wiley et al., 1957).

*Aquatic Invasive Species in the Lower Fox River*

Aquatic invasive species are a major concern in the Lower Fox River. There is an extensive history of invasive species entering Green Bay and Lake Michigan via seagoing vessels (Holeck et al., 2004). Because the Fox River flows into Green Bay, it serves as an avenue for the spread of invasive species from Green Bay to the rest of the state. Invasive species have the potential to lead to extensive ecological change through interspecific competition disturbance, and predation (Mills et al., 1994). In order to prevent the spread of sea lamprey and other aquatic invasive species from Green Bay to Lake Winnebago and other aquatic systems, the Rapide Croche Lock was sealed in 1988 and a permanent invasive species barrier was erected (Wisconsin State Statutes, 2008).

A number of aquatic invasive species such as zebra mussels, *Dreissena polymorpha*, round goby, *Neogobius melanostomus*, common carp, *Cyprinus carpio*, rusty crayfish, *Orconectes rusticus*, and the benthic amphipod, *Echinogammarus ischnus*, have already invaded and established themselves in the Lower Fox River, and a number of invasive species which are not yet established pose a high invasion risk (De Stasio, 2013). It is imperative that the spread of invasive species be limited, especially in the Fox River, because the Lower Fox River connects with Lake Winnebago, Green Bay, and many other water bodies throughout the state. The water quality and species composition of the Fox River is of particular importance because any changes to the river have the potential to impact not only Green Bay but the whole Laurentian Great Lakes system-a system which is an essential source of freshwater and a designated area of concern by the International Joint Commission of the United States and Canada (Sager & Wiersma, 1972). In the end, the Lower Fox River is a fairly typical lotic system in that it is regulated by a series of locks and dams, and that it has experienced its fair share of stress from pollution, development, and invasive species.

*The Fox River Navigational System Authority*

The Fox River Navigational System Authority (FRNSA) is a board of directors appointed by the Wisconsin governor, and was created to oversee the management of the Fox Locks after the transfer of the locks system from the Corps of Engineers to the State of Wisconsin in 2004 (Wisconsin State Statutes, 2008). The primary mission of FRNSA is to repair, rehabilitate, operate, and maintain the navigational system in order to stimulate tourism and recreational use, and to uphold and improve the physical, historic, and environmental character of the system (Fox River Navigational System Authority [FRNSA], 2011). Correspondingly, one of the main objectives of FRNSA is to monitor the presence of aquatic invasive species above and below the

Rapid Croche barrier, and to adopt an aquatic invasive species management plan based on their findings (FRNSA, 2011). This is one of FRNSA's main objectives because they plan to construct a boat transfer and cleansing system to enable the transport of watercraft past the Rapide Croche lock by 2017 (FRNSA, 2011). A boat cleansing system is included in the renovation plans in order to diminish the threat of aquatic invasive species; however, extensive information about the populations of aquatic invasive species before and after the transfer system is in place is needed to ensure that the new system is not enabling the spread of aquatic invasive species. Therefore, the FRNSA has worked in conjunction with Lawrence University to collect information on the fish, zooplankton, and benthic invertebrate communities above and below the Rapide Croche Lock (FRNSA, 2006). Plant communities were left out of the project due to the ease with which they are spread.

In accordance with the Invasive Species Monitoring Project, studies have been conducted each summer at a number of sites along the Lower Fox River from 2006 to 2014 (Figure 2). Following an initial sampling of sites immediately upstream and downstream of the Rapide Croche Lock in 2006 and 2007, efforts were expanded to include sites further upstream and downstream (De Stasio, 2013). Since 2008, sampling has occurred at sites spanning from above the Cedar Lock to below the DePere dam, with sites located immediately above and below the Rapide Croche lock and dam (FR3 and FR4) being sampled consistently from 2006 to 2014 (De Stasio, 2013; Figure 2).

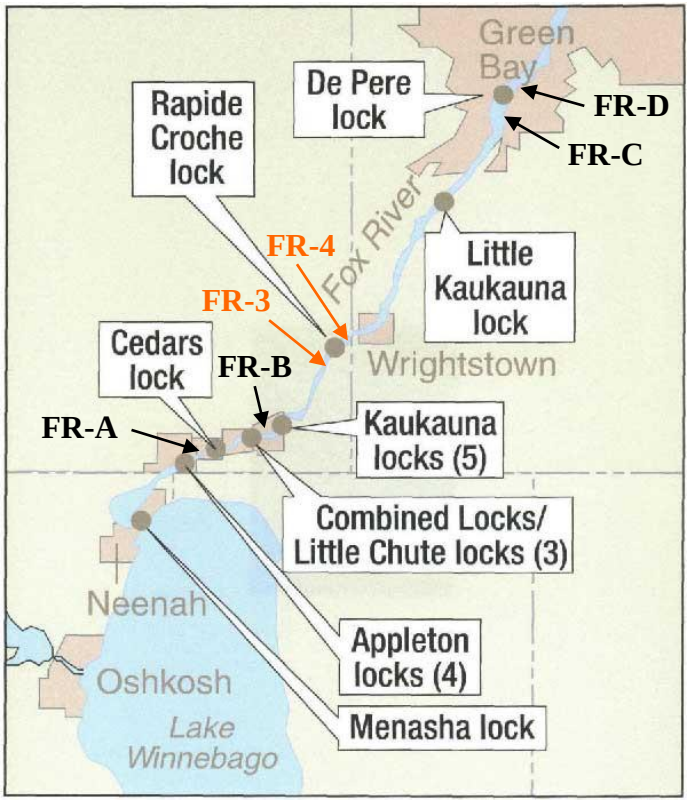



**Figure 2**: Aquatic Invasive Species Monitoring Project Sample Sites. All sites were sampled 2008-2014, sites labeled in orange were sampled in 2006 and 2007 as well. Figure modified from http://foxriverlocks.org/index.php/2012-11-23-09-10-09/advanced-stuff.

According to the FRNSA Aquatic Invasive Species Control and Monitoring Plan, the specific goal is to, "monitor the presence and map the distribution of fish and invertebrate aquatic invasive species in the Fox River two pools immediately up and downstream of Rapide Croche Lock" (FRNSA, 2006). The information gathered through the project's surveys provides consistent long-term data regarding the presence and absence of native and invasive species both upstream and downstream of the Rapide Croche Lock. This data set is a solid baseline of information against which future changes in fish, benthic invertebrate, and zooplankton communities can be compared. The ultimate objective of this project is to, through consistent and frequent sampling, provide early warning of any aquatic invasive species that become

established in the Lower Fox River. Control of invasive species is more effective when there is early warning of their presence because it is much easier to eradicate an unestablished species than an established one. Furthermore, effective invasive species control fosters ecological balance and an overall better functioning river system.

*Biological Assessment of the Lower Fox River, WI*

The Lower Fox River is a variable and dynamic ecosystem (Santy, 2001). The river has undergone many changes since the initial settlement of the Fox River Valley, and although water quality has improved since the passage of the Clean Water Act in 1972, the river is still an area of concern (WNDR, 1999). In recent years it has been found that there is a lower diversity of species downstream due to lower water quality and high sedimentation in the lower river (Santy, 2001). In order to truly assess the Lower Fox River ecosystem, the vast habitat variability of the river must be taken into account.

In the current study, a general ecological survey was conducted with the intent to increase our knowledge base regarding the condition and characteristics of the Lower Fox River. With the goal of building upon the basic information from the FRNSA Aquatic Invasive Species Monitoring Project reports, this analysis will bring a new approach to analyzing the Lower Fox River ecosystem by assessing the distribution of animals in the river over time and across locations. This study focuses on using fish, benthic invertebrate, and zooplankton community data to highlight the major ecological trends of a vital Wisconsin river from 2006-2014.

## Methods

Data were collected on three biological communities: zooplankton, benthic invertebrates, and fish. Sampling was conducted June through August through the years of 2006 to 2014. Studies were conducted at six sites along the Lower Fox River, Wisconsin, to encompass locations both above and below the existing invasive species barrier at the Rapide Croche Dam in Wrightstown, WI (Table 1). Separate boats were employed upstream and downstream of the Rapide Croche Dam site on each sampling date, and all nets and equipment were sanitized thoroughly using bleach prior to the next sampling event, according to the protocols established by the WI DNR to prevent the spread of aquatic invasive species (De Stasio, 2013; http://dnr.wi.gov/fish/documents/disinfection_protocols.pdf). At each site, sampling was conducted at locations in the center of the river channel as well as along the shorelines.

**Table 1**: Location of sample sites along the Lower Fox River, WI. All sites were sampled during the summers of 2008-2014. The only sites sampled during the summers of 2006-2007 include FR-3 and FR-4. Modified from De Stasio, 2013.

| Location | Latitude | Longitude |
|---|---|---|
| *Upstream of Rapide Croche* | | |
| FR-A (above Cedar Lock) | N 44$^{o}$ 16.562 | W 88$^{o}$ 20.541 |
| FR-B (above Kaukauna Guard Lock) | N 44$^{o}$ 16.665 | W 88$^{o}$ 17.042 |
| FR-3 (above Rapid Croche Lock) | N 44$^{o}$ 19.077 | W 88$^{o}$ 11.962 |
| *Downstream of Rapide Croche* | | |
| FR-4 (below Rapid Croche Lock) | N 44$^{o}$ 18.947 | W 88$^{o}$ 11.413 |
| FR-6 (Wrightstown Boat Launch) | N 44$^{o}$ 19.238 | W 88$^{o}$ 10.531 |
| FR-C (above DePere Dam) | N 44$^{o}$ 25.813 | W 88$^{o}$ 04.273 |
| FR-D (below DePere Dam) | N 44$^{o}$ 27.742 | W 88$^{o}$ 03.354 |

The Lower Fox River system is surrounded by numerous types of terrestrial habitats ranging from forest to urban and agricultural terrain. Each sample site is affected by its terrestrial surroundings as well as differences in depth, width, and stream flow. In addition, the prevalence of dams along the Lower Fox River makes it unreasonable to consider the river as a single continuous habitat. Each site sampled exhibits unique physical and biological characteristics.

***Site Descriptions***

FR-A is stationed upstream of the Rapide Croche Lock, above the Cedar Lock in Kimberly, Wisconsin (Figure 3). FR-A is a scoured bottom, rapid flow habitat. However, flow is somewhat slowed by bends in the river located both upstream and downstream of the site. This site was sampled 2008-2014.

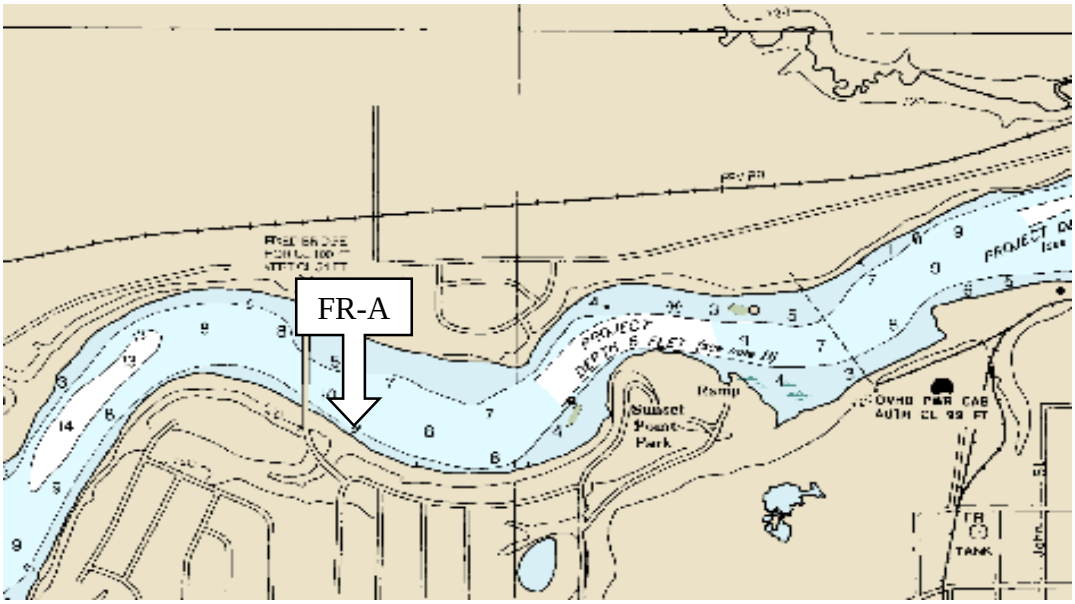



**Figure 3**: The Lower Fox River, WI, sample site FR-A. Modified from United States Department of Commerce, 2002.

FR-B is located upstream of the Rapide Croche Lock, in Kaukauna, between the Combined Locks and the Kaukauna Locks (Figure 4). FR-B is a pool habitat due to its location above the Kaukauna Locks and the slow water flow characteristics of the site. This site was sampled 2008-2014.

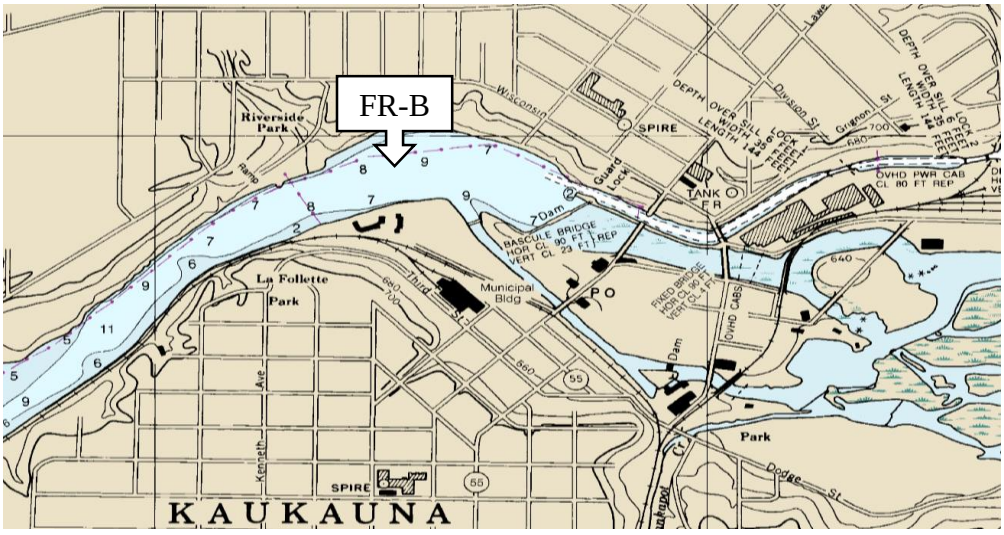



**Figure 4**: The Lower Fox River, WI, sample site FR-B. Modified from United States Department of Commerce, 2002.

Site FR-3 is positioned just upstream of the Rapide Croche Lock near Wrightstown, Wisconsin (Figure 5). This site is characterized as a pool habitat due to slow water flow and location directly upstream of a lock. This site was sampled 2006-2014.

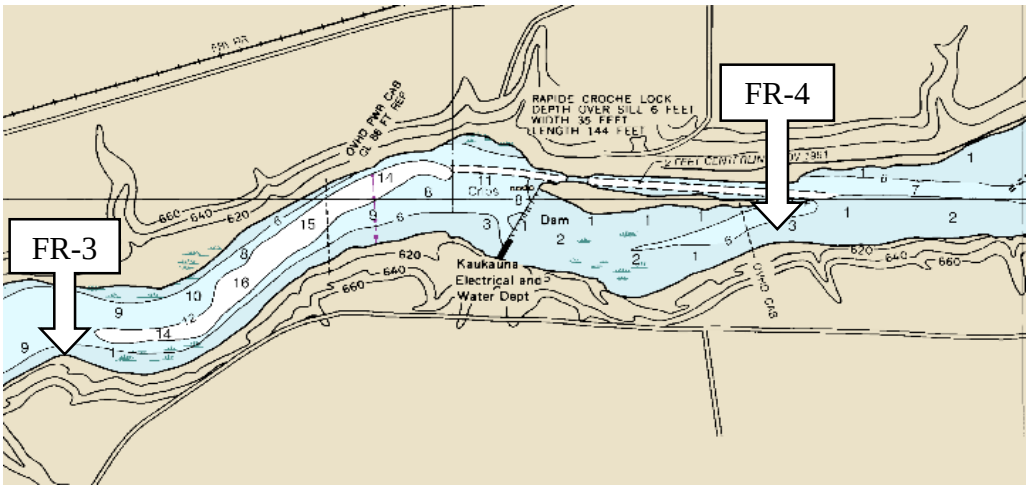



**Figure 5**: The Lower Fox River, WI, sample sites FR-3 and FR-4. Modified from United States Department of Commerce, 2002.

FR-4 is located just below the Rapide Croche Lock, near Wrightstown, Wisconsin (Figure 5). FR-4 is a high flow, scoured bottom site. This site was sampled 2006-2014.

