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Fish Assemblage Structure in Great Lakes Coastal Wetlands Over Ten Years

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FISH ASSEMBLAGE STRUCTURE IN GREAT LAKES COASTAL WETLANDS OVER TEN YEARS

Matthew Steven Silverhart

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Dedication

This thesis is dedicated to my mother, Cheryl Silverhart, and grandfather, Frank Hesselbart. The two of you have fostered my curiosity of the natural world since I was young. Without your support and the lessons you have taught me along the way, I would not be where I am or the person I am today.

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Abstract

Coastal wetlands in the Laurentian Great Lakes are important habitats for many fish species. The geographic scale of the watershed and the diversity of land uses in the region result in substantial environmental variation among coastal wetlands. During 2011-2020, annual surveys were conducted as part of the Great Lakes Coastal Wetland Monitoring Program (GLCWMP) to better understand the status and trends of coastal wetlands. Fish sampling consisted of fyke netting in monodominant vegetation zones. During this time, 1225 unique monodominant plant zones in coastal wetlands were sampled, resulting in 584,125 fishes captured that consisted of 113 different species. Yellow Perch (*Perca flavescens*) was the most abundant species collected (30.9% of the catch), and Bluegill/Pumpkinseed (*Lepomis macrochirus*/*Lepomis gibbosus*) were collected the most frequently (present in 68.4% of sampling events). The purpose of the study was to evaluate how fish assemblages in Great Lakes coastal wetlands are associated with Great Lake basin, monodominant vegetation type, hydrogeomorphic type, and sampling year. Fish characterized based on size in the field as young-of-year (YOY) comprised 69.7% of the total catch and 95.7% of the Yellow Perch collected, suggesting coastal wetlands may be important nursery habitats. I found that basin, hydrogeomorphic type, monodominant vegetation type, and sampling year influenced variation in fish assemblages with basin and monodominant vegetation type showing the strongest association with fish assemblages among the variables investigated. While significant patterns were identified, the variables evaluated explained small amounts of variation associated with fish assemblages in Great Lakes coastal wetlands. Fish assemblages in the oligotrophic Lakes Michigan, Huron, and Superior appeared more similar to each other than the more mesotrophic

Lakes Erie and Ontario. Yellow Perch was the strongest indicator of coastal wetland by basin, being most abundant in the catch of Lake Michigan and least abundant in the catch of Lake Erie. Fish assemblages were significantly associated with monodominant vegetation type, but the associations varied depending on basin. While fish assemblage structure in Great Lakes coastal wetlands have substantial amounts of variation, patterns were identified that further define how fish assemblages vary across the Great Lakes basin.

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Abbreviations

ANOVA: Analysis of Variance

cm: Centimeters

CPUE: Catch Per Unit Effort

DB: Dense Bulrush (*Schoenoplectus* spp.)

DRM: Drowned River Mouth

e.g.: *Exempli Gratia*

EPA: Environmental Protection Agency

GLCWMP: Great Lakes Coastal Wetland Monitoring Program

ha: Hectares

IBI: Index of Biotic Integrity

LE: Lake Erie

LH: Lake Huron

LM: Lake Michigan

LO: Lake Ontario

LS: Lake Superior

Li: Lily (*Brasenia* spp., *Nuphar* spp., and *Nymphaea* spp.)

m: Meters

mASL: Meters Above Sea Level

mm: Millimeters

MS-222: Tricaine Mesylate

NMDS: Non-metric Multidimensional Scaling

PERMANOVA: Permutational Multivariate Analysis of Variance

Ph: *Phragmites* (*Phragmites* spp.)

PP: *Peltandra*/*Pontedaria* (*Peltandra* spp. and *Pontedaria* spp.)

SAV: Submerged Aquatic Vegetation (primarily *Ceratophyllum* spp., *Chara* spp., *Myriophyllum* spp., and *Najas* spp.)

SE: Standard Error

SB: Sparse Bulrush (*Schoenoplectus* spp.)

SimPer: Similarity Percentages

Sp: *Sparganium* (*Sparganium* spp.)

Ty: *Typha* (*Typha* spp.)

USA: United States of America

WM: Wet Meadow (primarily *Juncus* spp. and *Eleocharis* spp.)

WR: Wild Rice (*Zizania* spp.)

YOY: Young-of-Year

Chapter 1: Introduction

1.1 Introduction

The Great Lakes region is a nexus of aquatic life and a source of both commercial and recreational income for the local economies that surround it (Melstrom & Lupi, 2013; Mitsch & Gosselink, 2000). Coastal wetlands are nearshore habitats that are seasonally or permanently inundated with water and have obligate wetland vegetation (Albert *et al.*, 2005; Snell, 1987; Uzarski *et al.*, 2017). Obligate wetland vegetation can be described as any vegetation that occurs almost exclusively in wetlands (*Phragmites* spp.*,* *Typha* spp.*,* *Nuphar* spp.*,* etc.). The biotic and abiotic characteristics of these wetlands allow them to support the diverse fishery within the Great Lakes as well as performing crucial ecosystem services (Albert *et al.*, 2005; Clapp & Dettmers, 2004; Jude & Pappas, 1992; Keough *et al.*, 1999; Sierszen *et al.*, 2012). Various species of fish use coastal wetland habitat as a source of refuge in various life stages, as well as serving as spawning grounds (Jude & Pappas, 1992; Trebitz *et al.*, 2009b; Uzarski *et al.*, 2005). Coastal wetlands serve as a dynamic interface between the terrestrial and aquatic ecosystems, protecting the shoreline from erosion and preventing sediment and pollutants from entering waterways (Sierszen *et al.*, 2012). These qualities of coastal wetlands, among others, impact the overall health of the Great Lakes ecosystem as well as local commercial and recreation fisheries (Melstrom & Lupi, 2013; Trebitz *et al.*, 2009b, 2011; Uzarski *et al.*, 2005).

Despite their importance, coastal wetlands in the Great Lakes basin have historically been undervalued and understudied. Human interference has resulted in the degradation of these habitats through activities such as shoreline modification, wetland draining, and vegetation removal (Brazner, 1997; Brazner *et al.*, 2007; Trebitz *et al.*, 2007). Less than 50% of coastal wetland habitat originally found within the Great Lakes region remains (Maynard *et al.*, 1996; Trebitz *et al.*, 2007). The wetlands that remain are often degraded, which has allowed for non-native species to outcompete original resident species that once were plentiful (Brazner, 1997; Brazner *et al.*, 2007).

1.2 Purpose

The intention of this study was to better understand spatial patterns of fish assemblages in Great Lakes coastal wetlands. More specifically, how they are associated with various biotic and abiotic factors. The factors being studied are Great Lakes basin, monodominant vegetation type, hydrogeomorphic type, and sampling year. This study uses data collected through the Environmental Protection Agency's (EPA) Great Lakes Coastal Wetland Monitoring Program (GLCWMP), which has compiled a spatially extensive dataset on fish assemblages in Great Lakes coastal wetlands.

1.3 Scope

Coastal wetlands as part of this sampling effort are defined as being larger than 4 ha, having a direct connection to one of the Great Lakes (either permanent or seasonal), have monodominant wetland vegetation (>70% coverage of a single vegetation type), and being influenced by Great Lakes hydrologic fluctuations. The data used was collected between 2011 and 2020, spanning the extent of the Great Lakes basin (excluding the St. Lawrence River). This is an ongoing effort to monitor the long-term status and trends of Great Lakes coastal wetlands.

1.4 Assumptions

This research is based on four main components. First, the sampling locations selected by the GLCWMP represent the condition of coastal wetlands within the Great Lakes basin. Second, fyke-net sampling accurately represents the fish assemblage in coastal wetlands. Third, setting fyke nets for approximately 1 day represents the overall fish assemblage in a coastal wetland during that period of time. Fourth, all sampling crews that contributed data to the GLCWMP followed the standard operating procedures.

1.5 Hypotheses

The current literature regarding the Great Lakes suggests there will be expected associations between fish assemblages and each variable of interest in this study. There have been numerous studies that support an expected result of greater variation in fish assemblages as the spatial extent increases (Janetski & Ruetz, 2015; Langer *et al.*, 2016; Trebitz *et al.*, 2009a, 2009b). Fish assemblages have been shown to respond to the biotic environment, which includes the vegetation which they reside in (Brazner *et al.*, 2007; Midwood & Chow-Fraser, 2012; Schrank & Lishawa, 2019). With this in mind, I expected to find significant differences in fish assemblages between different monodominant vegetation types (Brazner, 1997; Midwood & Chow-Fraser, 2012; Schrank & Lishawa, 2019). The changing abiotic conditions of the Great Lakes impact the habitat conditions, which have been shown to influence fish assemblages (Burgmer *et al.*, 2007; Fracz & Chow-Fraser, 2013; Langer *et al.*, 2018). These changes include, but are not limited to, variation in Great Lakes water levels, which would suggest a significant variation in fish assemblages over the temporal scale of this study (Burgmer *et al.*, 2007; Fracz & Chow-Fraser, 2013; Langer *et al.*, 2018). Not all abiotic characteristics of coastal wetlands change regularly, for example, the hydrogeomorphic type of the wetland (Albert *et al.*, 2005). The differences between the hydrogeomorphic types (dominant hydrologic source and hydrologic connectivity to the lake which influence water quality parameters) lead to an expected variation in fish assemblages when compared between each other. Lastly, coastal wetlands have been shown to be important nursery habitat for fish, which suggests that a large quantity of the fish collected throughout this study will be young-of-year (YOY) (Jude & Pappas, 1992; Uzarski *et al.*, 2005).

1.6 Significance

One of the greatest strengths of this research is the expansive spatial and temporal extent of the data collected. Sampling occurred across the entire Great Lakes basin (excluding the St. Lawrence River) from Lake Superior to Lake Ontario in both the USA and Canada. The dataset spans a decade of fish assemblages from 2011 to 2020. Conclusions from this study should be broadly applicable to the basin.

1.7 Definitions

ANOVA: Analysis of variance.

CPUE: Catch per unit effort.

EPA: United States Environmental Protection Agency.

GLCWMP: Great Lakes Coastal Wetland Monitoring Program.

NMDS: Non-metric multidimensional scaling.

PERMANOVA: Permutational multivariate analysis of variance.

Post-hoc: Analysis conducted on initial statistical test results.

R^2: Proportion of variation explained.

SimPer: Similarity percentages test.

YOY: Young-of-year.

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Chapter 2: Fish Assemblage Structure in Great Lakes Coastal Wetlands

2.1 Abstract

Coastal wetlands in the Laurentian Great Lakes are important habitats for many fish species. The geographic scale of the watershed and the diversity of land uses in the region result in substantial environmental variation among coastal wetlands. During 2011-2020, annual surveys were conducted as part of the Great Lakes Coastal Wetland Monitoring Program (GLCWMP) to better understand the status and trends of coastal wetlands. Fish sampling consisted of fyke netting in monodominant vegetation zones. During this time, 1225 unique monodominant plant zones in coastal wetlands were sampled, resulting in 584,125 fishes captured that consisted of 113 different species. Yellow Perch (*Perca flavescens*) was the most abundant species collected (30.9% of the catch), and Bluegill/Pumpkinseed (*Lepomis macrochirus*/*Lepomis gibbosus*) were collected the most frequently (present in 68.4% of sampling events). The purpose of the study was to evaluate how fish assemblages in Great Lakes coastal wetlands are associated with Great Lake basin, monodominant vegetation type, hydrogeomorphic type, and sampling year. Fish characterized based on size in the field as young-of-year (YOY) comprised 69.7% of the total catch and 95.7% of the Yellow Perch collected, suggesting coastal wetlands may be important nursery habitats. I found that basin, hydrogeomorphic type, monodominant vegetation type, and sampling year influenced variation in fish assemblages with basin and monodominant vegetation type showing the strongest association with fish assemblages among the variables investigated. While significant patterns were identified, the variables evaluated explained small amounts of variation associated with fish assemblages in Great Lakes coastal wetlands. Fish assemblages in the oligotrophic Lakes

Michigan, Huron, and Superior appeared more similar to each other than the more mesotrophic Lakes Erie and Ontario. Yellow Perch was the strongest indicator of coastal wetland by basin, being most abundant in the catch of Lake Michigan and least abundant in the catch of Lake Erie. Fish assemblages were significantly associated with monodominant vegetation type, but the associations varied depending on basin. While fish assemblage structure in Great Lakes coastal wetlands have substantial amounts of variation, patterns were identified that further define how fish assemblages vary across the Great Lakes basin.

Keywords: Laurentian Great Lakes, Coastal Wetlands, Fish Assemblages, Nonmetric Multi-Dimensional Scaling (NMDS)

2.2 Introduction

The Laurentian Great Lakes basin holds a majority of the surface freshwater in North America and provides both environmental and economic services (Melstrom & Lupi, 2013; Sierszen *et al.*, 2012; Wolf *et al.*, 2017). Coastal wetlands provide many important ecosystem services in the Great Lakes (Jude & Pappas, 1992; Schoen *et al.*, 2016; Sierszen *et al.*, 2012, 2019; Snell, 1987; Uzarski *et al.*, 2005). Coastal wetlands serve as an interface between the often-impaired shoreline and the open lake as well as habitat and refuge for aquatic species (Jude & Pappas, 1992; Schoen *et al.*, 2016; Sierszen *et al.*, 2012, 2019; Uzarski *et al.*, 2005). Many of these aquatic species contribute to the recreational fishing industry, which is economically important for communities surrounding the Great Lakes (Jude & Pappas, 1992; Melstrom & Lupi, 2013; Wolf *et al.*, 2017). Despite their importance environmentally and economically, coastal wetlands in the Great Lakes basin have experienced decades of degradation and destruction resulting in substantial losses of this resource (Brazner, 1997; Jude & Pappas, 1992;

Snell, 1987; Trebitz *et al.*, 2009a). Much of the destruction and degradation of coastal wetlands was associated with increased agricultural development and urbanization taking place within the Great Lakes basin (Seilheimer *et al.*, 2009; Trebitz *et al.*, 2009a). There has been an estimated loss of more than 50% of coastal wetlands that were once present in the Great Lakes basin (Maynard *et al.*, 1996). A further understanding of how fish assemblages are spatially structured in Great Lakes coastal wetlands and what is influencing those dynamics is needed to inform management of these critical ecosystems going forward. The Great Lakes Coastal Wetland Monitoring Program (GLCWMP) was established to evaluate the health of coastal wetlands across the Laurentian Great Lakes basin and collect long-term monitoring data (Uzarski *et al.*, 2017, 2019).

Using observations on fish assemblages collected as part of the GLCWMP, Cooper *et al.* (2018) created indices of biotic integrity (IBIs) to evaluate the ecological health of coastal wetlands. Vegetation composition and diversity found in coastal wetlands of the Great Lakes impact fish assemblages (Midwood & Chow-Fraser, 2012; Schrank & Lishawa, 2019; Uzarski *et al*., 2005). Schrank & Lishawa (2019) showed a correlation between fish communities and vegetation present within a wetland by evaluating how invasive *Typha* spp. monodominance resulted in lowered fish community diversity and abundance. Anthropogenic stressors cause changes in vegetation and fish communities present in Great Lakes coastal wetlands (Jacobus & Ivan, 2005; Kovalenko *et al*., 2018; Langer *et al*., 2018; Seilheimer *et al*., 2009; Trebitz *et al*., 2007a, 2009a). The continued degradation of wetlands in the Great Lakes basin leads to lowered diversity in both fish and vegetation communities, resulting in dominance by tolerant species (Schrank & Lishawa, 2019; Trebitz *et al*., 2007a, 2009a; Uzarski *et al*., 2005). Fish assemblages respond to various biotic and abiotic influences, many of which also shape the wetlands in which fish reside. These complex relationships show the importance of understanding how fish assemblages change across the Great Lakes basin.