FR-C is stationed downstream of the Rapide Croche Lock, between the Little Rapids Lock and the DePere Lock (Figure 6). This site is characterized as a riverine habitat with fast flowing water and a scoured bottom. This site was sampled 2008-2014.

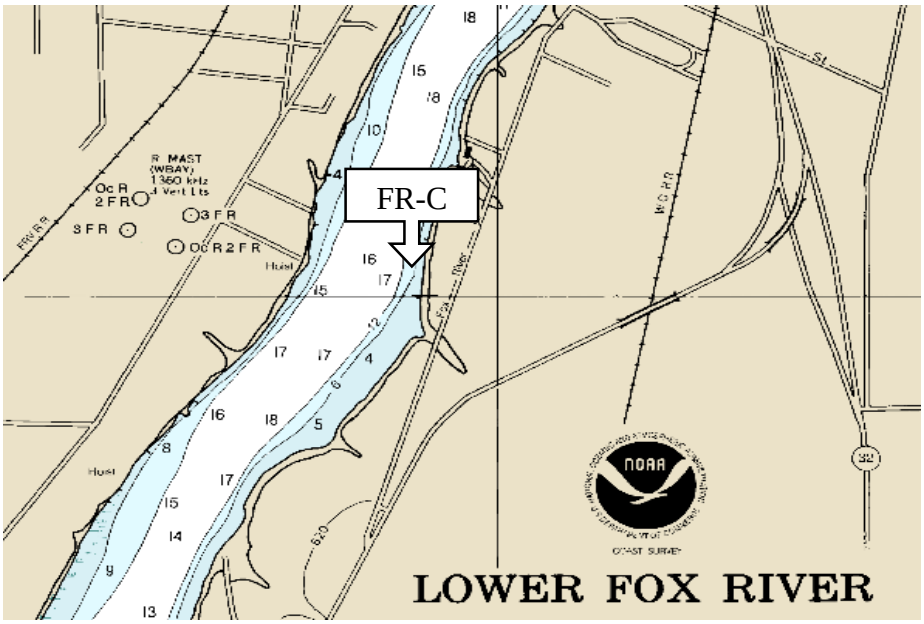



**Figure 6**: The Lower Fox River, WI, sample site FR-C. Modified from United States Department of Commerce, 2002.

FR-D is downstream of the Rapide Croche Lock, located below the DePere Lock in DePere, Wisconsin (Figure 7). FR-D is a slow-flowing pool habitat with a muck and sand bottom, and areas of sand shoreline-a characteristic that is not common among other sites. This site was sampled 2008-2014.

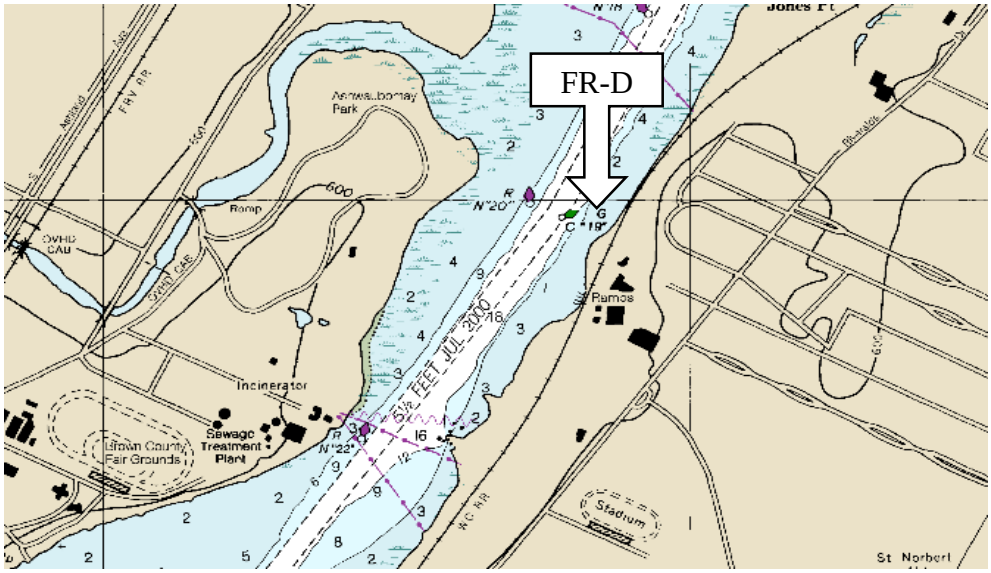



**Figure 7**: The Lower Fox River, WI, sample site FR-D. Modified from United States Department of Commerce, 2002.

***Data sampling***

*Zooplankton*—Oblique plankton tows were performed mid-channel at each sample site. A Wisconsin-type plankton net with retaining collar (mouth diameter=0.13m, mesh size=63 um) was used. Samples were transported to the laboratory where they were strained and preserved in 80% ethyl alcohol. Each sample was examined using 10X to 400X magnification, and all zooplankton in the samples were identified to the species level, when possible. Entire samples were examined to determine presence of each species; however, abundance was not recorded (De Stasio, 2013).

*Benthic invertebrates*—An Ekman grab sampler (0.15m X 0.15m box size) was used to collect replicate samples at each site from mid-channel areas. Once collected, grab samples were filtered through a mesh-bottom wash bucket (mesh size=500um). Dip netting techniques were used to sample the shoreline areas of each site. Dip net samples were washed into trays, and invertebrates were transferred to whirl-packs and transported back to the laboratory where they

were preserved with 80% ethyl alcohol. Once preserved, all specimens were identified to the species level, whenever possible. Entire samples were examined to determine presence of each species. The number of specimens of each species collected was not recorded consistently throughout all sample years (De Stasio, 2013).

During the 2006-2008 sampling years, periphyton, invertebrates that attach to solid substrates from a planktonic phase, were sampled using 16-glass-slide floating samplers. Samplers were anchored at each of the sites for two-week sampling periods. At the end of the two-week period, the slides were removed and preserved in 80% ethyl alcohol. Specimens on the slides were then identified to the species level, whenever possible. Entire samples were examined to determine presence of each species. The number of specimens of each species collected was not routinely recorded throughout all sample years (De Stasio, 2013).

*Fish*—A combination of trapping, seining, and electrofishing techniques were utilized to sample the fish populations at each site. Fish trapping comprised of employing three sizes of cod-end type traps; standard "minnow" traps (length=0.42m, opening=22mm, mesh=6.4mm), elongated eel traps (length=0.78m, opening=40mm, mesh=6.4mm), and larger hand-made traps of the same design (length=2m, opening=125mm, mesh= 12.5mm). All three sizes of traps were deployed at each site for a maximum of 24 hours, emptied, and redeployed during at least two different periods of the summer. Traps were set with and without bait during different years and on different dates to optimize the potential catch. In addition, at least five beach seine hauls (1/4 inch mesh, 20 ft length) were performed at each shoreline location on each sampling day. In 2010 and 2012, shoreline habitats were also sampled in a limited manner with electroshocking (Smith-Root Model LR-20 Backpack Electrofisher). Specimens from all sampling efforts were identified in the field to the species level, and then released whenever possible. Specimens of

new species and specimens difficult to identify in the field were transported live for identification in the laboratory. Upon return to the laboratory, specimens were identified and then frozen or transferred to ethyl alcohol (70%) for long-term preservation. All specimens were identified to the species level when possible, and the number of each species collected was recorded (De Stasio, 2013).

***Data analysis***

A catch-per-unit effort (CPUE) measure of fish abundance was determined by dividing the number of fish of each species taken from each site during each year by the number of sampling trips at that site during that year where beach seining took place. The same approximate number of seines took place at each site during each visit each year.

Matrices composed of presence–absence species data per sampling site and sampling year were created for zooplankton and benthic invertebrates. A matrix composed of the CPUE abundance data per sampling site and sampling year was also created for fish.

Principal component analysis (PCA) and cluster analysis procedures were used to explore trends in the matrices across years and sites. Principal component biplots were used to indicate benthic invertebrates and zooplankton species which were characteristic of sample years and to indicate fish species which were characteristic of sample sites. Spearman's Rank correlation was performed on the fish and invertebrate species that were found, through principal component analysis, to have influential loading values. The full Spearman's Rank correlation table can be found in the appendix (Table B 1). The aquatic invasive species which had correlations with other influential species and p-values below 0.05 were selected for further analysis and exploration in the form of jitter-plots, XY-plots, and chi-square tests. PCA, cluster analysis,

Spearman's Rank correlation, Chi-square tests, and jitter-plots were completed with the PAleontological STatistics (PAST) program (Hammer, Harper & Ryan, 2001). XY-plots were computed using Excel spreadsheet procedures (Microsoft Office 2013).

## Results

*Zooplankton Trends*

There were obvious changes in zooplankton-community composition and biodiversity over time. Cluster analysis of zooplankton community presence-absence data from the sites suggests that zooplankton communities vary by time rather than location (Figure 8).

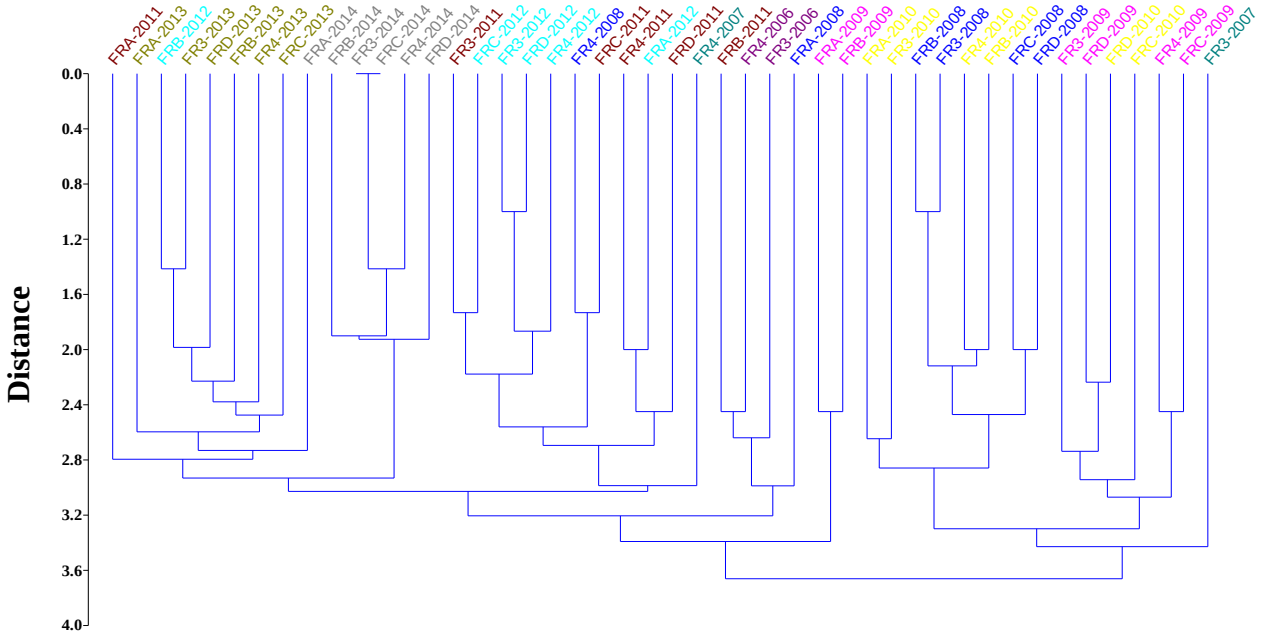



**Figure 8**: Dendrogram derived from paired group cluster analysis using Euclidean Distance measure of presence-absence zooplankton data from the six sample sites located on the Lower Fox River. Samples were collected from 2006 to 2014. Colors indicate sampling year as follows: 2006-purple, 2007-teal, 2008-blue, 2009-pink, 2010-yellow, 2011-red, 2012-bright blue, 2013-olive, and 2014-grey.

Principal component analysis of the same data also highlights changes in zooplankton community composition over time. In the principal component scatterplot, sample years are often grouped together. The 2013 sites are all positive for components 1 and 2, the 2010 sites are all negative for component 1 and positive for component 2, the 2008 sites are all negative for components 1 and 2, and the 2014 sites are all positive for component 1 and negative for

component 2 (Figure 9). The 2011 sites are all negative for component 2, the 2007 sites are all negative for component 1, and the 2006 sites are all positive for component 1 (Figure 9). Finally, the 2009 sites are primarily negative for component 1, while the 2012 sites are found in all quadrants of the scatterplot (Figure 9).

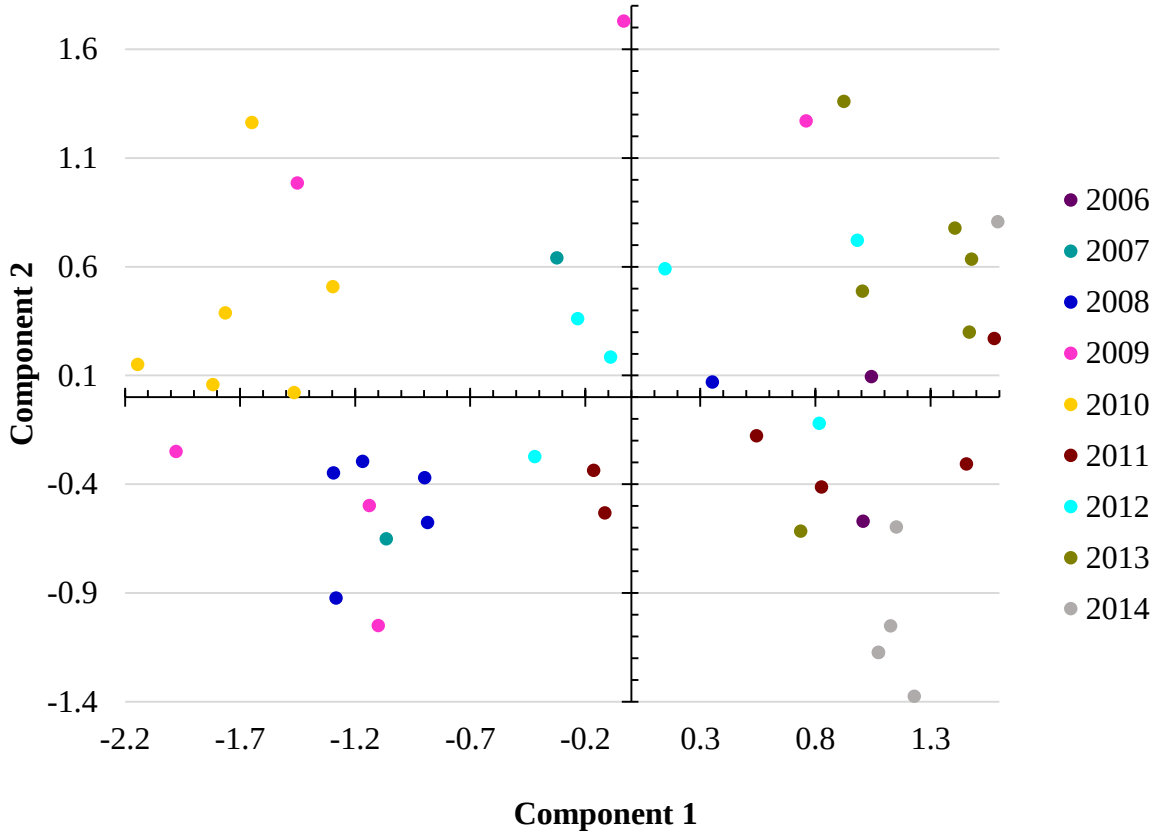



**Figure 9**: Scatterplot derived from principal component analysis of the presence-absence matrix of zooplankton species at six sites on the Lower Fox River from 2006 to2014.

The first two principal components accounted for 34.04% of community variation, and ordination results indicate noticeable separations based on year. The first component contrasts years with crustacean copepods verses rotifers. This axis is positively and strongly influenced by the crustacean copepods *Mesocylops edax*, *Acanthocyclops vernalis*, *Diacyclops thomasi*, and *Skistodiaptomus oregonensis*. It is negatively influenced by the rotifers *Keratella sp.*,

*Ascomorpha sp.*, and *Brachionus sp.* (Table 2). The full table of loading values is located in the Appendix (A3). The second component is positively and strongly influenced by the water fleas *Daphnia pulicaria* and *Cerodaphnia dubia*, and the crustacean copepod *Leptodiaptomus siciloides*. Negatively, it is influenced by the water flea *Anchistropus minor* and the crustacean copepod *Epischura lacustis* (Table 2).