Seasonal water-level changes impact fish assemblages due in part to its influence on habitat quality and abundance (Fracz & Chow-Fraser, 2013; Langer *et al.*, 2018; Midwood & Chow-Fraser, 2012). Great Lakes water-level changes can also be experienced over a larger time scale, stretching over decades, leading to large scale shifts in coastal wetlands and the fish assemblages that inhabit them (Angel & Kunkel, 2010; Fracz & Chow-Fraser, 2013; Gronewold *et al.*, 2013; Langer *et al.*, 2018; Midwood & Chow-Fraser, 2012; Quinn, 2002). Human interaction with the Great Lakes ecosystem has also changed over time, whether that be destruction of wetlands or from legislation intended to protect the diminishing habitats (Brazner, 1997; Seilheimer *et al.*, 2009; Snell, 1987; Trebitz *et al.*, 2009a). The continued degradation of Great Lakes coastal wetlands is impacted by the introduction and continued spread of invasive species (Lawrence *et al.*, 2016; Schrank & Lishawa, 2019; Zedler & Kercher, 2004). These invasive species, both flora and fauna, can push out native species and alter the communities present (Lawrence *et al.*, 2016; Schrank & Lishawa, 2019; Zedler & Kercher, 2004). Over time, the abiotic and biotic conditions within and surrounding Great Lakes coastal wetlands are changing, which can impact the fish assemblages that inhabit them (Trebitz *et al.*, 2007b, 2009a).

Great Lakes coastal wetlands can be described as one of three broad hydrogeomorphic types: lacustrine, riverine, and barrier-protected (barrier) (Albert *et al.*, 2005). These hydrogeomorphic types differ in their makeup and have unique ecosystem qualities that further differentiate coastal wetlands from those of different hydrogeomorphic types (Albert *et al.*, 2005; Keough *et al.*, 1999). Many of the riverine coastal wetlands are located within drowned river mouth (DRM) ecosystems, which are protected from the main lake system and are home to diverse fish communities (Janetski & Ruetz, 2015). Lacustrine wetlands are open to the main lake and subject to wave action that occurs in these less protected areas (Albert *et al.*, 2005; Keough *et al.*, 1999). Barrier wetlands are protected from direct wave action associated with the main lake, much like the riverine wetlands, but are not subject to the turbid effluent that riverine wetlands may experience, leading to a potential for less tolerant species to inhabit them (Albert *et al.*, 2005; Keough *et al.*, 1999; Trebitz *et al.*, 2007a). These differences can drive changes between coastal wetlands and fish communities present, but there also should be consideration given to how each of the Great Lake's basins differ from one another. Species pools differ among the Great Lakes, which would suggest it would affect fish assemblage structure in different coastal wetlands (Janetski & Ruetz, 2015).

Due to the large spatial extent of the Great Lakes basin, there is variation in land use among the watershed and the geomorphic structure of the lakes. The southern extent of the basin is dominated by agricultural land use that leads to excess nutrient loading and algal blooms (Kovalenko *et al.*, 2018; Mader *et al.*, 2023; Wolf *et al.*, 2017). Mean lake depth is a key factor in determining the trophic state of each basin; Lake Erie is shallow and warm in comparison to Lake Superior, which is deep and cold (Beeton, 1965). Land use and geomorphic changes explain why Lakes Erie and Ontario are more mesotrophic, while Lakes Michigan, Superior, and Huron are more oligotrophic (Beeton, 1965). These large-scale differences in shoreline use and geomorphology should affect fish community structure in coastal wetlands of the Great Lakes basin.

The aim of this research is to explore patterns of fish assemblages in Great Lakes coastal wetlands. More specifically, how is fish assemblage composition in Great Lakes coastal wetlands associated with basin, wetland hydrogeomorphic type, vegetation zone, and sampling year. Thus, the overarching question is: how are fish communities in Great Lakes coastal wetlands influenced by environmental factors? Better understanding of how basin, wetland hydrogeomorphic types, monodominant plant types, and sampling years influence fish community structure can lead to more effective management and protection of these habitats and the Great Lakes fishery as a whole.

2.3 Methods

2.3.1 *Site Selection*

The experimental design and sampling methods are described in detail in Uzarski *et al.,* (2017) and Cooper *et al.,* (2018) and will be summarized here. The Great Lakes Coastal Wetland Consortium used arial imagery to identify possible wetland sites along the Great Lakes coastline (Albert *et al.,* 2005). These sites were used to create criteria to determine which wetlands to sample. For a site to be included, it needed to be 4 ha or larger in size, have a direct connection to the Great Lakes (allowing fish passage at least once a year), be influenced by changing Great Lakes water levels (whether through seasonal water-level changes or seiches), and contain wetland vegetation zones. With these criteria in mind and after site visits, the list of possible sites was refined to 1014 coastal wetland sites covering ~140,376 ha.

After the sites were selected, they were put into a stratified-random selection and assigned to one of five panels. The panels were sampled on a rotating annual basis, ensuring that each major coastal wetland in the Great Lakes basin could be sampled at least once every five years. Over the 10 years of this analysis, an average (± SE) of 81.8 ± 2.89 unique coastal wetlands across the Great Lakes basin were sampled per year. The variation in samplings per year is due to inability to sample assigned sites due to extreme water levels, absence of wetland vegetation, and access issues among other reasons.

The sampling conducted as part of this long-term monitoring project began in 2011 and has continued since. In this study, the focus will be on the first 10 years of sampling (2011-2020). During that period, 498 unique coastal wetland sites were sampled for fish across a total of 1225 sampling events (Figure 1, Table 1). Each sampling event represented three fyke nets set in a monodominant vegetation zone within a site, meaning that a site can be sampled multiple times across the project depending on the number of monodominant vegetation zones present at a site in a given year and whether the site was able to be sampled in the year it was designated for sampling.

2.3.2 *Sample Collection*

Sampling took place annually between mid-June and early-September starting in 2011. Sites located farther south would be sampled first, moving north to follow seasonal wetland vegetation community development. To be sampled for fish, the wetland needed to have at least one monodominant vegetation zone (≥75% emergent or floating leaf-type vegetation coverage from aerial view) that was greater than 400 m^2 in size if contiguous or with a minimum patch size of 100 m^2 and summing to greater than 400 m^2 if in patches. Up to three monodominant vegetation zones were sampled for fish at each site. If there were more monodominant vegetation zones than could be reasonably sampled in a day, then the largest and most representative vegetation zones were the ones sampled.

Three fyke nets were set in each monodominant vegetation zone to sample fish in water depths between 11 cm and 150 cm. Small fyke nets were typically used for water depths between

10 cm and 50 cm, while large fyke nets were used for depths greater than 50 cm. Any combination of small and large fyke nets were used as needed to achieve three fyke nets set in the zone. The fyke nets (large / small) used for sampling consisted of a 4.76-mm mesh lead (7.62 m x 0.91 m / 7.62 m x 0.46 m) with floats on top and a weighted line on the bottom. The lead was attached to a fyke trap with 4.76-mm mesh consisting of two frames (1.2 m x 0.91 m / 0.91 m x 0.46 m) separated apart (0.91 m / 0.46 m), followed behind (0.91 m / 0.46 m) by five hoops (0.76 m / 0.3 m diameter) separated apart (0.46 m / 0.3 m) with funnels (16.51 cm / 10.16 cm funnel hole inside diameter) on the first and third hoops. Two wings (1.82 m x 0.91 m / 1.82 m x 0.46 m) were attached to the first frame.

Fyke nets were set a minimum of ~20 m and a maximum of ~250 m from the nearest fyke net in a monodominant vegetation zone. To obtain better representation of the fish assemblage within the monodominant vegetation zone, the three fyke nets were set in locations that represented the variability within the vegetation zone. If a particular monodominant vegetation zone had surrounding shoreline of vegetated, rip rap, and beach, the three fyke nets would be placed near each of these shoreline types rather than all placed near only one of the shoreline types. This was to obtain a more accurate representation of the fish community present within that monodominant vegetation zone. Each fyke net was set with the lead extending into the monodominant vegetation. The two wings were set at a 45-degree angle extending from the mouth of the frame into the vegetation. The mouth of the frame was set inside of or directly against the edge of the monodominant vegetation zone to target fish that use the vegetation zone rather than swimming along the edge of the zone.