**Table 2**: Principal component analysis loading values for the most influential zooplankton species for the six sites sampled along the Lower Fox River 2006-2014.

| **Component 1** | |
|---|---|
| **Species** | **Loading Value** |
| *Mesocyclops edax* | 0.8107 |
| *Acanthocyclops vernalis* | 0.756 |
| *Diacyclops thomasi* | 0.6267 |
| *Skistodiaptomus oregonensis* | 0.6239 |
| *Keratella sp.* | -0.7538 |
| *Ascomorpha sp.* | -0.6286 |
| *Brachions sp* | -0.6286 |
| **Component 2** | |
| **Species** | **Loading Value** |
| *Daphnia pulicaria* | 0.6835 |
| *Leptodiaptomus siciloides* | 0.5952 |
| *Cerodaphnia dubia* | 0.5609 |
| *Epischura lacustis* | -0.462 |
| *Anchistropus minor* | -0.4085 |

*Benthic Invertebrate Trends*

Cluster analysis illustrates that there were changes in benthic invertebrate community composition and biodiversity over time. Analysis of benthic invertebrate community presence-

absence data indicates that benthic invertebrate community composition also varied more strongly over time rather than across locations (Figure 10).

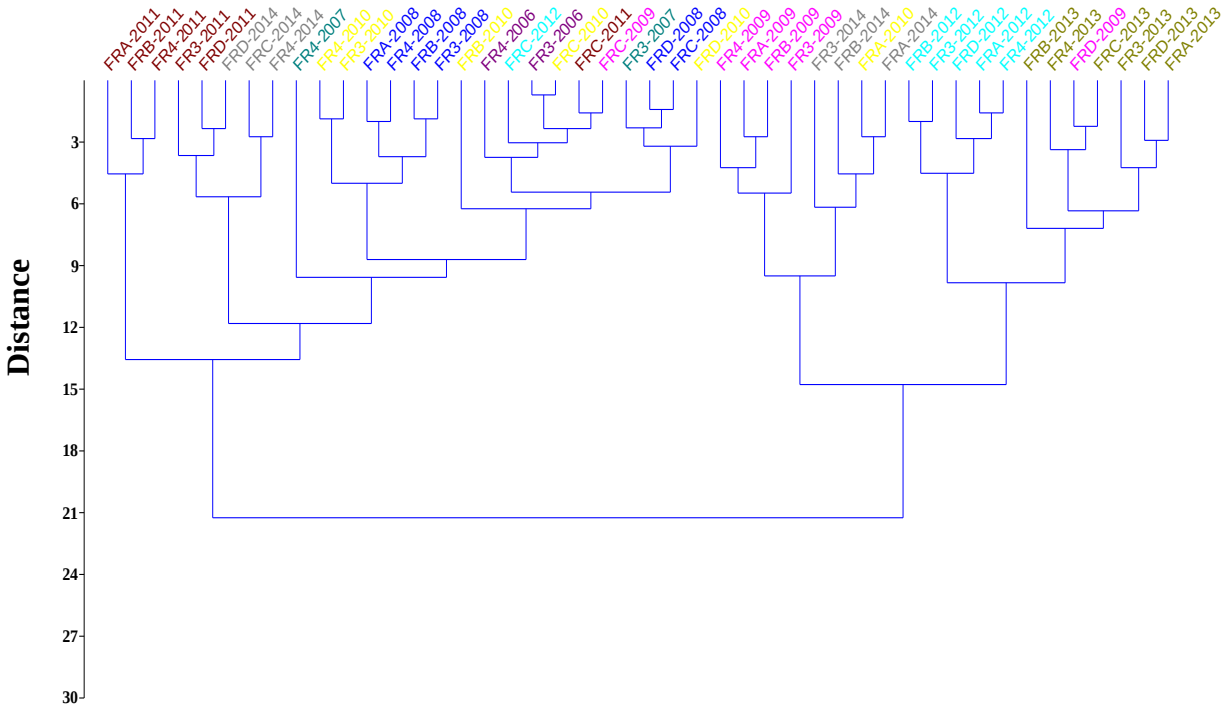



**Figure 10**: Dendrogram derived from Ward's method cluster analysis of percent similarity values measured by Euclidean Distance for the presence-absence matrix of benthic invertebrates at six sites on the Lower Fox River 2006-2014. Colors indicate sampling year as follows: 2006-purple, 2007-teal, 2008-blue, 2009-pink, 2010-yellow, 2011-red, 2012-bright blue, 2013-olive, and 2014-grey.

Principal component analysis of the same data also indicates that changes in benthic invertebrate community composition are related to years rather than sample sites. In the principal component scatterplot, sample years are frequently found grouped together. Points associated with the 2013 sample year are positive for component 1 and negative for component 2 while the points for the 2006 sample year are negative for components 1 and 2 (Figure 11). The years of 2007, 2008, and 2011 are negative for component 1 (Figure 11). The points for the 2012 and 2009 sample years are either positive for components 1 and 2, negative for components 1 and 2,

or positive for component 1 and negative for component two (Figure 11). The 2010 and 2014 points are either positive for components 1 and 2, negative for component 1 and positive for component 2, or negative for both components 1 and 2 (Figure 11).

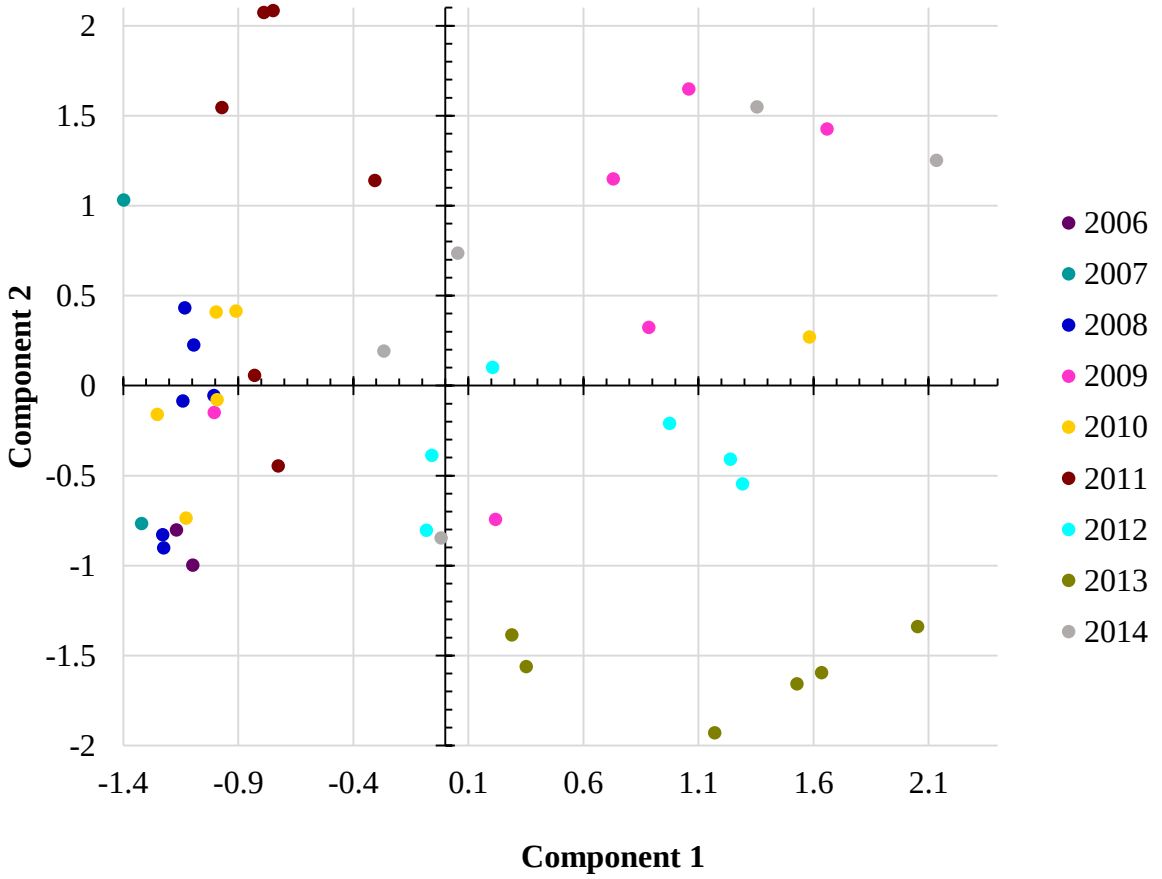



**Figure 11**: Scatterplot derived from principal component analysis of the presence-absence matrix of benthic invertebrate species at six sites on the Lower Fox River from 2006 to2014.

The first two principal components accounted for 23.99% of community variation, and ordination results indicate noticeable separations based on year. The first component is positively and strongly influenced by the water boatman taxa *Trichocorixica sp.* and *Palmacorixa sp.*, as well as the snail *Physella sp*. It is negatively influenced by the mayfly *Ephemerella sp.*, amphipod *Echinogammarus ischnus*, and worm *Tubifex sp.* (Table 3). The full loading table is located in the appendix (Table A2). The second component is positively and strongly influenced

by the sideswimmer scuds *Monoporeia sp.*, *Gammarus sp.*, and *Hyalella azteca*, as well as the aquatic snowbug *Caecidotea sp.*, and negatively by the midge fly *Ablabesmyia sp.*, leech *Helobdella stagnalis*, and water mite *Limnesia sp.* (Table 3). The full loading table is located in the appendix (Table A2).

**Table 3**: Principal component analysis loading values for the most influential benthic invertebrate species for the six sights sampled along the Lower Fox River 2006-2014.

| **Component 1** | |
|---|---|
| **Species** | **Loading Value** |
| *Trichocorixica sp.* | 0.874 |
| *Palmacorixa sp.* | 0.8433 |
| *Physella sp.* | 0.8035 |
| *Ephemerella sp.* | -.3232 |
| *Echinogammarus ischnus* | -0.2789 |
| *Tubifex sp.* | -0.2548 |
| **Component 2** | |
| **Species** | **Loading Value** |
| *Monoporeia sp.* | 0.6686 |
| *Gammarus sp.* | 0.6147 |
| *Caecidotea sp.* | 0.5876 |
| *Hyalella azteca* | 0.5638 |
| *Ablabesmyia sp.* | -0.4779 |
| *Helobdella stagnalis* | -0.4608 |
| *Limnesia sp.* | -0.4426 |

*Fish Trends*

The fish abundance matrix indicated that there are differences in fish community composition and biodiversity across sample sites. Analysis of fish community abundance data from the sample sites resulted in identification of sites as distinct from one another (Figure 12).

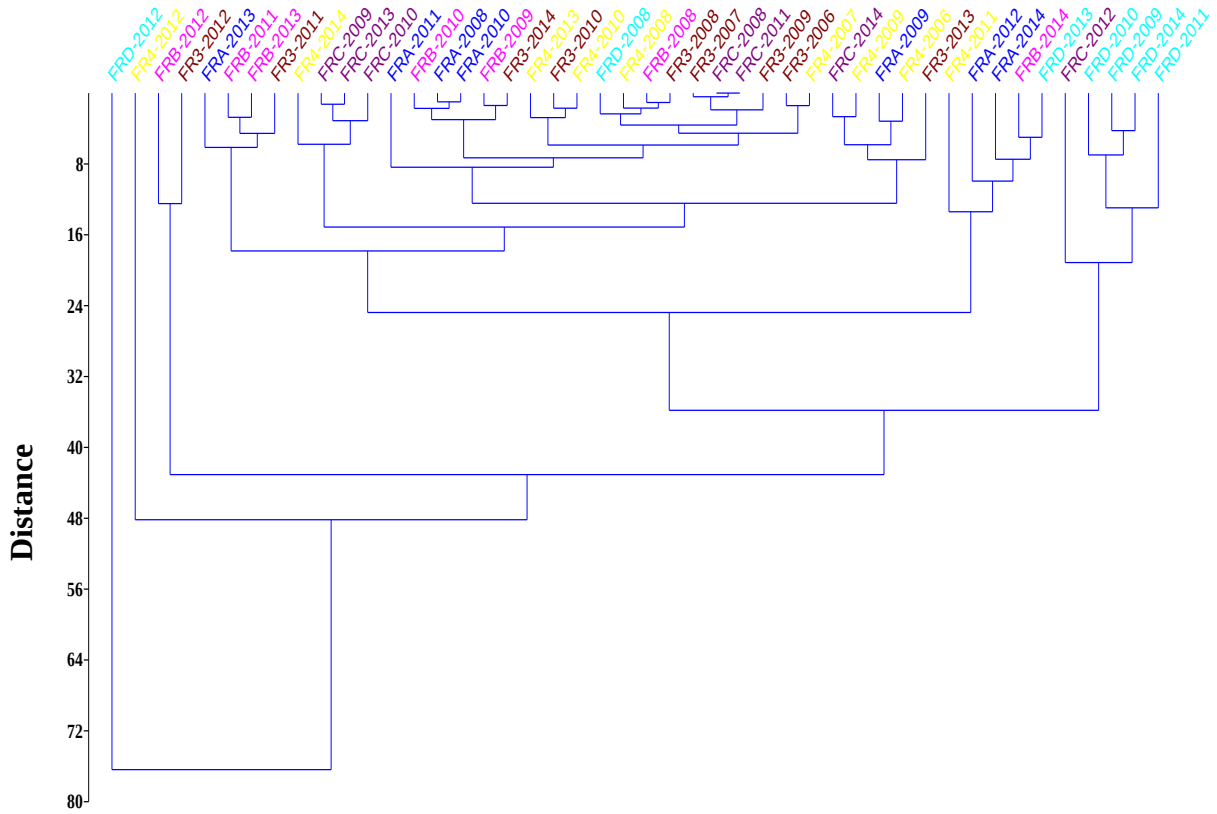
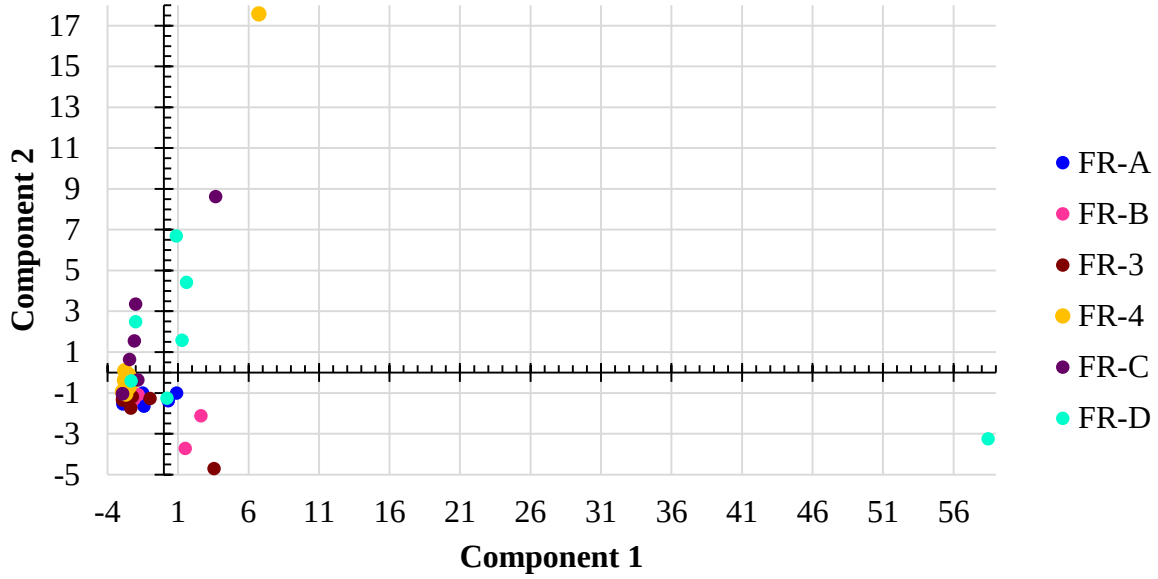



**Figure 12**: Dendrogram derived from cluster analysis of percent similarity Euclidean Distance values for the abundance matrix of fish species at six sites on the Lower Fox River 2006-2014. Wards method was used. Colors indicate sampling sites as follows: FR-A-blue, FR-B-pink, FR-3-red, FR-4-yellow, FR-C-purple, and FR-D-bright blue.

Principal component analysis of the fish abundance data also highlights clear differences in fish community composition across sites (Figure 13). In particular, it seems that the downstream sites (FR-4, FR-C, and FR-D) have positive, or low negative scores for component 2 while upstream sites (FR-A, FR-B, and FR-3) exhibit negative scores along component 2 (Figure 13).

**a**)




**b)**

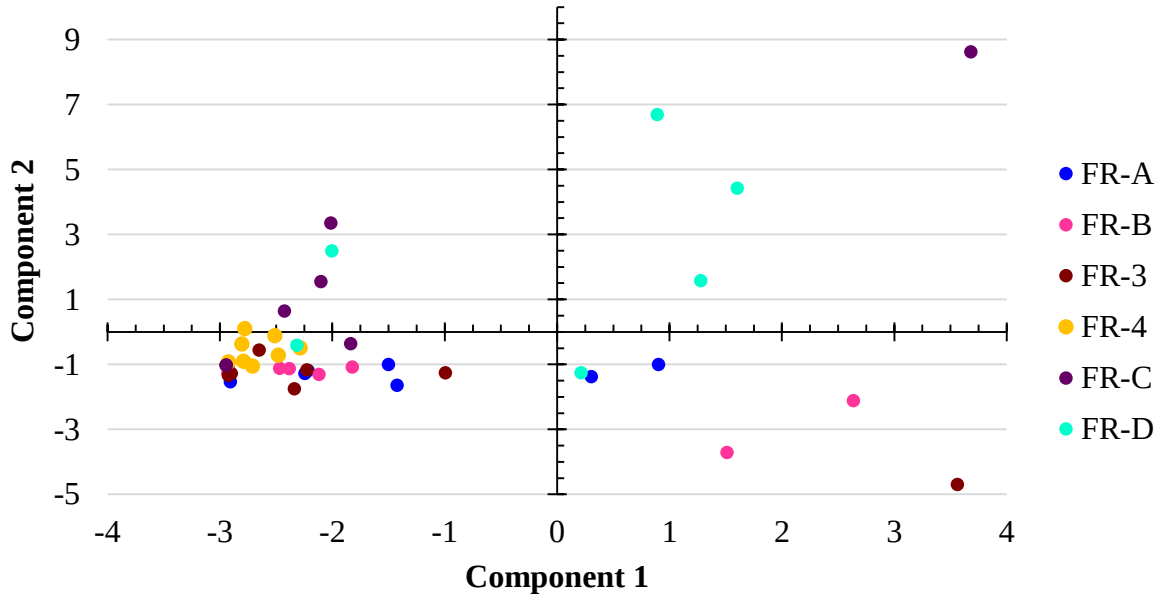



**Figure 13**: a) Scatterplot derived from principal component analysis of the abundance matrix of fish species at six sites on the Lower Fox River from 2006 to 2014. b) Scatterplot derived from principal component analysis of the abundance matrix of fish species at six sites on the Lower Fox River from 2006 to 2014 with the following outliers removed = FR-4, 2012: (19.07, -4.0005) and FR-C, 2012 (11.104, 1.4862).

The first two principal components accounted for 73.18% of community variation, and ordination results indicate noticeable separations based on sample site. The first component is positively and strongly influenced by quillback, *Carpiodes cyprinus*, gizzard shad, *Dorosoma cepedianum*, darter, *Etheostoma sp.*, and yellow perch, *Perca flavescens* (Table 4). The first component is powerfully and negatively influenced by pumpkinseed, *Lepomis gibbosus*, spottail shiner, *Notropis hudsonius*, and trout-perch *Percopsis omiscomaycus* (Table 4). The full loading table for component one is located in the appendix (Table A1). The second component is positively and strongly influenced by round goby, *Neogobius melanostomus*, emerald shiner, *Notropis antherinoides*, fathead minnow, *Pimephales promelas*, and bullhead minnow, *Pimephales vigilax* (Table 4). It is negatively affected by bluegill, *Lepomis macrochirus*, common carp, *Cyprinus carpio*, green sunfish, *Lepomis cyanellus*, largemouth bass, *Micropterus salmoides*, and johnny darter, *Etheostoma nigrum* (Table 4). The full loading plot for component two is located in the appendix (Table A1).

**Table 4:** Principal component analysis loading values for the most influential fish species for the six sights sampled along the Lower Fox River 2006-2014.

| Component 1 | | Component 2 | |
|---|---|---|---|
| **Species** | **Loading Value** | **Species** | **Loading Value** |
| *Dorosoma cepedianum* | 0.9899 | *Notropis antherinoides* | 0.7956 |
| *Etheostoma sp.* | 0.9617 | *Neogobius melanostomus* | 0.7771 |
| *Perca flavescens* | 0.9421 | *Pimephales vigilax* | 0.7509 |
| *Carpiodes cyprinus* | 0.9044 | *Pimephales promelas* | 0.7045 |
| *Lepomis gibbosus* | -0.1038 | *Lepomis macrochirus* | -0.2509 |
| *Notropis hudsonius* | -0.09826 | *Cyprinus carpio* | -0.2474 |
| *Percopsis omiscomaycus* | -0.08459 | *Lepomis cyanellus* | -0.2041 |
| | | *Etheostoma nigrum* | -0.2026 |
| | | *Micropterus salmoides* | -0.1993 |

*Characterization of sample years and sites*

**Table 5**: Characterization of sample years based on zooplankton and benthic invertebrate species. Characterizing species were taken from the principal component biplots.

| Sample Year | Characteristic Zooplankton | Characteristic Benthic Invertebrates |
|---|---|---|
| **2006** | *Mesocyclops edax* (crustacean cyclopoid copepod)<br>Eubosmina coregoni (water flea) | *Dromogomphus sp.* (dragonfly larvae)<br>*Buenoa sp.* (water boatman) |
| **2007** | *Asplanchna sp.* (rotifer) | *Crangonyx sp.* (amphipod)<br>*Echinogammarus ischnus* (invasive amphipod)<br>*Ephemerella sp*. (mayfly) |
| **2008** | *Brachionus sp*. (rotifer) | *Crangonyx sp*. (amphipod)<br>*Echinogammarus ischnus* (invasive amphipod)<br>*Ephemerella sp*. (mayfly) |
| **2009** | *Asplanchna sp*. (rotifer) | *Trichocorixa sp*. (water boatman)<br>*Palmacorixa sp*. (water boatman)<br>*Physella sp*. (left-handed snail)<br>*Pleurocera sp*. (freshwater snail)<br>*Chironomus sp*. (bloodworm) |
| **2010** | *Euchlanis sp*. (rotifer)<br>*Keratella sp.* (rotifer)<br>*Chydorus sp*. (water flea) | *Crangonyx sp*. (amphipod)<br>*Echinogammarus ischnus* (invasive amphipod)<br>*Ephemerella sp*. (mayfly) |
| **2011** | *Brachionus sp*. (rotifer)<br>*Epischura lacustis* (calanoid copepod)<br>*Anchistropus minor* (water flea) | *Crangonyx sp*. (amphipod)<br>*Echinogammarus ischnus* (invasive amphipod)<br>*Ephemerella sp*. (mayfly) |
| **2012** | *Euchlanis sp*. (rotifer)<br>*Keratella sp*. (rotifer)<br>*Chydorus sp*. (water flea)<br>*Daphnia pulicaria* (water flea)<br>*Leptodiaptomus siciloides* (calanoid copepod)<br>*Acanthocyclops vernalis* (cyclopoid copepod) | *Helobdella stagnalis* (leech)<br>*Ablabesmyia sp.* (midge larvae)<br>*Limnesia sp.* (water mite)<br>*Orconectes rusticus* (rusty crayfish)<br>*Palmacorixa sp*. (water boatman)<br>*Physella sp.* (left-handed pond snail) |
| **2013** | *Daphnia pulicaria* (water flea)<br>*Leptodiaptomus siciloides* (calanoid copepod)<br>*Acanthocyclops vernalis* (cyclopoid copepod) | *Orconectes rusticus* (rusty crayfish)<br>*Ablabesmyia sp.* (midge larvae)<br>*Limnesia sp*. (water mite) |
| **2014** | *Epischura lacustis* (calanoid copepod)<br>*Anchistropus minor* (cladoceran) | *Monoporeia sp*. (amphipod)<br>*Gammarus sp*.(amphipod)<br>*Pleurocera sp.* (right handed snail) |

The 2006 sample year is distinct from other sample years in that it is characterized by benthic invertebrate and zooplankton species that are not distinguishing of any other sample years. The sample years of 2007 and 2008 are typified by similar zooplankton and benthic invertebrate taxa (rotifer, amphipod, and mayfly). The 2009 sample year is characterized by similar zooplankton taxa to the 2007 and 2008 sample years (rotifer) but it is characterized by invertebrate taxa that are similar to the 2012 sample year (water boatman, snail, and midge larvae). The same benthic invertebrates and similar zooplankton taxa distinguish the 2010 and 2011 sample years (water flea, rotifer, amphipod, and mayfly). All of the species that characterize the 2013 sample year also characterize the 2012 sample year (water flea, calanoid and cyclopoid copepods). The 2014 sample year is typified by two amphipod taxa which are not characteristic of any other sample year and a right handed snail, *Pleurocera sp*., which is also characteristic of the 2009 sample year (Table 5).

**Table 6**: Characterization of sample sites based on fish species. Characterizing species were taken from the principal component biplot.

| Sample Site | Characteristic Fish |
|---|---|
| **Upstream** | |
| **FR-A** | *Dorosoma cepedianum* (gizzard shad)<br>*Cyprinus carpio* (common carp) |
| **FR-B** | *Dorosoma cepedianum* (gizzard shad)<br>*Cyprinus carpio* (common carp) |
| **FR-3** | *Dorosoma cepedianum* (gizzard shad)<br>*Cyprinus carpio* (common carp) |
| **Downstream** | |
| **FR-4** | *Luxilus cornutus* (common shiner)<br>*Etheostoma nigrum* (johnny darter) |
| **FR-C** | *Luxilus cornutus* (common shiner)<br>*Etheostoma nigrum* (johnny darter) |
| **FR-D** | *Notropis antherinoides* (emerald shiner)<br>*Neogobius melanostomus* (round goby) |

All of the upstream sites (FR-A, FR-B, and FR-3) are typified by the same two fish species, *Dorosoma cepedianum* and *Cyprinus carpio*. Two of the downstream sites (FR-4 and FR-C) are characterized by the same species, *Luxilus cornutus* and *Etheostoma nigrum*, while the other upstream site (FR-D) is characterized by the following species which do not characterize any other sites: *Neogobius melanostomus*, and *Notropis antherinoides* (Table 6).

*Interactions among Species of Interest*

Spearman's Rank correlation indicated a positive correlation between the invasive rusty crayfish *Orconectes rusticus* and the water boatman *Palmacorixa sp.* (p= 0.049, $\rho = 0.292$). *Orconectes rusticus* and *Palmacorixa sp.* were both absent from sites more than expected by chance, but were both present at sites approximately as often as is expected by chance (Figure 14; $\chi^2 = 5.826$ and p = 0.120).

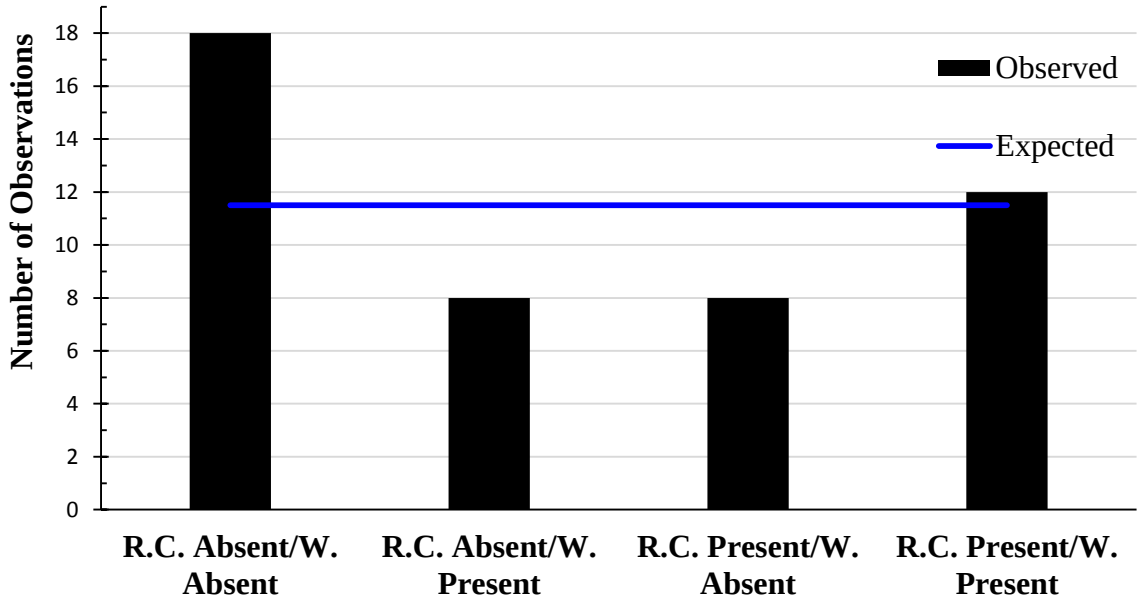



**Figure 14**: Relationship of *Orconectes rusticus* and *Palmacorixa sp.* presence-absence. R.C. = *Orconectes rusticus* (rusty crayfish) and W. = *Palmacorixa sp.* (water boatman). $\chi^2 = 5.826$ and p = 0.120

A positive correlation between the invasive rusty crayfish *Orconectes rusticus* and the midge larvae *Ablabesmyia sp.* was revealed by Spearman's Rank correlation (p= 0.014, $\rho$ = 0.361). More often than expected by chance, *Orconectes rusticus* and *Ablabesmyia sp.* were both absent from sites or *Orconectes rusticus* was present and *Ablabesmyia sp.* absent (Figure 15; $\chi^2$ = 28.609 and p = 0.00000271). Less often than expected by chance, *Orconectes rusticus* was absent and *Ablabesmyia sp*. was present or both were present (Figure 15; $\chi^2$ = 28.609 and p = 0.00000271).

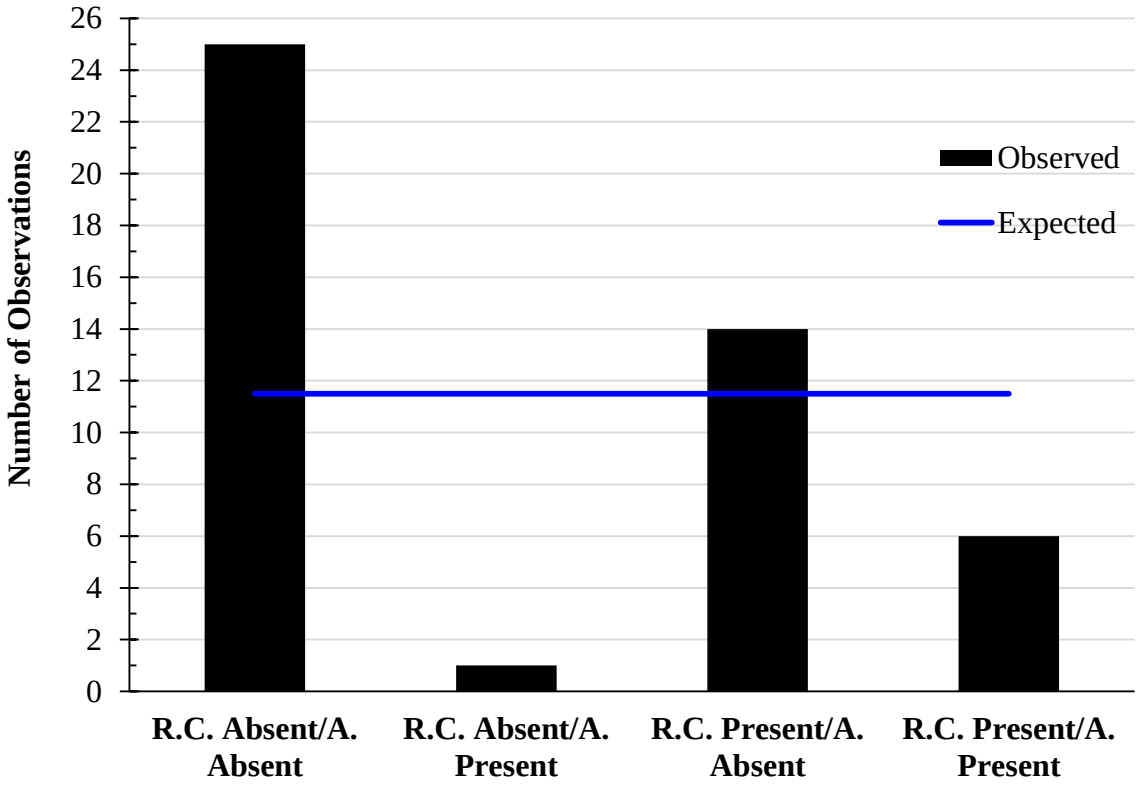



**Figure 15**: Relationship of *Orconectes rusticus* and *Ablabesmyia sp.* presence-absence. R.C. = *Orconectes rusticus* (rusty crayfish) and A. = *Ablabesmyia sp.* (midge larvae). $\chi^2$ = 28.609 and p = 0.00000271

The invasive round goby, *Neogobius melanostomus*, and sideswimmer *Gammarus sp.* were found, by Spearman's Rank correlation, to have a negative correlation (p= 0.0329, $\rho$ = -0.315). *Gammarus sp.* is more likely to be absent when *Neogobius sp.* is present in higher abundance (Figure 16).