The nets were left overnight (12-36 hours) for an average (± SE) of 20.99 ± 2.83 hours to passively sample the fish in the monodominant vegetation zone. On the following day, the nets were typically removed from the wetland in the order they were set. Fish were identified to species and released near the point of capture. However, some individuals were humanely euthanized by immersion in a lethal dose of anesthetic (typically MS-222) when required by government agencies or to confirm identification of small or difficult to identify species.

If a fyke net did not fish properly (e.g., holes in the net or water level dropping below internal funnels), then catch was not recorded. If two of three fyke nets in a vegetation zone did not fish properly or the total fish catch in the three fyke nets was less than 10, then no observations of catch were recorded and all three fyke nets were reset. Fish were determined to be YOY in the field based on size and species. The 10 monodominant vegetation types sampled included Dense Bulrush (*Schoenoplectus* spp.), Lily (*Brasenia* spp., *Nuphar* spp., and *Nymphaea* spp.), Peltandra/Pontedaria (*Peltandra* spp. and *Pontedaria* spp.), Phragmites (*Phragmites* spp.), submerged aquatic vegetation (SAV; primarily *Ceratophyllum* spp., *Chara* spp., *Myriophyllum* spp., and *Najas* spp.), Sparganium (*Sparganium* spp.), Sparse Bulrush (*Schoenoplectus* spp.), Typha (*Typha* spp.), wet meadow (primarily *Juncus* spp. and *Eleocharis* spp.), and Wild Rice (*Zizania* spp.).

2.3.3 *Statistical Analysis*

Statistical analysis was performed using the R programming language and computing environment, version 4.2.2 (R Core Team, 2022). The experimental unit for statistical analyses was the “sampling event,” which was a monodominant plant zone within a site. CPUE was reported as catch per three fyke nets, which accounted for rare occasions when only two nets successfully fished in a plan zone. Sites were often sampled more than once due to there being multiple types of monodominant plant zones within a site.

We used non-metric multidimensional scaling (NMDS) to investigate how four factors (one spatial, two habitat, and one temporal) explained variation in fish assemblages across Great Lakes coastal wetlands (Borcard *et al.*, 2018). The spatial variable evaluated was basin. The habitat variables evaluated were hydrogeomorphic type and monodominant vegetation type. The temporal variable was the sampling year in which the fish were collected. Post-hoc permutational multivariate analysis of variance (PERMANOVA) tests using distance matrices were then conducted on each of the groupings to determine whether there were significant differences ($p < 0.05$) between the groupings (Borcard *et al.*, 2018). If significant differences were found, then a pairwise comparisons for permutational multivariate analysis of variance (pairwise PERMANOVA) test using distance matrices was conducted to evaluate which groupings had significant differences ($p < 0.05$) in fish assemblage (Borcard *et al.*, 2018). A similarity percentages (SimPer) test was then used to identify which species were contributing most to the overall dissimilarity among fish assemblages in the groupings presented (Clarke & Green, 1988). If there were significant differences found between multiple of the aforementioned factors, then additional analysis was conducted by specific groupings (e.g., monodominant vegetation zones in each basin).

2.4 Results

A total of 113 species comprising 584,125 fishes were captured across 1,225 monodominant plant zones, representing 498 sites, between 2011 and 2020. There was an average (± SE) of 9.03 ± 0.11 species and 476.84 ± 51.87 individuals collected per sampling event. The species most frequently collected (percent of total catch) were Yellow Perch (*Perca flavescens*) (30.9%), Black or Brown Bullhead (*Ameiurus melas* / *Ameiurus natalis*) (13.2%), Mimic Shiner (*Notropis volucellus*) (11.1%), Bluegill or Pumpkinseed (*Lepomis macrochirus* / *Lepomis gibbosus*) (9.0%), and White Sucker (*Catostomus commersonii*) (5.0%) (Figure 2). These seven species account for 69.2% of the total catch across the entire Great Lakes basin. The species collected the most often (percent of sampling events) were Bluegill or Pumpkinseed (68.4%), Black or Brown Bullhead (63.3%), Yellow Perch (56.0%), Largemouth Bass (*Micropterus salmoides*) (50.6%), and Rock Bass (*Ambloplites rupestris*) (45.1%) (Figure 3). Fish classified as YOY comprised 64.7% of the total catch and 95.6% of the Yellow Perch catch.

Based on NMDS analysis and the following post-hoc PERMANOVA tests, there was evidence that basin (Figure 4), monodominant vegetation type (Figure 5), hydrogeomorphic type (Figure 6), and sampling year (Figure 7) were significantly ($p < 0.001$) associated with fish assemblages, although the strength of those associations varied among the four factors. For these analyses, R^2 represents the proportion of variation in fish assemblages that was explained by the variable being examined (Borcard *et al.*, 2018; Clarke & Green, 1988). Based on the post-hoc PERMANOVA analysis, basin ($R^2 = 0.0495$, $p < 0.001$) had the largest influence on fish assemblages followed by monodominant vegetation type ($R^2 = 0.03819$, $p < 0.001$), hydrogeomorphic type ($R^2 = 0.00532$, $p < 0.001$), and sampling year ($R^2 = 0.00344$, $p < 0.001$). These results suggest that there were significant ($p < 0.05$) associations between fish assemblages and all variables evaluated, but they explained a small proportion of the variation in fish assemblages.

Post-hoc pairwise PERMANOVA tests of fish assemblages evaluated by basin showed significant differences between all basins ($p < 0.05$; Table 2). The farther a basin was from another within the watershed in terms of connectivity, the greater the dissimilarity in fish assemblages (Table 2), which was also visible in Figure 4. Lake Ontario and Lake Superior showed the greatest dissimilarity ($R^2 = 0.06434$, $p < 0.05$) in fish assemblages (Table 2). The basins with the most similar fish assemblages ($R^2 = 0.01194$, $p < 0.05$) were Lake Huron and Lake Michigan, which exhibited the greatest connectivity of all basins, being separated only by the Straits of Mackinac (Figure 1). Thus, there were significant but weak patterns in fish assemblages among Great Lakes basin (Figure 4, Table 2).

Post-hoc pairwise PERMANOVA tests of fish assemblages evaluated by monodominant vegetation type showed significant differences ($p < 0.05$) between various vegetation types (Table 3). Fish assemblages associated with *Phragmites*, SAV, *Sparganium*, Sparse Bulrush, and Wet Meadow monodominant vegetation types were observed to be significantly different ($p < 0.05$) from all other monodominant vegetation types (Table 3). *Typha* associated fish assemblages were significantly different ($p < 0.05$) from fish assemblages associated with all monodominant vegetation types except for *Peltandra*/*Pontedaria* (Table 3). Fish assemblages associated with Wild Rice, Lily, and *Peltandra*/*Pontedaria* monodominant vegetation were not significantly different ($p > 0.05$) from one another (Table 3). The most variation explained between two monodominant vegetation types was $R^2 = 0.08492$ ($p < 0.05$) between Wild Rice and *Sparganium*. While significant differences ($p < 0.05$) were reported for 75.93% of the comparisons between fish assemblages grouped by monodominant vegetation type, the average (± SE) variation explained by associations with monodominant vegetation type was $R^2 = 0.02059$ (± 0.01428), showing the pattern was weak. There was no recognizable pattern that suggested fish assemblages associated with emergent monodominant vegetation (*Typha*, *Phragmites*, Bulrush) were significantly different ($p < 0.05$) from fish assemblages associated with non-emergent monodominant vegetation (SAV and Lily) any more than they were from other emergent monodominant vegetation types. Fish assemblages associated with emergent monodominant vegetation (*Typha*, *Phragmites*, Bulrush) were no more different from fish assemblages associated with non-emergent monodominant vegetation (SAV and Lily) than they were from themselves.