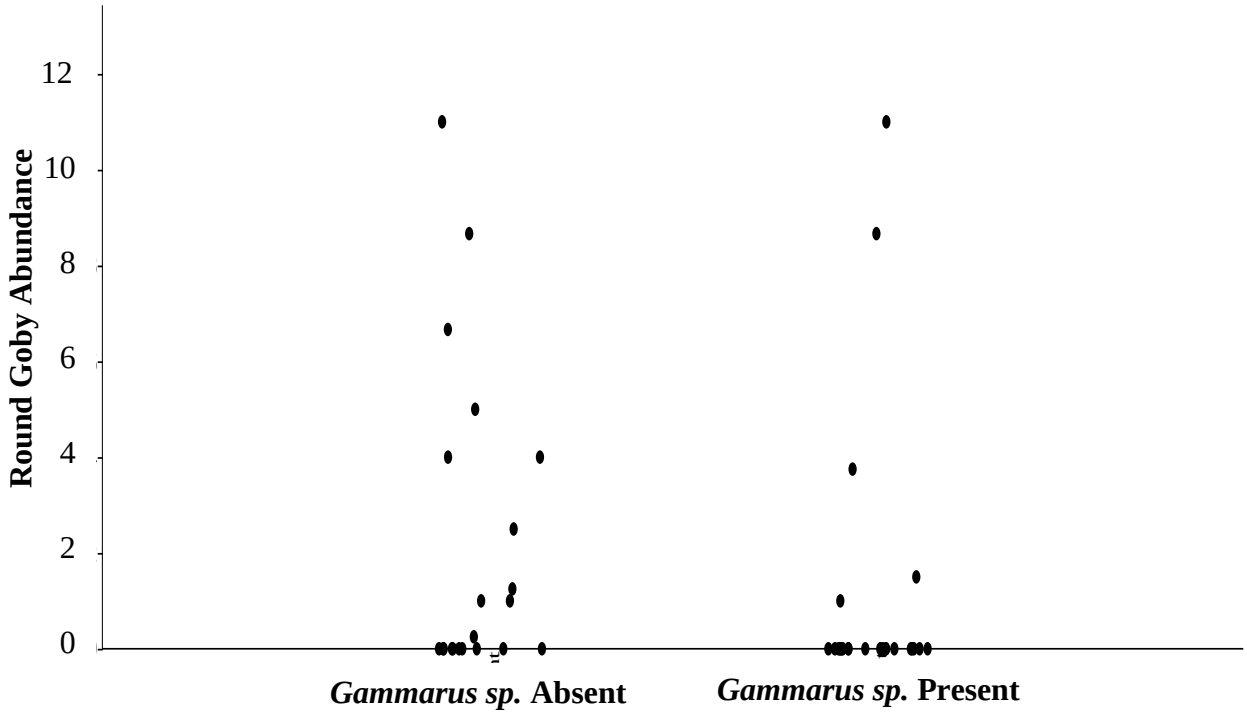



**Figure 16**: Relationship of *Neogobius melanostomus* (round goby) abundance and *Gammarus sp.* (amphipod) presence-absence.

Spearman's Rank correlation indicated a positive correlation between the emerald shiner *Notropis antherinoides* and round goby *Neogobius melanostomus* (p= 0.00487, $\rho$ = 0.408). In general, as *Notropis antherinoides* abundance increases *Neogobius melanostomus* abundance also increases (Figure 17).

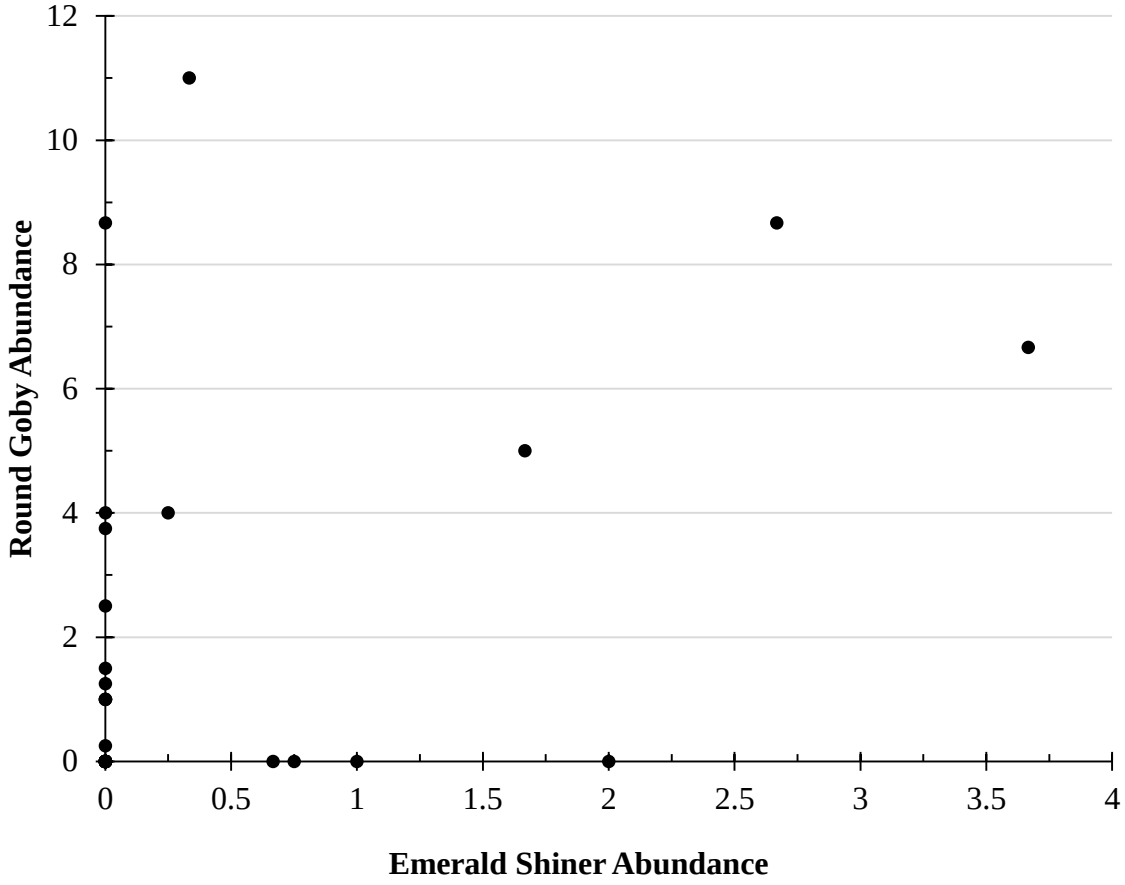



**Figure 17**: Relationship of *Neogobius melanostomus* (round goby) and *Notropis antherinoides* (emerald shiner) abundance.

A positive correlation between rusty crayfish, *Orconectes rusticus*, presence-absence and yellow perch, *Perca flavescens*, abundance was indicated by Spearman's Rank correlation analysis (p= 0.0138, $\rho$ = 0.361). As *Perca flavescens* abundance increases, *Orconectes rusticus* are more often present than absent (Figure 18).

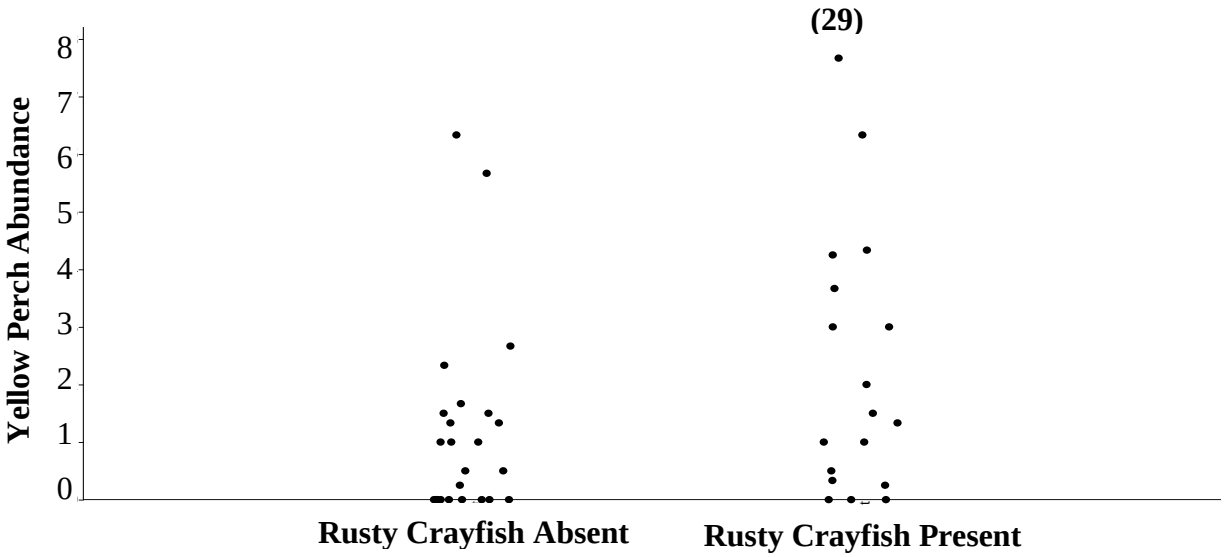



**Figure 18**: Relationship of *Orconectes rusticus* (rusty crayfish) presence-absence and *Perca flavescens* (yellow perch) abundance.

Spearman's Rank correlation indicated positive correlation between the bluegill *Lepomis macrochirus* abundance and rusty crayfish *Orconectes rusticus* (p= 0.0493, $\rho$ = 0.292). When *Orconectes rusticus* is present, *Lepomis macrochirus* is often more abundant (Figure 19).

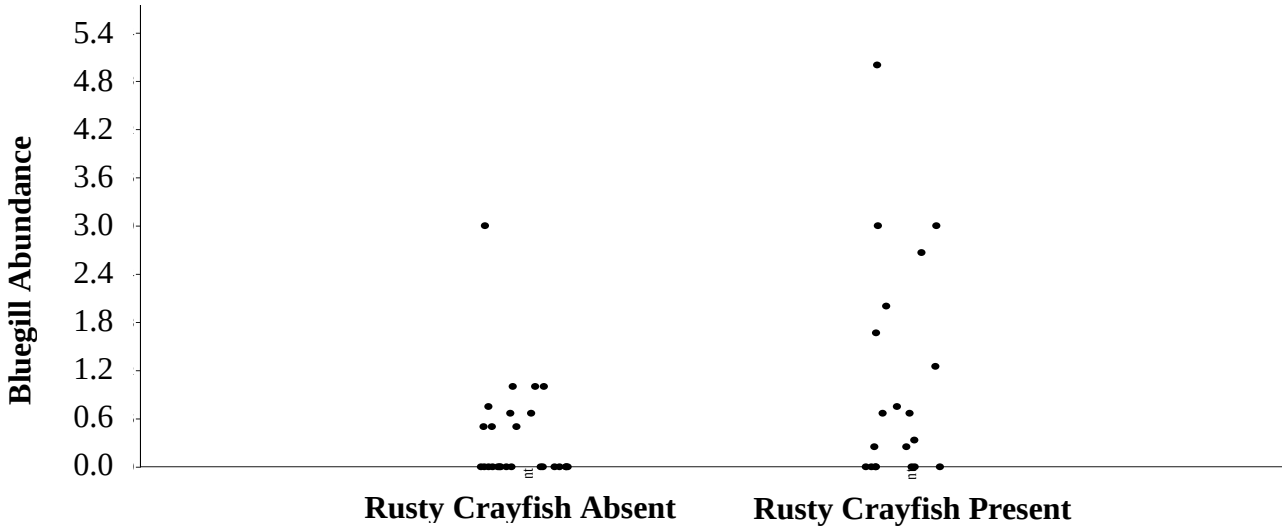



**Figure 19**: Relationship of *Orconectes rusticus* (rusty crayfish) presence-absence and *Lepomis macrochirus* (bluegill) abundance.

Spearman's Rank correlation revealed that common carp, *Cyprinus carpio,* abundance and rusty crayfish, *Orconectes rusticus,* have a positive correlation (p= 0.0095, $\rho$ = 0.379). When *Cyprinus carpio* abundance is high, *Orconectes rusticus* is likely to be present (Figure 20).

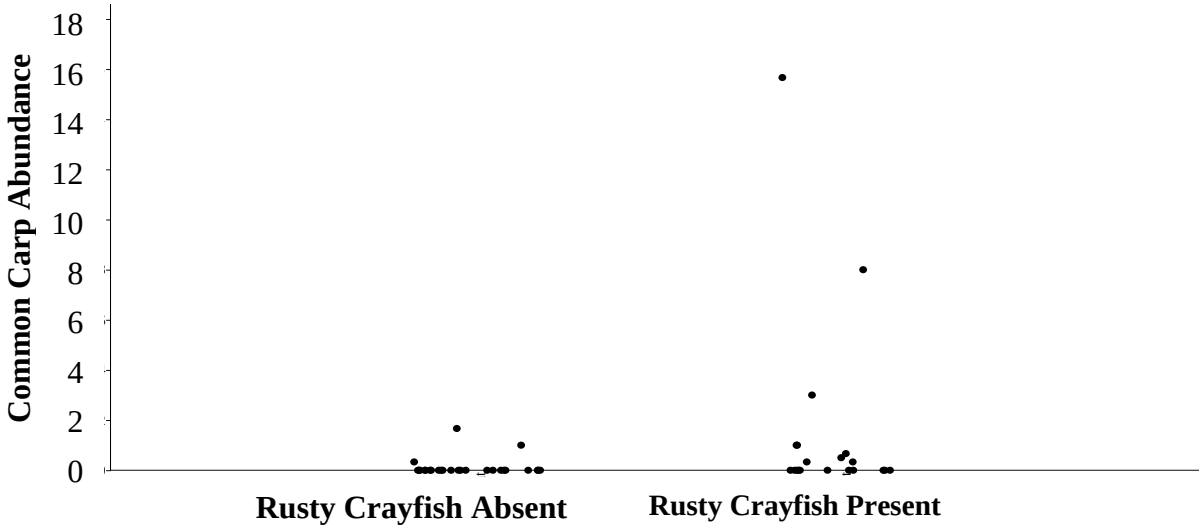



**Figure 20**: Relationship of *Orconectes rusticus* (rusty crayfish) presence-absence and *Cyprinus carpio* (common carp) abundance.

A positive correlation between common carp, *Cyprinus carpio,* and yellow perch, *Perca flavescens,* abundance was indicated by Spearman's Rank correlation (p= 0.043, $\rho$ = 0.3). *Cyprinus carpio* was absent when *Perca flavescens* was present more than expected by chance while *Cyprinus carpio* was present when *Perca flavescens* was absent less than expected by chance (Figures 21 and 22; $\chi^2$ = 18.0 and p = 0).

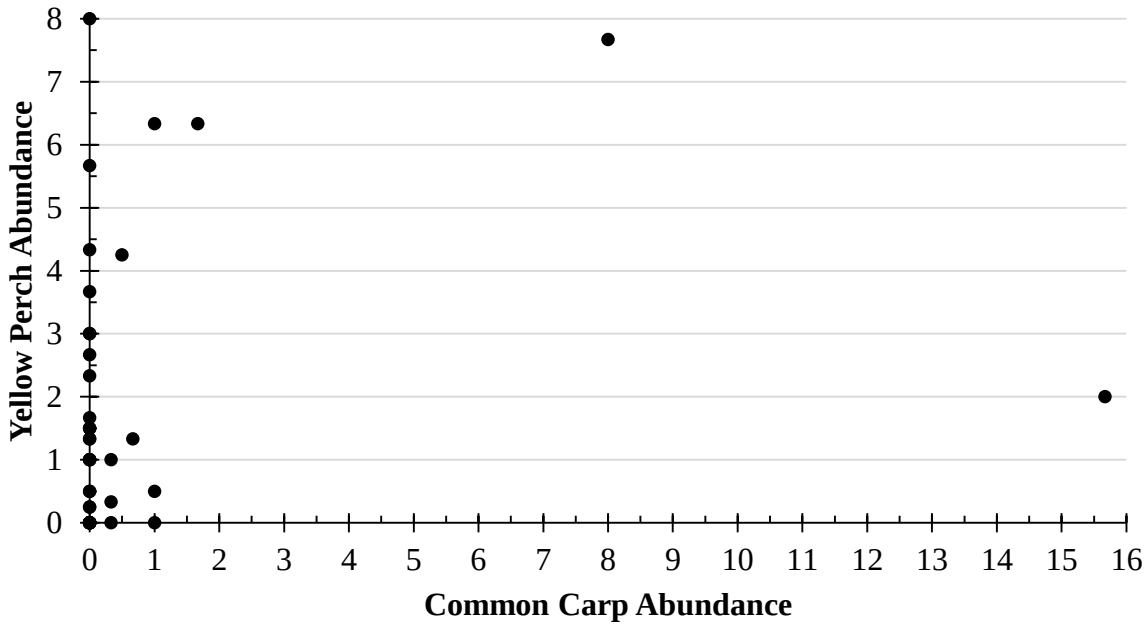



**Figure 21**: Relationship of *Cyprinus carpio* (common carp) and *Perca flavescens* (yellow perch) abundance.

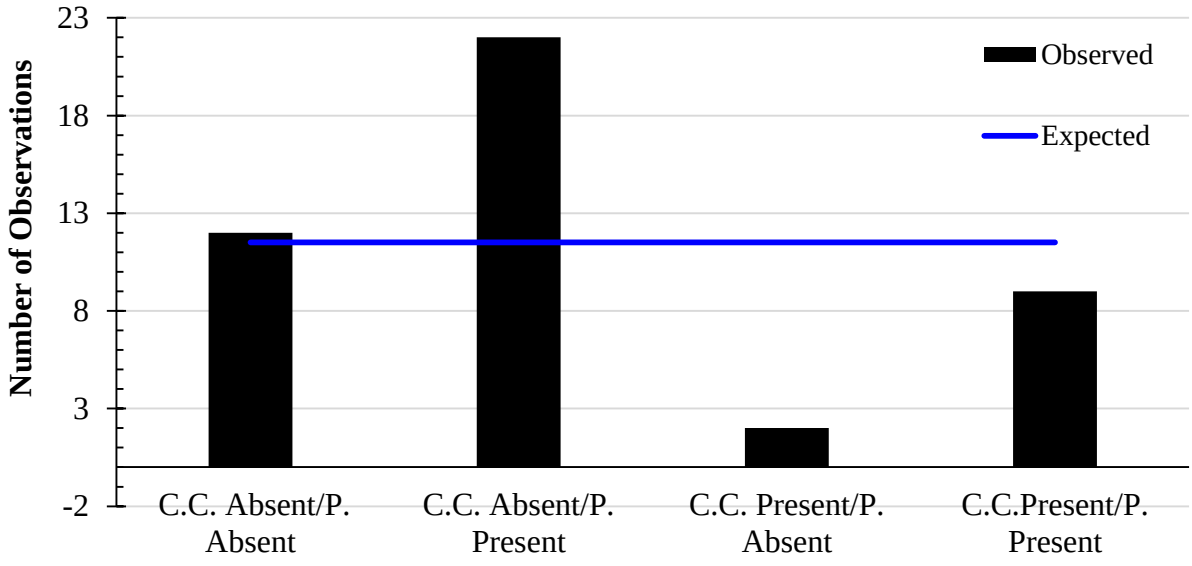



**Figure 22**: Relationship of *Cyprinus carpio* and *Perca flavescens* presence-absence. C.C. = *Cyprinus carpio* (common carp) and P. = *Perca flavescens* (yellow perch). $\chi^2 = 18.0$ and p = 0.0004

*Lepomis cyanellus* and *Cyprinus carpio* were both absent more than expected by chance and were infrequently found together (Figures 23 and 24; $\chi^2 = 28.087$ and p = 0.00000348). Spearman's Rank correlation indicated positive correlation between the green sunfish *Lepomis cyanellus* and common carp *Cyprinus carpio* abundances (p= 0.0359, $\rho = 0.31$).

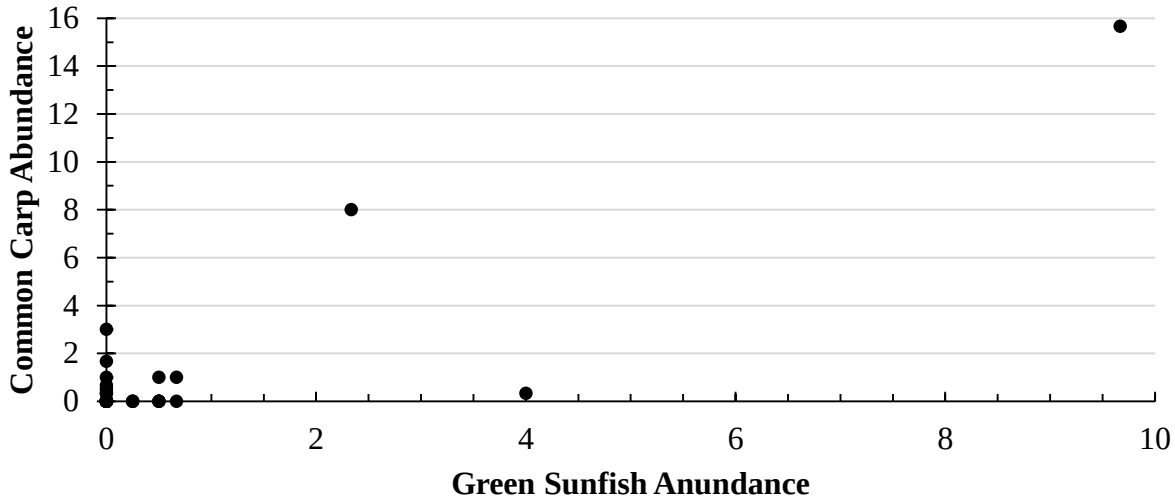



**Figure 23**: Relationship of *Lepomis cyanellus* (green sunfish) and *Cyprinus carpio* (common carp) abundance.

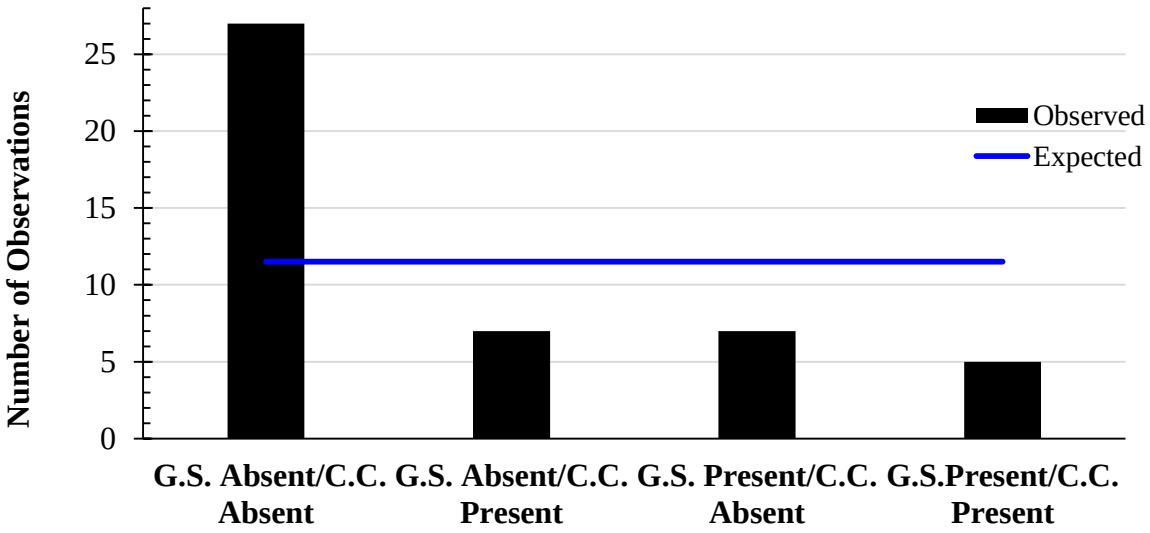



**Figure 24**: Relationship of *Lepomis cyanellus* and *Cyprinus carpio* presence-absence. C.C. = *Cyprinus carpio* (common carp) and G.S. = *Lepomis cyanellus* (green sunfish). $\chi^2 = 28.087$ and p = 0.00000348.

## Discussion

The goal of this study was to analyze the Lower Fox River ecosystem and thereby provide insight concerning the biological conditions and characteristics of the river. Current information on the biological communities of the Lower Fox River is scarce because previous studies have focused on physical and chemical characteristics. This study provides a more extensive biological analysis, which indicates that both spatial and temporal analyses of the river are critical. Data compiled from biological surveys demonstrate that zooplankton and benthic invertebrate communities of the Lower Fox River vary year to year, while fish communities vary based on location. In order to gain a better understanding of the functioning of the whole Lower Fox River ecosystem, the river must be both frequently and regularly monitored at numerous locations. This type of methodology will enable the complex and dynamic interactions of the zooplankton, benthic invertebrate, and fish communities to be better appreciated.

### *Interpretation of General Trends*

Both zooplankton and benthic invertebrates have limited mobility, and thus their spacing patterns and foraging activities are strongly affected by water flow. Benthic invertebrates and zooplankton both undergo strong seasonal abundance cycles and, in general, have short life cycles. These mobility and life cycle characteristics help explain why the composition of zooplankton and benthic invertebrate populations in the Lower Fox River remain fairly similar across sites in a given year, but vary based on sampling year. Because of their limited mobility and short life cycles, zooplankton and benthic invertebrates can undergo rapid responses at the community level and thus community compositions can more readily differ across sampling years.

The fish assemblages of Wisconsin rivers are determined by climate, river size, summer water temperature, and permanency of flow (Lyons, 2012). Fish contain prey and predatory species, and in general, move through several trophic levels as they mature. The Lower Fox River contains warm-water fish communities composed of large predators, middle trophic level species, and lower trophic level species (WDNR, 1995). Changes in fish community structure can indicate a recent ecosystem disturbance. For example, decreased numbers of large fish can indicate a recent fish kill due to anoxic conditions. This is because larger fisher require a longer recovery time due to slow growth and recolonization on account of the increased mortality risk associated with growth and long-term exposure to pollutants (Stewart & Loar, 1994). Fish have highly variable numbers of new young fish that enter a population in a given year and thus strong year classes of predatory fish can drive food web dynamics in aquatic ecosystems for years. In the Lower Fox River, fish community composition of a given site remains similar across time, but varies among sites in each year. Longer life-cycles and superior mobility likely explain these trends (Stewart & Loar, 1994). The upstream/downstream divide in characterization of sites by fish species is likely due to the invasive species barrier at Rapide Croche as well as the presence of locks and dams throughout the system (Table 6). These barriers affect fish community structure because they segment river habitat and thereby affect the ability of fish to move from one site to another. This segmentation is clearly the reason that invasive species like the round goby are found only below the barrier at Rapide Croche.

*Characterization of Sample Sites*

All three upstream sites were characterized by common carp, *Cyprinus carpio*, and gizzard shad, *Dorosoma cepedianum*. Both of these are warm-water fish species. Common carp, an invasive species in the Fox River, prefer benthic habitats and are tolerant to environmental

degradation. Gizzard shad are moderately tolerant to environmental degradation and prefer to reside in the water column (Lyons, 2012). The features of these fish, which typify upstream sites, suggests that the upstream region of the Lower Fox River is a warm-water habitat with some level of environmental degradation.

Two of the downstream sites, FR-4 and FR-C, are typified by common shiner, *Luxilus cornutus*, and johnny darter, *Etheostoma nigrum*. Common shiner and johnny darter are both insectivores that are moderately tolerant of environmental degradation. Common shiner prefer warm water and reside in the water column (Lyons, 2012). Johnny darter, on the other hand, prefer cool-water benthic habitats and are adapted for rapid colonization of new or transient habitats (Lyons, 2012). FR-D is uniquely classified by emerald shiner, *Notropis antherinoides*, and round goby, *Neogobius melanostomus*. Emerald shiner can adapt to a variety of temperatures and have a diet that consists of chironomids, copepods, amphipods, and other aquatic invertebrates (Mendelson, 1975). Round goby is an invasive species that has a broad diet and is able to live in a wide variety of habitats (Corkum et al., 2004). The downstream region of the Lower Fox River, based on the fish species that characterize it, also has some level of environmental degradation, with FR-D being a somewhat unique site. Both of the species that typify FR-D are highly adaptable suggesting that the habitat of FR-D may be especially dynamic.

*Interactions Among Species of Interest*

Altered habitats are more vulnerable to incursion by invasive species. This is because nonnative species may have competitive, reproductive, or resource location strategies that are more suited for the altered habitat than the native species. In addition, invasive species likely have fewer predators and more prey than native species, giving them an additional advantage over native species and providing them with the opportunity to eliminate native species through

intense predation and competition. Essentially, there is an undeniable link between invasive species and altered habitats because invaders may be better adapted to the new conditions than the native species. If populations of native predators and competitors have been reduced or destabilized, there is the potential for invasive species to dominate and ultimately the ecosystem is thrown out of balance (Moyle, 1994).

It is rare to find a body of water that has not been occupied by invasive species; this is a testament to the scarcity of pristine rivers, and the frequency with which invasive species are being introduced by anglers, agencies, or by accident. If an invasive species introduction is successful, it has the potential to disrupt the original lotic community until an apparent steady state that includes the introduced species is established. The degree to which the ecosystem is affected by the introduced species varies depending on the species that is introduced. Piscivorous fishes, for example, are more likely to cause major alterations to lotic fish communities than detritivores or omnivores (Moyle, 1994). It is clear based on the characteristic species and the species of interest that invasive species have a huge impact on the biological communities of the Lower Fox River and that the introduction of these species has caused major ecological alterations.

The invasive rusty crayfish, *Orconectes rusticus*, is an omnivorous species that can act as an intermediate consumer, potentially affecting multiple trophic levels within a single food web. Rusty crayfish can have profound effects on lotic food webs in the areas that they invade (Bobeldyk & Lamberti, 2010). Through direct predation, rusty crayfish cause declines in food resources such as detritus and benthic invertebrates (Haughton, Dimick, & Frie, 1998). They indirectly affect higher trophic levels, such as fish, by limiting the resources available to them (Bobeldyk & Lamberti, 2010). In comparison to native crayfish, such as the northern/virile

crayfish *Orconectes virilis*, rusty crayfish are able to reach higher densities, have higher consumption rates, and are less susceptible to fish predation (Bobeldyk & Lamberti, 2010). Based on the data of this study, rusty crayfish in the Lower Fox River are correlated with the following organisms: the water boatman taxa *Palmacorixa sp*., the midge larvae *Ablabesmyia sp*., yellow perch *Perca flavescens*, and green sunfish, *Lepomis macrochirus.*

Rusty crayfish and the water boatman taxa *Palmacorixa sp.* were found to have a positive correlation; they were most often found, or not found, together (Figure 14; p= 0.049, $\rho$ = 0.292). Water boatman inhabiting lotic systems prefer to reside in benthic regions with sheltering vegetation (Oscarson, 1987). Fish predation often constrains water boatman abundance and distribution. *Palmacorixa sp.* and rusty crayfish most likely inhabit similar areas of the river not only due to their preference for similar benthic habitats, but also because they are both avoiding predation by fish (Oscarson, 1987).

Rusty crayfish and the midge larvae of *Ablabesmyia sp.* were also found to have a positive correlation (p= 0.014, $\rho$ = 0.361). Midge larvae and the rusty crayfish were most often observed to both be absent from sites; there was only one occasion where *Ablabesmyia sp.* was present at a site and rusty crayfish was not (Figure 15). Midge larvae can be found in almost any aquatic habitat and are often associated with degraded, low biodiversity ecosystems because of their ability to survive in nearly anoxic conditions and dominate in polluted waters (Hilsenhoff, 1982). Midge larvae also serve as an important food source for fish and a variety of other aquatic organisms, such as water boatman and predatory water beetles (Armitage, 1995). Rusty crayfish and the midge larvae *Ablabesmyia sp*. may be both absent from sites because they are both avoiding predation by fish or because they are both associated with disturbed habitats, and thus are both absent from less disturbed habitats.

Yellow perch, *Perca flavescens*, was also found to have a positive correlation with rusty crayfish (p= 0.0138, $\rho$ = 0.361). Yellow perch prefer pelagic (mid-water column) habitats while rusty crayfish favor littoral (nearshore) zones (Lyons, 2012; Bobeldyk & Lamberti, 2010). Mature yellow perch are primarily insectivores, however, they are also known to consume fish eggs, crayfish, and juvenile fish (Lyons, 2012; Tetzlaff, Roth, Weidel, & Kitchell, 2011). Although there is a positive correlation between rusty crayfish and yellow perch (which is a known predator of rusty crayfish), rusty crayfish populations likely remain high because the Fox River is a eutrophic environment with high food availability for both the yellow perch and the rusty crayfish. This high food availability may cause the yellow perch to pursue other food sources besides the rusty crayfish. Therefore, the lack of predatory pressure combined with an abundance of food allows the rusty crayfish to flourish regardless of the presence of yellow perch.

Bluegill, *Lepomis macrochirus*, and rusty crayfish were found to have a positive correlation and were often present in the same locations (p= 0.0493, $\rho$ = 0.292). Bluegill function primarily as insectivores but are also know to consume juvenile crayfish (Lyons, 2012; Tetzlaff et al., 2011). The correlation between bluegill and rusty crayfish indicates that bluegill predation is not a limiting factor for rusty crayfish. The positive correlation between the species may be because they are utilizing similar food sources, which are not highly limited, or because they are both avoiding predation by larger, more predatory fish.