The post-hoc pairwise PERMANOVA tests conducted on the groupings based by hydrogeomorphic type showed that fish assemblages within lacustrine wetlands were significantly different ($p < 0.05$) than fish assemblages in riverine ($R^2 = 0.00461$) and barrier ($R^2 = 0.00290$) wetlands (Table 4). Fish assemblages in riverine and barrier wetlands were not observed to have significant differences ($p > 0.05$; Table 4). Although significant differences ($p < 0.05$) were reported between lacustrine fish assemblages and riverine / barrier fish assemblages, the association between fish assemblage and hydrogeomorphic type were weak, meaning R^2 was small (Table 4).

Sampling year was the variable least associated ($R^2 = 0.00344$) with fish assemblages, although still significant ($p < 0.05$; Figure 7). Post-hoc pairwise PERMANOVA results showed that 82.22% of the comparisons between fish assemblages and their sampling year were significantly different (Table 5). The average (± SE) variation in fish assemblages explained by sampling year was small with $R^2 = 0.01044$ (± 0.00046), indicating significant differences when grouped by year, but minor variation explained (Table 5). Fish assemblages sampled in 2012 and 2017 were significantly different ($p < 0.05$) than fish assemblages from the other sampling years (Table 5). While significant ($p < 0.05$) associations were found many sampling years, the most variation explained was $R^2 = 0.01738$, indicating weak patterns (Table 5). There was no recognizable pattern between fish assemblages in wet years (2016-2020) versus dry years (2011-2015).

Fish assemblages were then split into their respective basins and analyzed based on monodominant vegetation types (the second most associated variable with fish assemblages). NMDS plots from Lakes Erie (Figure 8), Huron (Figure 9), Michigan (Figure 10), Ontario (Figure 11), and Superior (Figure 12) showed visual groupings and differences between fish assemblages when grouped by monodominant vegetation type. The following post-hoc PERMANOVA analyses showed that Lake Erie ($R^2 = 0.02595$), Huron ($R^2 = 0.04102$), Michigan ($R^2 = 0.05779$), Ontario ($R^2 = 0.0501$), and Superior ($R^2 = 0.07889$) had significant differences ($p < 0.001$) between fish assemblages when analyzed by monodominant vegetation types in each basin (Figures 8-12).

Post-hoc pairwise PERMANOVA tests showed that patterns in fish assemblages based on monodominant vegetation type changed depending on the basin they were present in (Tables 6-10). In Lake Huron, fish assemblages associated with Wet Meadow and *Phragmites* monodominant vegetation were significantly different ($p < 0.05$) from fish assemblages associated with all other monodominant vegetation types (Table 7). The only other similar case was in Lake Erie where fish assemblages in SAV monodominant wetlands were significantly different ($p < 0.05$) from fish assemblages associated with all other monodominant vegetation types (Table 6). Fish assemblages associated with Wet Meadow monodominant vegetation were consistently different ($p < 0.05$) from fish assemblages associated with other monodominant vegetation types, showing significant ($p < 0.05$) differences 84.21% of the time (Tables 7-8, 10). There was no recognizable pattern in fish assemblage association with emergent versus non-emergent monodominant vegetation types. While significant ($p < 0.05$), fish assemblage association with monodominant vegetation type explained a small proportion of variation through all basins.

Fish assemblages were then split into their respective basins and analyzed based on sampling year (because of different patterns in water-level fluctuations among basins). NMDS plots and post-hoc PERMANOVA analysis for Lakes Erie (Figure 13), Huron (Figure 14), Michigan (Figure 15), and Ontario (Figure 16) showed possible associations between fish assemblages and sampling year. The post-hoc PERMANOVA analyses showed that Lake Erie ($R^2 = 0.02399$), Huron ($R^2 = 0.00884$), Michigan ($R^2 = 0.00835$), and Ontario ($R^2 = 0.01098$) had significant differences ($p < 0.05$) between fish assemblages when analyzed by monodominant vegetation types in each basin (Figures 8-12). The NMDS plot and post-hoc PERMANOVA analysis showed that sampling year in Lake Superior was not associated with differences in fish assemblages (Figure 17).

Post-hoc pairwise PERMANOVA tests showed that patterns in fish assemblages based on sampling year were not consistent depending on the basin (Tables 11-14). Lake Erie fish assemblages sampled in 2011 and 2014 were significantly different ($p < 0.05$) from fish assemblages sampled in all other years from Lake Erie (Table 11). Much like the other differences, the variation explained by sampling year was relatively low across all basins. The most variation explained by sampling year was in Lake Erie ($R^2 = 0.02399$; Figure 13) and the least variation explained by sampling year was in Lake Superior ($p > 0.05$; Figure 17).

Due to all basins showing significant difference from one another ($p < 0.001$), a SimPer test was performed to determine which species were driving dissimilarity in fish assemblages between basins (Table 15). Yellow perch, Bluegill or Pumpkinseed, and Black Bullhead or Brown Bullhead were among the top five contributors to the dissimilarities in fish assemblages between each basin (Table 15). The largest dissimilarity was shown when comparing Yellow Perch catch in Lake Michigan to the other basins (Table 15). Yellow Perch was the species most associated with fish assemblage differentiation throughout the Great Lakes basin with Bluegill or Pumpkinseed and Black or Brown Bullhead also having strong association (Table 15).

2.5 Discussion

This study showed that fish assemblages in Great Lakes coastal wetlands were most associated with basin and monodominant vegetation type among the four factors assessed. When evaluated by basin, the patterns of fish assemblage association with monodominant vegetation types changed depending on the basin in question. Hydrogeomorphic type and sampling year had smaller association with fish assemblages than hypothesized. A majority (~70%) of fish captured in Great Lakes coastal wetlands were comprised of seven species (Yellow Perch, Black or Brown Bullhead, Mimic Shiner, Bluegill or Pumpkinseed, and White Sucker). Yellow Perch inhabited Great Lakes coastal wetlands more than any other species collected during sampling. There was heavy use from YOY fish of Great Lakes coastal wetlands, especially by Yellow Perch.

The spatial variation of fish assemblages observed between basins supports overarching concepts that much of the literature regarding fish assemblages relies upon (Janetski & Ruetz, 2015; Langer *et al.*, 2016; Trebitz *et al.*, 2009a, 2009b). As the biotic and abiotic characteristics and stressors of each basin shift from one into the other, fish assemblages are expected to respond to those changes, resulting in differing fish assemblages across the lakescape (Janetski & Ruetz, 2015; Langer *et al.*, 2016; Trebitz *et al.*, 2009a, 2009b). While this alone is not a new concept, it is important to recognize that the results of this study suggest that coastal wetland fish assemblages were responding to factors on a geographic scale. An observation that should be noted from this study is that greater variation between fish assemblages occurred between basins that were farther apart in terms of connectedness. For example, Lake Superior fish assemblages were more similar to Lake Huron fish assemblages than they were to those found in Lake Ontario (Figure 4, Table 2). Future research should focus on further investigating patterns in fish assemblages within each basin by breaking them down into different regions. Saginaw Bay, located in Lake Huron, is relatively shallow and flat in comparison to most of Lake Huron. Based on the patterns observed in fish assemblages across the basin, one might expect to find that fish assemblages in Saginaw Bay are different than those in the rest of Lake Huron and more similar to those found in Lake Erie, which is similarly shallow and flat. This approach could be used to investigate the other basins on a similar scale.

While the strong association between fish assemblages and monodominant vegetation type was expected based on current literature (Schrank & Lishawa, 2019; Trebitz *et al.*, 2007b, 2009b), the patterns observed were an interesting development. Conventional thought would suggest that emergent vegetation species would be more similar to one another, but in this case *Typha* and *Phragmites* were more strongly associated with Lily and SAV than they were with Sparse and Dense Bulrush (Figure 5, Table 3). This could be a result of the lack of density found in Bulrush monodominant zones, both dense and sparse, in comparison to that found in *Phragmites* and *Typha*. The lack of density may allow for easier movement within the monodominant vegetation type as well as more influence from the surrounding open water system in terms of abiotic and biotic conditions. Wet Meadow was significantly different from all vegetation zones (Table 3). This was not surprising as the habitat created by a Wet Meadow tends to be shallower than is found in the other emergent and submergent vegetation types. These findings provide additional support to the concept that abiotic conditions which influence the presence and absence of vegetation are also driving fish assemblage differences both directly and indirectly (Midwood & Chow-Fraser, 2012; Trebitz *et al*., 2009a). While there were significant differences in fish assemblages among many of the monodominant vegetation types, the low amount of variation explained by monodominant vegetation type suggests that other factors not considered in this analysis may be more important.