The round goby, *Neogobius melanostomus*, is an aggressive, multiple-spawning fish native to the Ponto-Caspian region (Corkum, Sapota & Skora, 2004). The diet of the round goby varies based on substrate type and light intensity, and includes amphipods, chironomids, cladocerans, crayfish, dragonflies, dreissenids, isopods, mayflies, fish eggs, and larvae (Corkum

et al., 2004). In general round gobies prefer rocky substrates, but are also found in sand and gravel habitats (Corkum et al., 2004). The broad diet, wide aggressive behavior, tolerance of abiotic factors, and high fecundity of round goby allows them to be a successful invader in a wide variety of habitats (Corkum et al., 2004). Negative effects following invasion by round goby include reduced fecundity of native fishes (round goby eat fish eggs) and enhanced algal biomass due to consumption of grazing invertebrates by round goby (Corkum et al., 2004). Round goby are preyed upon by smallmouth bass, freshwater drum, and yellow perch (Corkum et al., 2004). Round goby were found to have correlations with the side swimmers, *Gammarus sp*. and emerald shiners, *Notropis antherinoides*.

Round goby and *Gammarus sp.* have a negative correlation (p= 0.0329, $\rho$ = -0.315). This relationship can be explained by the fact that amphipods such as *Gammarus sp*. are a part of the round goby diet (Corkum et al., 2004). *Gammarus sp.* are more likely to be absent from a site when round goby are present in higher abundances (Figure 16). Round goby predation on *Gammarus sp*. has likely reduced *Gammarus sp*. populations in areas where round goby are abundant.

A positive correlation was found between round goby and emerald shiner, *Notropis antherinoides* (p= 0.00487, $\rho$ = 0.408). As emerald shiner abundance increases, round goby abundance also seems to increase. Emerald shiner prefer to inhabit mid-water edge habitats with sandy bottoms. Their diet consists of chironomids, copepods, amphipods, and other invertebrates (Mendelson, 1975). The similarity of round goby and emerald shiner diets suggests that the positive correlation between these species is likely due to the fact that they are seeking out similar food sources; resources which do not appear to be limiting.

The common carp, *Cyprinus carpio*, is an invasive species that was intentionally introduced to the Great Lakes region in 1881 as a potential new food source (WDNR, 1999). Common carp can successfully populate a wide variety of habitats due to their ability to withstand a wide range of temperatures and very low oxygen concentrations. They prefer, however, to reside in warm, shallow, shoreline habitats (WDNR, 1999). Since the initial introduction of common carp to the Great Lakes region, there have been numerous reports on their wide scale negative effects on aquatic ecosystems. For example, it has been found that common carp increase water temperatures and suspended sediment as a result of their aggressive uprooting of shoreline vegetation, and that they compete with a wide range of native species for food resources and spawning area (WDNR, 1999). The data of this study indicate that the common carp located in the Lower Fox River have correlations with the following organisms: rusty crayfish, *Orconectes rusticus*, yellow perch, *Perca flavescens*, and green sunfish, *Lepomis cyanellus*.

Common carp and rusty crayfish were found to have a positive correlation, with rusty crayfish being more likely to be present when common carp are present in higher abundances (Figure 20; p= 0.0095, $\rho$ = 0.379). Both rusty crayfish and common carp are omnivorous invasive species that prefer nearshore habitats (Bobeldyk & Lamberti, 2010; WDNR, 1995). The positive correlation between the two species can likely be explained by the similarity of their behaviors and habitat preferences.

Common carp and yellow perch were also found to have a positive correlation (p= 0.043, $\rho$ = 0.3). Yellow perch function primarily as insectivores, while common carp are more generalized omnivores (WDNR, 1995). Yellow perch and common carp may be positively

correlated because they are utilizing different food resources, but prefer the same type of nearshore habitat.

Green sunfish, *Lepomis cyanellus*, and common carp were found to have a positive correlation ($p= 0.0359$, $\rho = 0.31$). Common carp and green sunfish both frequent shallow water, and occasionally compete for spawning area (WDNR, 1999). Similar to common carp, green sunfish are tolerant to environmental degradation and thus can survive in poor water conditions (Lyons, 2012). Their diet can include a range of foods from aquatic insects and larvae to snails, but they function mainly as insectivores (Lyons, 2012; WDNR, 1995). Although green sunfish and common carp are known to compete for resources such as spawning area, the results of this study indicate that the shared resources of common carp and green sunfish are not limited in the Lower Fox River. Because the resources that both species require are readily available, they are not competing, but rather are in a state of cohabitation.

Invasive species often lead to reduced aquatic food web complexity, which is in turn associated with instability. It is imperative to recognize aquatic invasive species that reduce food web complexity as especially problematic sources of stress. Right now, monitoring efforts are focused on attempting to quantify stress on the biotic communities of aquatic ecosystems. However, biotic data – no matter how they are manipulated – give rise only to diagnoses, not to solutions. In addition, biotic data are more subject to informed interpretation than chemical analyses, such as dissolved oxygen content (Hynes, 1994).

*Conclusion*

The results of this study suggest that the eutrophic nature of the Lower Fox River cause complex and dynamic relationships where competition for resources is not the limiting factor for species occurrence patterns, but rather the ability to survive in fluctuating temperature, dissolved oxygen, flow, and water level conditions becomes more important. The biological survey data indicate that zooplankton and benthic invertebrate community composition is consistent across sites, but varies year-to-year, while fish community composition is consistent across years, but varies based on location.

In terms of developing effective management plans and making well-informed decisions, consistent sampling data of the biological communities of the river taken from different sites along the river at different times would be helpful. In addition, collection of physical and chemical data in addition to biological data would enable a more in-depth exploration of ecosystem trends. Finally, if benthic invertebrate samples were collected in accordance with the methods laid out by Hilsenhoff (1982), a measure of organic pollution based on benthic invertebrate data could be made.

Heavy use of the Lower Fox River has negatively affected water quality and the overall health of the system (Markert, 1981). Unhealthy rivers cannot function properly. The Lower Fox River connects to the many other important waterbodies, including Green Bay and the larger Great Lakes system. Due to the historical and current biological and economic value of the Lower Fox River, preservation and proper functioning of the ecosystem is of vital importance. After the 1972 legislation of the Clean Water Act and the regulations of the US Environmental Protection Agency, the Wisconsin Department of Natural Resources became responsible for the management of the river. There have been marked improvements in the quality of the water since

the early analyses of the river. However, the results of this study indicate that further monitoring and regulation have the opportunity to further improve the quality of the water and ensure a more varied and resilient ecosystem capable of supporting diverse biological interactions.

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Appendix A
Loading Value Table for Component One and Two

**Table A1**: Fish loading values. Loading values for components one and two from principal component analysis of fish abundance matrix.

| Species | Component 1 | Component 2 |
|---|---|---|
| *Notropis atherinoides* (emerald shiner) | 0.2544 | 0.7956 |
| *Neogobius melanostomus* (round goby) | 0.4769 | 0.7771 |
| *Pimephales vigilax* (bullhead minnow) | 0.1118 | 0.7509 |
| *Pimephales promelas* (fathead minnow) | 0.1213 | 0.7045 |
| *Percina phoxocephala* (slenderhead darter) | 0.3742 | 0.4051 |
| *Pimephales notatus* (bluntnose minnow) | 0.09375 | 0.3959 |
| *Fundulus diaphanus* (banded killifish) | 0.01479 | 0.2857 |
| *Macrhybopsis hyostoma* (shoal chub) | 0.01479 | 0.2857 |
| *Minytrema melanops* (spotted sucker) | 0.01479 | 0.2857 |
| *Notropis sp.* (common shiner) | -0.04363 | 0.1654 |
| *Enneacanthus obesus* (banded sunfish) | -0.03343 | 0.143 |
| *Lepisosteus osseus* (longnose gar) | -0.0629 | 0.1153 |
| *Pomoxis nigromaculatus* (black crappie) | 0.07957 | 0.08206 |
| *Ammocrypta clara* (western sand darter) | 0.02122 | 0.06724 |
| *Percina caprodes* (logperch) | -0.0782 | 0.06617 |
| *Percina shumardi* (river darter) | 0.001485 | 0.06529 |
| *Ictiobus cyprinellus* (bigmouth buffalo) | 0.02184 | 5.68E-02 |
| *Catostomus commersonii* (white sucker) | 0.2798 | 0.04715 |
| *Pomoxis annularis* (white crappie) | -0.01432 | 0.02737 |
| *Percopsis omiscomaycus* (trout-perch) | -0.08459 | 0.02085 |
| *Notropis wickliffi* (channel shiner) | -0.03409 | 0.01329 |
| *Perca flavescens* (yellow perch) | 0.9421 | 0.00948 |
| *Notropis hudsonius* (spottail shiner) | -0.09826 | 0.006117 |
| *Micropterus dolomieu* (smallmouth bass) | 0.06226 | -0.007207 |

**Table A1 Continued**

| Species | Component 1 | Component 2 |
|---|---|---|
| *Cyprinella spiloptera* (spotfin shiner) | -0.0624 | -0.0171 |
| *Alosa crysochloris* (skipjack herring) | -0.03841 | -0.01769 |
| *Esox lucius* (northern pike) | -0.03841 | -0.01769 |
| *Sander vitreus* (walleye) | -0.03841 | -0.01769 |
| *Notropis dorsalis* (bigmouth shiner) | -0.03796 | -0.02114 |
| *Etheostoma flabellare* (fantail darter) | -0.04401 | -0.02394 |
| *Carpiodes cyprinus* (quillback) | 0.9044 | -0.04062 |
| *Etheostoma chlorosoma* (bluntnose darter) | -0.02257 | -0.04243 |
| *Esox americanus vermiculatus* (grass pickerel) | 0.015 | -0.0432 |
| *Semotilus atromaculatus* (creek chub) | 0.015 | -0.0432 |
| *Aplodinotus grunniens* (freshwater drum) | -0.01593 | -0.0433 |
| *Ictalurus punctatus* (channel catfish) | -0.04865 | -0.04609 |
| *Morone chrysops* (white bass) | 0.009551 | -0.05093 |
| *Esox masquinongy* (muskellunge) | 0.003552 | -0.05404 |
| *Culaea inconstans* (brook stickleback) | -0.03514 | -0.056 |
| *Campostoma anomalum* (central stoneroller) | 0.00516 | -0.06037 |
| *Notemigonus crysoleucas* (golden shiner) | -0.06748 | -0.06386 |
| *Carpiodes carpio* (river carpsucker) | -0.01415 | -0.06719 |
| *Notropis heterolepis* (blacknose shiner) | 0.01793 | -0.06978 |
| *Lepomis gibbosus* X *Lepomis cyanellus* (pumpkinseed X green sunfish hybrid) | -0.04044 | -0.07285 |
| *Dorosoma cepedianum* (gizzard shad) | 0.9899 | -0.07845 |
| *Lepomis gibbosus* (pumpkinseed) | -0.1038 | -0.1066 |
| *Ambloplites rupestris* (rock bass) | -0.04138 | -0.1203 |
| *Etheostoma sp.* (darter) | 0.9617 | -0.1246 |
| *Micropterus salmoides* (largemouth bass) | 0.1257 | -0.1993 |
| *Etheostoma nigrum* (johnny darter) | -0.05752 | -0.2026 |
| *Lepomis cyanellus* (green sunfish) | 0.03946 | -0.2041 |
| *Cyprinus carpio* (common carp) | 0.2279 | -0.2474 |
| *Lepomis macrochirus* (bluegill) | 0.1915 | -0.2509 |

**Table A2**: Benthic invertebrate loading values. Loading values for components one and two from principal component analysis of benthic invertebrate presence-absence matrix.

| Species | Component 1 | Component 2 |
|---|---|---|
| *Pteronarcys sp.* (stonefly) | -0.1832 | 0.1492 |
| *Anthopotomus sp*. (mayfly) | -0.1832 | 0.1492 |
| *Baetisca sp.* (mayfly) | -0.1832 | 0.1492 |
| *Baetis hiemalis* (mayfly) | 0.1357 | 0.2669 |
| *Caenis sp*. (mayfly) | 0.008451 | 0.4552 |
| *Callibaetis sp*. (mayfly) | 0.2861 | 0.3722 |
| *Dannella sp.* (mayfly) | 0.1775 | 0.2242 |
| *Ephemerella sp.* (mayfly) | -0.3232 | 0.3285 |
| *Metretopus sp.* (mayfly) | 0.2144 | -2.31E-01 |
| *Neoephemera sp.* (mayfly) | -0.1198 | 0.278 |
| *Parameletus sp.* (mayfly) | -0.1832 | 0.1492 |
| *Pseudiron sp.* (mayfly) | 0.007084 | 0.1067 |
| *Rhithrogena sp.* (mayfly) | -0.1641 | -0.02309 |
| Siphlonuridae (either *Isonychia spp*. or *Siphlonurus spp.* mayfly) | -0.1274 | 0.2237 |
| *Stenacron interpunctatum* (mayfly) | -0.1832 | 0.1492 |
| *Stenonema sp*. (mayfly) | 0.3094 | 0.05428 |
| *Tricorythodes sp*.(mayfly) | 0.02763 | 0.4561 |
| *Amphiagrion hastatum* (damselfly) | 0.2799 | 0.1813 |
| *Anax sp.* (dragonfly) | -0.1495 | -0.01227 |
| *Argia moesta* (damselfly) | -0.0675 | 0.2471 |
| *Coenagrion sp.* (damselfly) | 0.1973 | 0.2402 |
| *Dromogomphus sp.* (dragonfly) | -0.1439 | -0.1443 |
| *Enallagma sp.* (damselfly) | -0.07536 | 0.5061 |
| *Erythemus sp.* (dragonfly) | 0.05497 | 0.07042 |
| *Hetaerina americana* (damselfly) | -0.1305 | 0.05925 |
| *Ischnura verticalis* (damselfly) | 0.1759 | -2.56E-01 |
| *Lestes sp.* (dragonfly) | -0.02481 | 0.05202 |
| *Libellulidae sp.* (dragonfly) | -0.1439 | -0.1443 |
| *Nehalennia sp.* (damselfly) | 0.2107 | 0.3771 |
| *Sympetrum/Tarnetrum sp.* (dragonfly) | -0.1034 | 0.3001 |
| *Agraylea sp.* (caddisfly) | 0.2799 | 0.1813 |
| *Diplectrona modesta (*caddisfly) | -0.1427 | 4.53E-01 |

**Table A2 Continued**

| Species | Component 1 | Component 2 |
|---|---|---|
| *Leptocerus sp.* (long-horned caddisfly) | -0.1034 | 0.3001 |
| *Macronema sp*. (caddisfly) | 0.00277 | 0.1218 |
| *Molanna tryphena* (caddisfly) | -0.1034 | 0.3001 |
| *Paramyctiophylax sp.* (caddisfly) | -0.1034 | 0.3001 |
| *Pseudostenophylax sp*. (caddisfly) | 0.02856 | -0.1076 |
| *Sialis sp.* (alderfly) | 0.02447 | 0.1837 |
| *Agabus sp.* (beetle) | 0.2314 | -0.4248 |
| *Berosus sp.* (beetle) | 0.2003 | -0.2398 |
| *Brychius sp.* (crawling water beetle) | 0.3433 | -0.04185 |
| *Curculionidae sp.* (aquatic beetle) | 0.2799 | 0.1813 |
| *Dibolocelus sp*. (water beetle) | 0.04612 | -0.2259 |
| *Dineutus sp*. (whirligig beetle) | 0.1387 | 0.2387 |
| *Stenelmis sp.*(riffle beetle) | 0.06909 | 0.2364 |
| *Haliplidae sp*. (aquatic beetle) | 0.2799 | 0.1813 |
| *Haliplus sp*. (crawling water beetle) | 0.2987 | -0.02387 |
| *Laccophilus sp*. (water beetle) | 0.125 | 0.1289 |
| *Oreodytes sp*. (aquatic beetle) | 0.3242 | 0.1925 |
| *Peltodytes sp.* (spotted beetle) | -0.1768 | 0.1114 |
| *Ablabesmyia sp.* (true fly) | 0.5058 | -0.4779 |
| *Aedes sp.*(mosquito) | 0.3458 | -0.3036 |
| *Atherix sp.* (ibis fly) | -0.09821 | 0.3017 |
| *Bittacomorpha sp.* (crane fly) | 0.3242 | 0.1925 |
| *Chironomus sp.* (midge fly/bloodworm larvae) | 0.5311 | 0.2186 |
| *Dixella sp.* (meniscus midge) | -0.2221 | 0.2667 |
| *Chrysops sp.* (Deer fly) | -0.1613 | 0.3757 |
| *Crangonyx pseudogracilis* (amphipod) | 0.1408 | 0.2976 |
| *Crangonyx sp.* (amphipod) | -0.2213 | 0.3593 |
| *Echinogammarus ischnus* (amphipod) | -0.2789 | 0.01847 |
| *Gammarus fasciatus* (amphipod) | -0.1943 | 0.4875 |
| *Gammarus sp.* (amphipod) | 0.1982 | 0.6147 |
| *Hyalella azteca* (amphipod) | 0.1526 | 0.5638 |
| *Hyalella sp.* (amphipod) | 0.01219 | -0.06477 |