Although association between fish assemblages and monodominant vegetation types was observed when evaluated by each basin, the patterns with which the associations existed changed by basin (Figures 8-12). For example, fish assemblages in Lily monodominant vegetation were significantly different from fish assemblages in *Typha* monodominant vegetation within Lake Michigan but not in any of the other lakes (Tables 6-10). This supports the previous conclusion from this study that basin was the factor most strongly associated with fish assemblages in Great Lakes coastal wetlands. There is ample evidence that supports the concept of fish assemblages responding to habitat factors on a large spatial scale, especially anthropogenic stressors such as pollution, shoreline structures, and land use in the watershed (Brazner, 1997; Trebitz *et al.*, 2007a, 2009a). Future research could focus on what exactly is driving the changes in fish assemblage association with monodominant vegetation type between basins as it seems fish assemblages may be responding to the difference in vegetation more in some basins than others.

Hydrogeomorphic type did not show strong association with fish assemblages in this study (Figure 6, Table 4). While a significant difference was found in fish assemblages between riverine and lacustrine wetlands, it only explained a small amount of the variation between fish assemblages (Table 4). A similar pattern was observed between barrier wetland fish assemblages and lacustrine fish assemblages where a significant difference ($p < 0.05$) was observed, but minor variation (0.0029) was explained, making it difficult to report a clear ecological pattern (Table 4). This observation is not consistent with the current literature as it would be expected that fish assemblages would change in response to the differing habitat conditions found in these hydrogeomorphic types (Albert *et al.*, 2005; Keough *et al.*, 1999; Trebitz *et al.*, 2007a). These hydrogeomorphic types are believed to have biotic communities that are significantly different from one another in response to their distinct ecosystem characteristics (Albert *et al.*, 2005; Keough *et al.*, 1999). One of the stronger limitations for fish in the Great Lakes basin is the level of turbidity present in a system (Trebitz *et al.*, 2007a). When describing a coastal wetland as riverine or lacustrine, one of the primary differentiating characteristics is the average level of turbidity found in riverine systems (higher) compared to lacustrine systems (lower) (Albert *et al.*, 2005; Keough *et al.*, 1999). A possible explanation for the low amount of variation explained by hydrogeomorphic type could be a correlation between basin and hydrogeomorphic type.

Results of the study suggested that while there were significant associations between fish assemblages and sampling year, the amount of variation explained by sampling year was minimal and no clear ecological patterns were identified between high (2016-2020) and low water (2011-2015) years (Figure 7, Table 5). Furthermore, when analysis was performed by sampling year in each basin (Figures 13-17), the amount of variation explained was even less and was not significant in Lake Superior (Figure 17). The lack of variance explained in fish assemblages between sampling years contradicted current literature regarding the topic (Fracz & Chow-Fraser, 2013; Langer *et al.*, 2018; Midwood & Chow-Fraser, 2012). The results of these studies suggested that fish assemblages responded to changing water levels, which occur on short and long temporal scales (Figure 18; Fracz & Chow-Fraser, 2013; Gronewold *et al.*, 2013; Langer *et al.*, 2018; Midwood & Chow-Fraser, 2012). A possible explanation for the lack of evidence supporting current literature regarding sampling year's effect on fish assemblages could be the shifting of monodominant vegetation. This study focused on sampling in monodominant vegetation zones, not pre-specified locations to be sampled regardless of the presence of a monodominant vegetation type. Coastal wetland vegetation has been shown to be influenced by Great Lakes water levels, going as far as to respond to water depth changes on seasonal and longer temporal scales by gradually moving to be in the optimal depth (Lemein *et al.*, 2017; Midwood & Chow-Fraser, 2012). As observed earlier in the study, fish assemblages exhibited stronger association with monodominant vegetation types (at least when compared to sampling year), and if they are shifting with water levels, it is possible that the fish assemblages are moving with them to “follow” their preferred monodominant vegetation type. Sampling year and the changing water levels associated with them may be influencing the location of monodominant vegetation zones within coastal wetlands, but the results of this study support the hypothesis that fish assemblages across the basin are not changing in response to them. The low amount of variation explained by this dataset suggests that a more sophisticated model and approach may be required to better understand how these variables influence community structure.

The seven most common species captured (percent of catch) during this sampling were Yellow Perch, Black or Brown Bullhead, Mimic Shiner, Bluegill or Pumpkinseed, and White Sucker, which accounted for nearly 70% of the total catch (Figure 2). These results, and those of other studies in Great Lakes coastal wetlands, show that these habitats are used by a diverse assemblage of fish species (Jude & Pappas, 1992; Trebitz *et al.*, 2009b; Uzarski *et al.*, 2005). Being the most collected species throughout this project, they were strongly associated with explaining variation in coastal wetland fish assemblages across basins, often explaining >50% of the variation exhibited with only those species (Table 15). These species comprising such a large quantity of the total catch also explains why there was a relatively high amount of overlap in all the NMDS plots (Figures 4-17) as fish assemblages often differed significantly, but were very often comprised of the same species, just in differing quantities (Table 15).

A high percentage of fish collected during the sampling were characterized as YOY (nearly 70% of the total catch), especially Yellow Perch (nearly 96% of the total catch of Yellow Perch). This supported research showing that Great Lakes coastal wetlands serve as an important nursery habitat for many fish species (Jude & Pappas, 1992; Sierszen *et al.*, 2012). If coastal wetlands in the Great Lakes basin continue to be degraded and destroyed as they have been historically, it could result in consequential losses to the overall fishery population as well as negative impacts on the communities which are supported by them.

In conclusion, fish assemblages in coastal wetlands vary significantly across the entire Great Lakes watershed. Basin explained the most variation in fish assemblages in Great Lakes coastal wetlands followed by monodominant vegetation type among the factors examined in this analysis. Coastal wetlands were used by YOY fish, suggesting coastal wetlands may be important nursery habitats. This study emphasized the need to protect and restore coastal wetlands in the Great Lakes as they have been shown to be important to communities within and surrounding them. To better protect and restore Great Lakes coastal wetlands, research needs to be conducted to further understand the fish assemblages using them and what is influencing them. Future research should be conducted to further dissect the Great Lakes basins into regions depending on different environmental characteristics and analyze how fish assemblages vary within basins.

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2.7 Figure Captions

Figure 1. Sampling sites from the Great Lakes Coastal Wetland Monitoring Program between 2011 and 2020 used for this project. Most of the sites were either lacustrine or riverine with barrier wetlands being the most infrequent. Imagery obtained from Google Earth.

Figure 2. The proportion of total catch the top twenty-five species contributed for 1225 sampling events between 2011 and 2020. Yellow Perch contributed to over 30% of the 584,125 fish collected in this study.

Figure 3. The twenty-five most frequent species occurring during the 1225 sampling events between 2011 and 2020. Bluegill or Pumpkinseed, Black or Brown Bullhead, Yellow Perch, and Largemouth Bass were all present in >50% of the sampling events.

Figure 4. NMDS ordination of fish assemblages throughout the Great Lakes basin organized by basin. Lakes Superior, Huron, and Michigan appear to have a cluster separate from Lakes Erie and Huron. This is supported by post-hoc PERMANOVA results in Table 2. Ellipses represent ± SE around the average fish assemblage. (LE = Lake Erie, LH = Lake Huron, LM = Lake Michigan, LO = Lake Ontario, LS = Lake Superior, dissimilarity index = Bray-Curtis, stress = 26.92, n = 1225)

Figure 5. NMDS ordination of fish assemblages throughout the Great Lakes basin organized by monodominant vegetation type. While groupings can be made out, post-hoc PERMANOVA test results (Table 3) suggest small amounts of variation in fish assemblages is explained by the groupings presented. Ellipses represent ± SE around the average fish assemblage. (DB = dense Bulrush, Li = Lily, PP = *Peltandra*/*Pontedaria*, Ph = *Phragmites*, SAV = submerged aquatic vegetation, Sp = *Sparganium*, SB = sparse Bulrush, Ty = *Typha*, WM = wet meadow, WR = wild rice, dissimilarity index = Bray-Curtis, stress = 26.91, n = 1225)

Figure 6. NMDS ordination of fish assemblages throughout the Great Lakes basin organized by hydrogeomorphic type. All hydrogeomorphic types have significant overlap with one another. Ellipses represent ± SE around the average fish assemblage. (B = barrier, L = lacustrine, R = riverine, dissimilarity index = Bray-Curtis, stress = 26.91, n = 1225)

Figure 7. NMDS ordination of fish assemblages throughout the Great Lakes basin organized by sampling year. There are no identifiable patterns that would express sampling year having influence on fish assemblages. Ellipses represent ± SE around the average fish assemblage. (Dissimilarity index = Bray-Curtis, stress = 26.91, n = 1225)

Figure 8. NMDS ordination of fish assemblages throughout the Lake Erie basin organized by monodominant vegetation type. Ellipses represent ± SE around the average fish assemblage. (DB = dense Bulrush, Li = Lily, PP = *Peltandra*/*Pontedaria*, Ph = *Phragmites*, SAV = submerged aquatic vegetation, Ty = *Typha*, dissimilarity index = Bray-Curtis, stress = 27.32, n = 154)

Figure 9. NMDS ordination of fish assemblages throughout the Lake Huron basin organized by monodominant vegetation type. Ellipses represent ± SE around the average fish assemblage. (DB = dense Bulrush, Li = Lily, Ph = *Phragmites*, SAV = submerged aquatic vegetation, SB = sparse Bulrush, Ty = *Typha*, WM = wet meadow, dissimilarity index = Bray-Curtis, stress = 26.01, *n* = 441)

Figure 10. NMDS ordination of fish assemblages throughout the Lake Michigan basin organized by monodominant vegetation type. Ellipses represent ± SE around the average fish assemblage. (DB = dense Bulrush, Li = Lily, Ph = *Phragmites*, SAV = submerged aquatic vegetation, SB = sparse Bulrush, Ty = *Typha*, WM = wet meadow, dissimilarity index = Bray-Curtis, stress = 26.32, *n* = 213)

Figure 11. NMDS ordination of fish assemblages throughout the Lake Ontario basin organized by monodominant vegetation type. Ellipses represent ± SE around the average fish assemblage. (DB = dense Bulrush, Li = Lily, PP = *Peltandra*/*Pontedaria*, SAV = submerged aquatic vegetation, SB = sparse Bulrush, Ty = *Typha*, WR = wild rice, dissimilarity index = Bray-Curtis, stress = 21.26, *n* = 277)

Figure 12. NMDS ordination of fish assemblages throughout the Lake Superior basin organized by monodominant vegetation type. Ellipses represent ± SE around the average fish assemblage. (DB = dense Bulrush, Li = Lily, PP = *Peltandra*/*Pontedaria*, SAV = submerged aquatic vegetation, Sp = *Sparganium*, SB = sparse Bulrush, Ty = *Typha*, WM = wet meadow, dissimilarity index = Bray-Curtis, stress = 24.42, *n* = 140)

Figure 13. NMDS ordination of fish assemblages throughout the Lake Erie basin organized by sampling year. Ellipses represent ± SE around the average fish assemblage. (Dissimilarity index = Bray-Curtis, stress = 27.32, *n* = 154)

Figure 14. NMDS ordination of fish assemblages throughout the Lake Huron basin organized by sampling year. Ellipses represent ± SE around the average fish assemblage. (Dissimilarity index = Bray-Curtis, stress = 25.99, *n* = 441)

Figure 15. NMDS ordination of fish assemblages throughout the Lake Michigan basin organized by sampling year. Ellipses represent ± SE around the average fish assemblage. (Dissimilarity index = Bray-Curtis, stress = 26.34, *n* = 213)

Figure 16. NMDS ordination of fish assemblages throughout the Lake Ontario basin organized by sampling year. Ellipses represent ± SE around the average fish assemblage. (Dissimilarity index = Bray-Curtis, stress = 21.17, *n* = 271)

Figure 17. NMDS ordination of fish assemblages throughout the Lake Superior basin organized by sampling year. Ellipses represent ± SE around the average fish assemblage. (Dissimilarity index = Bray-Curtis, stress = 24.58, *n* = 140)

Figure 18. Great Lakes water levels (meters above sea level, mASL) based on monthly mean levels, 2011-2020. The red line represents the average water level between 1918-2022. Data downloaded from the US Army Corps of Engineers Detroit District Website (https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Information-2/Water-Level-Data/).

2.8 Tables

Table 1. Sampling events that took place each year as part of the GLCWMP. Note that 2020 had a lower number of sampling events due to COVID-19 and the obstacles it created.

	Year										
Basin	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020***	**Total**
Erie	21	16	14	16	10	20	10	19	19	9	154
Huron	56	41	34	47	48	46	47	38	49	35	441
Michigan	24	23	21	12	31	28	28	23	17	6	213
Ontario	47	40	27	27	31	27	15	26	17	20	277
Superior	17	25	23	14	9	10	13	15	11	3	140
Total	165	145	119	116	129	131	113	121	113	73	1225

Table 2. Pairwise PERMANOVA R^2 results of fish assemblages grouped by basin. The farther a wetland is from Lake Superior towards Lake Ontario, the greater dissimilarity is exhibited in fish assemblage. (Dissimilarity index = Bray-Curtis, *n* = 1225)

Basin	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Lake Superior	**0.01639**	**0.01675**	**0.04331**	**0.06434**
Lake Michigan	-	**0.01194**	**0.03448**	**0.05794**
Lake Huron	**0.01194**	-	**0.01761**	**0.04065**
Lake Erie	**0.03448**	**0.01761**	-	**0.02167**

Values in bolded text indicate significance ($p < 0.05$)

Table 3. Pairwise PERMANOVA R^2 results of fish assemblages grouped by monodominant vegetation type. Observed differences do not lean towards emergent versus non-emergent communities. (DB = dense Bulrush, Li = Lily, PP = *Peltandra*/*Pontedaria*, Ph = *Phragmites*, SAV = submerged aquatic vegetation, Sp = *Sparganium*, SB = sparse Bulrush, Ty = *Typha*, WM = wet meadow, WR = wild rice, dissimilarity index = Bray-Curtis, *n* = 1225)

Vegetation	Li	PP	Ph	SAV	Sp	SB	Ty	WM	WR
DB	**0.02877**	**0.01365**	**0.00989**	**0.03298**	**0.01217**	**0.00613**	**0.01252**	**0.02394**	**0.01767**
Li	-	0.00539	**0.01866**	**0.01036**	**0.01339**	**0.03640**	**0.00847**	**0.02323**	0.00706
PP	0.00539	-	**0.01420**	**0.00923**	**0.04600**	**0.02225**	0.00396	**0.01894**	0.02009
Ph	**0.01866**	**0.0142**	-	**0.02367**	**0.01702**	**0.01729**	**0.00772**	**0.01728**	**0.02168**
SAV	**0.01036**	**0.00923**	**0.02367**	-	**0.01406**	**0.03608**	**0.01791**	**0.03936**	**0.00683**
Sp	**0.01339**	**0.04600**	**0.01702**	**0.01406**	-	**0.01142**	**0.00675**	**0.01966**	**0.08492**
SB	**0.03640**	**0.02225**	**0.01729**	**0.03608**	**0.01142**	-	**0.02065**	**0.03830**	**0.02442**
Ty	**0.00847**	0.00396	**0.00772**	**0.01791**	**0.00675**	**0.02065**	-	**0.01319**	**0.00714**
WM	**0.02323**	**0.01894**	**0.01728**	**0.03936**	**0.01966**	**0.03830**	**0.01319**	-	**0.02001**