**Table A2 Continued**

| Species | Component 1 | Component 2 |
|---|---|---|
| *Torrenticola sp.* (water mite) | 0.1805 | -0.3083 |
| *Wandesia sp.* (water mite) | 0.2631 | -0.3645 |
| *Buenoa sp*. (water boatman) | -0.1439 | -0.1443 |
| *Callocorixa sp*. (water boatman) | 0.2175 | 0.2064 |
| *Cenocorixa sp*. (water boatman) | 0.2547 | 0.3183 |
| *Corisella sp*. (water boatman) | 0.2018 | 0.1567 |
| *Hespercorixa sp*. (water boatman) | 0.5486 | 0.1515 |
| *Notonecta sp*. (backswimmer) | -0.07336 | 0.2373 |
| *Palmacorixa sp*. (water boatman) | 0.874 | -0.1075 |
| *Ramphocorixa sp*. (water boatman) | 0.03998 | 0.5313 |
| *Sigara sp.* (water boatman) | 0.3908 | 0.007218 |
| *Trichocorixica sp.* (water boatman) | 0.8035 | -0.1643 |
| *Belostoma sp.* (giant water bug) | 0.1098 | 0.1602 |
| *Gerris sp*. (water strider) | -0.236 | 0.1876 |
| *Limnogonus sp*. (water strider) | -0.1485 | 0.06271 |
| *Limnoporus sp*. (water strider) | -0.1317 | -0.02156 |
| *Metrobates sp.* (water strider) | 0.1148 | 0.1725 |
| *Neogerris sp.* (water strider) | 0.1159 | 0.04702 |
| *Rheumatobates sp*. (water strider) | 0.2003 | -0.2398 |
| *Trepobates sp.* (water strider) | 0.08114 | -0.05389 |
| *Mesovelia mulsanti* (water treader) | -0.1193 | 0.05999 |
| *Mesovelia sp.* (water treader) | -0.00246 | -0.1224 |
| *Nepidae sp.* (water scorpion) | 0.1387 | 0.2387 |
| *Ranatra sp.* (water scorpion) | 0.6308 | 0.046 |
| *Helobdella robusta* (leech) | 0.5572 | 0.1862 |
| *Helobdella stagnalis* (leech) | 0.3778 | -0.4608 |
| *Macrobdella sp.* (leech) | 0.1181 | -0.03296 |
| *Placobdella sp.* (segmented worm/leech) | 0.2692 | -0.1938 |
| *Cura foremanii* (flatworm) | 0.2144 | -0.2307 |
| *Planaria sp.* (flatworm) | -0.205 | 0.3213 |
| *Tubifex sp.* (tubifex worm) | -0.2548 | 0.02747 |
| *Orconectes propinquus* (northern clear-water crayfish) | -0.1034 | 0.3001 |
| *Orconectes rusticus* (rusty crayfish) | 0.3617 | -0.3245 |
| *Orconectes virilis* (virile/northern crayfish) | 0.1893 | 0.02576 |

**Table A2 Continued**

| Species | Component 1 | Component 2 |
|---|---|---|
| *Monoporeia sp*. (amphipod) | -0.1325 | 0.6686 |
| *Talitridae sp.* (amphipod) | 0.2144 | -0.2307 |
| *Asellus sp.* (aquatic snowbug) | 0.318 | 0.04277 |
| *Caecidotea sp.* (isopod) | 0.07266 | 0.5876 |
| *Amnicola sp*. (Right Handed Snail) | 0.1924 | 0.1166 |
| *Aplexa sp.* (snail) | 0.2144 | -0.2307 |
| *Bulimus sp.* (Right Handed Snail) | 0.2669 | 0.3612 |
| *Ferrisia sp.* (freshwater limpet) | 0.4953 | 0.2802 |
| *Fossaria sp.* (right handed snail) | 0.09284 | 0.1817 |
| *Goniobasis sp*. (snail) | -0.1613 | 0.3757 |
| *Gyraulus sp.* (disc-shaped snail) | 0.5213 | 0.1626 |
| *Helisoma sp.* (Snail) | 0.4208 | 0.5214 |
| *Physella sp.* (left handed pond snail) | 0.8433 | -0.07994 |
| *Planorbula sp*. (aquatic snail) | 0.2692 | -0.1938 |
| *Pleurocera sp*. (right handed snail) | 0.4861 | 0.525 |
| *Stagnicola sp*. (snail) | 0.3716 | 0.04 |
| *Valvata sp.* (right handed snail) | 0.2403 | 0.09585 |
| *Viviparus sp.* (aquatic snail) | -0.00246 | -0.1224 |
| *Dreissena polymorpha* (zebra mussel) | 0.0259 | 0.4458 |
| *Corbicula fluminea* (clam) | 0.132 | 0.2366 |
| *Sphaeriidae sp.* (clam) | -0.01994 | 0.09616 |
| *Arrenurus sp.* (water mite) | 0.4622 | 0.2412 |
| *Hydrachna sp*. (water mite) | 0.2024 | 0.2555 |
| *Hydrodroma sp.* (water mite) | 0.3357 | -0.3101 |
| *Koenikea sp.* (water mite) | 0.3271 | 0.2899 |
| *Lebertia sp.* (water mite) | 0.2036 | -0.1043 |
| *Limnesia sp.* (water mite) | 0.4433 | -0.4426 |
| *Mideopsis sp.* (water mite) | 0.1775 | 0.2242 |
| *Neumania sp.* (water mite) | 0.3099 | -0.06987 |
| *Oxus sp.* (water mite) | 0.4512 | -0.3505 |
| *Prozia sp.* (water mite) | 0.3023 | -0.3381 |
| *Pseudohydrophantes sp.* (water mite) | 0.1775 | 0.2242 |
| *Teutonia sp.* (water mite) | 0.1535 | -0.279 |

**Table A3**: Zooplankton loading values. Loading values for components one and two from principal component analysis of zooplankton presence-absence matrix.

| Species | Component 1 | Component 2 |
|---|---|---|
| *Epischura lacustis* (calanoid copepod) | 0.3019 | -0.462 |
| *Anchistropus minor* (water flea, Chydoridae family) | 0.4043 | -0.4085 |
| *Daphnia retrocurva* (water flea, Daphniidae family) | 0.3356 | -0.2488 |
| *Macrocyclops albidus* (cyclopoid copepod) | 0.1451 | -0.2173 |
| *Monostyla sp.* (rotifer) | -0.1416 | -0.217 |
| *Dicyclops nanus* ( cyclopoid copepod) | 0.2452 | -0.2156 |
| *Eubosmina coregoni* (water flea, Bosminidae family) | 0.4513 | -0.2009 |
| *Ascomorpha sp.* (rotifer) | -0.6286 | -0.1918 |
| *Brachionus sp*. (rotifer) | -0.6286 | -0.1918 |
| Harpacticoida (order of copepods) | -0.01216 | -0.1579 |
| *Skistodiaptomus oregonensis* (calanoid copepod) | 0.6239 | -0.1517 |
| *Bosmina longirostris* (water flea, Bosminidae family) | -0.04574 | -0.1148 |
| *Diacyclops thomasi* (cyclopoid copepod) | 0.6267 | -0.1081 |
| *Scapholeberis aurita* (water flea, Daphniidae family) | 0.08746 | -0.07699 |
| *Synchaeta sp.* (rotifer) | -0.4716 | -0.0641 |
| *Diaphanosoma birgei* (water flea, Sididae family) | 0.4743 | -0.04896 |
| *Bythotrephes longimanus* (spiny water flea) | -0.03337 | -0.03669 |
| *Leptodora kindtii* (predatory water flea of the Leptodoridae family) | 0.3477 | -0.02859 |
| *Leptodiaptomus ashlandi* (calanoid copepod) | 0.3405 | -0.01479 |
| *Platyias patulus* (rotifer) | -0.3799 | -0.01461 |
| *Asplanchna sp*.(rotifer) | -0.4981 | 0.01023 |
| *Lecane sp*. (rotifer) | -0.2342 | 0.01208 |
| *Mesocyclops edax* (cyclopoid copepod) | 0.8107 | 0.0442 |
| *Leptodiaptomus sicilis* (calanoid copepod) | 0.2261 | 0.05313 |
| *Candona sp.* (ostrocod) | 0.5076 | 0.06411 |
| *Daphnia lumholtzii* (water flea, Daphniidae family) | -0.2272 | 0.07999 |
| *Tricocerca sp.* (rotifer) | -0.3236 | 0.09591 |

**Table A3 Continued**

| Species | Component 1 | Component 2 |
|---|---|---|
| *Latona setifera* (water flea, Sididae family) | 0.1294 | 0.1007 |
| *Epiphanes sp.* (rotifer) | -0.167 | 0.105 |
| *Daphnia magna* (water flea, Daphniidae family) | -0.159 | 0.113 |
| *Senecella calanoides* (calanoid copepod) | 0.1904 | 0.1313 |
| *Eucyclops agilis* (cyclopoid copepod) | -0.04174 | 0.1323 |
| *Keratella sp*. (Rotifer) | -0.7538 | 0.1693 |
| *Acanthocyclops vernalis* (Cyclopoid copepod) | 0.756 | 0.2009 |
| *Daphnia parrula* (small crustacean of the Daphniidae family) | -0.2124 | 0.261 |
| *Cephalodella sp.* (rotifer) | 0.09794 | 0.2626 |
| *Alona sp.* (water flea, Chydoridae family) | 0.4667 | 0.2935 |
| *Polyarthra sp.* (rotifer) | -0.1662 | 0.3713 |
| *Daphnia mendotae* (water flea, Daphniidae family) | 0.2834 | 0.3715 |
| *Euchlanis sp*. (rotifer) | -0.5128 | 0.4233 |
| *Daphnia longiremis* (water flea, Daphniidae family) | 0.1616 | 0.4332 |
| *Chydorus sp.* (water flea, Chydoridae family) | -0.5031 | 0.5039 |
| *Ceriodaphnia dubia* (water flea, Daphniidae family) | -0.3632 | 0.5609 |
| *Leptodiaptomus siciloides* (calanoid copepod) | 0.5558 | 0.5952 |
| *Daphnia pulicaria* (water flea, Daphniidae family) | 0.4009 | 0.6835 |

Appendix B
Spearman's Rank Correlation Table

**Table B1**: Spearman's Rank correlation of fish and invertebrate species of interest. A presence-absence matrix was used for fish and an abundance matrix was used for benthic invertebrates.

| | ***Palmacorixa sp.*** (water-boatman) | ***Physella sp.*** (left handed pond snail) | ***Ephemerella sp.*** (mayfly) | ***Echinogammarus ischnus*** (amphipod) | ***Gammarus sp.*** (amphipod) |
|---|---|---|---|---|---|
| ***Palmacorixa sp.*** (water boatman) | 0 | 1.54E-10 | 0.053368 | 0.2228 | 0.5105 |
| ***Physella sp.*** (left handed pond snail) | 0.78087 | 0 | 0.039038 | 0.16779 | 0.35674 |
| **Ephemerella sp.** (mayfly) | -0.28673 | -0.30538 | 0 | 0.33245 | 0.6199 |
| ***Echinogammarus ischnus*** (invasive amphipod) | -0.18327 | -0.20686 | 0.14615 | 0 | 0.17732 |
| ***Gammarus sp.*** (amphipod) | 0.099523 | 0.13905 | 0.075094 | -0.20241 | 0 |
| ***Monoporeia sp.*** (amphipod) | -0.1264 | -0.15921 | 0.36163 | 0.20428 | 0.34005 |
| ***Limnesia sp.*** (water mite) | 0.56233 | 0.31809 | -0.081717 | -0.14802 | -0.098058 |
| ***Ablabesmyia sp.*** (true fly) | 0.48305 | 0.46225 | -0.19439 | -0.09562 | -0.097733 |
| ***Orconectes rusticus*** (rusty crayfish) | 0.29231 | 0.25263 | -0.17103 | 0.12516 | -0.1646 |
| ***Neogobius melanostomus*** (Round goby) | 0.052468 | 0.096699 | 0.28465 | 0.12421 | -0.31524 |
| ***Notropis atherinoides*** (Emerald Shiner) | -0.13045 | -0.031887 | -0.12272 | 0.029257 | -0.34165 |
| ***Perca flavescens*** (Yellow perch) | 0.41425 | 0.4757 | -0.16451 | -0.18127 | 0.058419 |
| ***Lepomis gibbosus*** (Pumpkinseed) | -0.077355 | 7.54E-20 | 0.22569 | 0.027661 | 0.18555 |
| ***Lepomis macrochirus*** (Bluegill) | 0.17139 | 0.24267 | -0.14559 | -0.13348 | 0.010551 |
| ***Cyprinus carpio*** (Common carp) | -0.019256 | 0.063881 | -0.03358 | 0.054704 | -0.16396 |
| ***Lepomis cyanellus*** (Green sunfish) | -0.22046 | -0.24497 | -0.14556 | -0.099499 | 0.16402 |

**Table B1 Continued**

| ***Monoporeia sp.*** (amphipod) | ***Limnesia sp.*** (water mite) | ***Ablabesmyia sp.*** (true fly) | ***Orconectes rusticus*** (rusty crayfish) | ***Neogobius melanostomus*** (Round goby) | ***Notropis atherinoides*** (Emerald Shiner) |
|---|---|---|---|---|---|
| 0.40255 | 4.76E-05 | 0.00067321 | 0.048695 | 0.72912 | 0.38754 |
| 0.29056 | 0.031215 | 0.00122 | 0.090285 | 0.52263 | 0.83338 |
| 0.013533 | 0.58928 | 0.19549 | 0.25577 | 0.055196 | 0.41651 |
| 0.17326 | 0.32624 | 0.5273 | 0.40724 | 0.41082 | 0.84695 |
| 0.020764 | 0.51678 | 0.51817 | 0.27435 | 0.032847 | 0.020137 |
| 0 | 0.076158 | 0.18493 | 0.40255 | 0.068056 | 0.56551 |
| -0.26408 | 0 | 4.12E-08 | 0.42638 | 0.53128 | 0.084193 |
| -0.19898 | 0.70644 | 0 | 0.013721 | 0.98589 | 0.13978 |
| -0.1264 | 0.12016 | 0.36096 | 0 | 0.26696 | 0.39599 |
| -0.27142 | 0.094705 | 0.0026819 | -0.16712 | 0 | 0.0048694 |
| -0.086965 | -0.25739 | -0.2211 | 0.12816 | 0.40812 | 0 |
| -0.12229 | 0.027245 | 0.14814 | 0.36058 | 0.16564 | 0.21334 |
| 0.15685 | 0.096664 | 0.18888 | 0.077355 | -0.1257 | -0.27601 |
| 0.036294 | 0.19431 | 0.23167 | 0.29155 | -0.19275 | -0.035198 |
| -0.10987 | -0.17914 | -0.12697 | 0.37871 | 0.017202 | 0.21521 |
| -0.13409 | -0.1899 | -0.13884 | -0.012842 | -0.096621 | 0.064121 |

**Table B1 Continued**

| ***Perca flavescens*** (Yellow perch) | ***Lepomis gibbosus*** (Pumpkin-seed) | ***Lepomis macrochirus*** (Bluegill) | ***Cyprinus carpio*** (Common carp) | ***Lepomis cyanellus*** (Green sunfish) |
|---|---|---|---|---|
| 0.0042087 | 0.60937 | 0.25474 | 0.89892 | 0.14096 |
| 0.00083408 | 1 | 0.10416 | 0.67319 | 0.10083 |
| 0.2746 | 0.13153 | 0.33434 | 0.82467 | 0.33442 |
| 0.22797 | 0.85521 | 0.37651 | 0.71804 | 0.5106 |
| 0.69976 | 0.21698 | 0.94452 | 0.27623 | 0.27605 |
| 0.41814 | 0.29787 | 0.81075 | 0.46731 | 0.37431 |
| 0.85736 | 0.52278 | 0.19568 | 0.23358 | 0.20621 |
| 0.32585 | 0.2087 | 0.12134 | 0.40041 | 0.35747 |
| 0.013827 | 0.60937 | 0.049312 | 0.0094514 | 0.9325 |
| 0.27127 | 0.40519 | 0.19935 | 0.90966 | 0.52297 |
| 0.15457 | 0.063347 | 0.81636 | 0.1509 | 0.67203 |
| 0 | 0.48571 | 0.33154 | 0.042972 | 0.17311 |
| 0.1054 | 0 | 0.0057676 | 0.33383 | 0.028677 |
| 0.14643 | 0.40085 | 0 | 0.32392 | 0.84725 |
| 0.29977 | 0.14574 | 0.14872 | 0 | 0.035873 |
| 0.20435 | 0.32278 | -0.0292 | 0.31024 | 0 |

I Hereby Reaffirm the Lawrence University Honor Code

Emily Lynn Kiehnau