Values in bolded text indicate significance ($p < 0.05$)

Table 4. Pairwise PERMANOVA R^2 results of fish assemblages grouped by hydrogeomorphic type. While differences are seen in fish assemblages, they appear minor. The largest difference occurring between riverine and lacustrine wetlands, but the grouping only explaining 0.46% of dissimilarity. (Dissimilarity index = Bray-Curtis, *n* = 1225)

Hydrogeomorphic Type	Lacustrine	Riverine
Barrier	**0.00290**	0.00236
Lacustrine	**-**	**0.00461**

Values in bolded text indicate significance ($p < 0.05$)

Table 5. Pairwise PERMANOVA R^2 results of fish assemblages grouped by sampling year. No clear pattern was able to be pulled from the observed dissimilarities which were very minor to begin with. (Dissimilarity index = Bray-Curtis, *n* = 1225)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
2011	**0.00796**	0.00496	**0.00884**	**0.00881**	**0.00566**	**0.01472**	**0.00626**	**0.00870**	**0.01366**
2012	-	**0.00701**	**0.01453**	**0.01460**	**0.00734**	**0.01172**	**0.0102**	**0.00888**	**0.01057**
2013	**0.00701**	-	**0.01092**	**0.00777**	0.00450	**0.00891**	0.00561	**0.00713**	**0.01316**
2014	**0.01453**	**0.01092**	-	0.00319	**0.01316**	**0.01369**	**0.00961**	**0.01252**	**0.01738**
2015	**0.01460**	**0.00777**	0.00319	-	**0.00983**	**0.01152**	**0.00785**	**0.01122**	**0.01537**
2016	**0.00734**	0.00450	**0.01316**	**0.00983**	-	**0.00848**	0.00520	0.00440	**0.01041**
2017	**0.01172**	**0.00891**	**0.01369**	**0.01152**	**0.00848**	-	**0.00989**	**0.00878**	**0.00956**
2018	**0.01020**	0.00561	**0.00961**	**0.00785**	0.00520	**0.00989**	-	0.00471	**0.00977**
2019	**0.00888**	**0.00713**	**0.01252**	**0.01122**	0.00440	**0.00878**	0.00471	-	0.00739

Values in bolded text indicate significance ($p < 0.05$)

Table 6. Pairwise PERMANOVA R^2 results of fish assemblages grouped by monodominant vegetation type in Lake Erie. (DB = dense Bulrush, Li = Lily, PP = *Peltandra*/*Pontedaria*, Ph = *Phragmites*, SAV = submerged aquatic vegetation, Ty = *Typha*, dissimilarity index = Bray-Curtis, *n* = 154)

Vegetation	PP	Ph	SAV	Ty
Li	0.02595	**0.03488**	**0.04859**	0.01733
PP	-	0.02989	**0.07455**	0.02071
Ph	0.02989	-	**0.05232**	0.01551
SAV	**0.07455**	**0.05232**	-	**0.03928**

Values in bolded text indicate significance ($p < 0.05$)

Table 7. Pairwise PERMANOVA R^2 results of fish assemblages grouped by monodominant vegetation type in Lake Huron. (DB = dense Bulrush, Li = Lily, Ph = *Phragmites*, SAV = submerged aquatic vegetation, SB = sparse Bulrush, Ty = *Typha*, WM = wet meadow, dissimilarity index = Bray-Curtis, $n = 441$)

Vegetation	Li	Ph	SAV	SB	Ty	WM
DB	**0.01901**	**0.01230**	**0.01496**	0.00756	**0.01519**	**0.02870**
Li	-	**0.04427**	0.02293	**0.03109**	0.00819	**0.02453**
Ph	**0.04427**	-	**0.03775**	**0.01453**	**0.02218**	**0.03813**
SAV	0.02293	**0.03775**	-	**0.02422**	0.01252	**0.01825**
SB	**0.03109**	**0.01453**	**0.02422**	-	**0.02720**	**0.04699**
Ty	0.00819	**0.02218**	0.01252	**0.02720**	-	**0.02394**

Values in bolded text indicate significance ($p < 0.05$)

Table 8. Pairwise PERMANOVA R^2 results of fish assemblages grouped by monodominant vegetation type in Lake Michigan. (DB = dense Bulrush, Li = Lily, PP = *Peltandra*/*Pontedaria*, SAV = submerged aquatic vegetation, Sp = *Sparganium*, SB = sparse Bulrush, Ty = *Typha*, WM = wet meadow, dissimilarity index = Bray-Curtis, $n = 213$)

Vegetation	Li	Ph	SAV	SB	Ty	WM
DB	**0.06334**	0.03632	**0.04808**	0.03240	**0.02158**	**0.05692**
Li	-	**0.05437**	**0.05381**	**0.05998**	**0.02024**	0.03903
Ph	**0.05437**	-	**0.04455**	**0.03710**	0.01352	0.03417
SAV	**0.05381**	**0.04455**	-	0.02282	**0.01954**	**0.06441**
SB	**0.05998**	**0.03710**	0.02282	-	**0.02216**	**0.07099**
Ty	**0.02024**	0.01352	**0.01954**	**0.02216**	-	**0.01890**

Values in bolded text indicate significance ($p < 0.05$)

Table 9. Pairwise PERMANOVA R^2 results of fish assemblages grouped by monodominant vegetation type in Lake Ontario. (DB = dense Bulrush, Li = Lily, Ph = *Phragmites*, SAV = submerged aquatic vegetation, SB = sparse Bulrush, Ty = *Typha*, WM = wet meadow, dissimilarity index = Bray-Curtis, $n = 277$)

Vegetation	Li	PP	SAV	SB	Ty	WR
DB	**0.03430**	0.04126	**0.01624**	**0.08900**	0.02968	0.04994
Li	-	0.01294	**0.01725**	**0.02710**	0.01870	**0.02990**
PP	0.01294	-	**0.01184**	**0.11115**	0.02071	0.05289
SAV	**0.01725**	**0.01184**	-	0.01092	**0.01899**	**0.02388**
SB	**0.02710**	**0.11115**	0.01092	-	**0.07287**	**0.16845**
Ty	0.01870	0.02071	**0.01899**	**0.07287**	-	0.03011

Values in bolded text indicate significance ($p < 0.05$)

Table 10. Pairwise PERMANOVA R^2 results of fish assemblages grouped by monodominant vegetation type in Lake Superior. (DB = dense Bulrush, Li = Lily, PP = *Peltandra*/*Pontedaria*, SAV = submerged aquatic vegetation, SB = sparse Bulrush, Ty = *Typha*, WR = wild rice, dissimilarity index = Bray-Curtis, *n* = 140)

Vegetation	Li	PP	SAV	Sp	SB	Ty	WM
DB	0.03377	0.03810	**0.04778**	**0.04617**	0.02753	**0.04067**	**0.07000**
Li	-	0.02919	0.03569	0.02582	**0.04010**	0.02927	**0.06877**
PP	0.02919	-	0.05254	0.06993	0.04932	0.03321	**0.14372**
SAV	0.03569	0.05254	-	0.04351	0.03009	**0.05606**	**0.09327**
Sp	0.02582	0.06993	0.04351	-	0.03697	0.03571	**0.09759**
SB	**0.04010**	0.04932	0.03009	0.03697	-	**0.04397**	**0.06535**
Ty	0.02927	0.03321	**0.05606**	0.03571	**0.04397**	-	0.04527

Values in bolded text indicate significance ($p < 0.05$)

Table 11. Pairwise PERMANOVA R^2 results of fish assemblages grouped by sampling year in Lake Erie. (Dissimilarity index = Bray-Curtis, *n* = 154)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
2011	**0.06085**	**0.05796**	**0.11735**	**0.05183**	**0.04876**	**0.07520**	**0.08900**	**0.08925**	**0.08912**
2012	-	0.04478	**0.06757**	0.04623	0.02918	**0.08722**	**0.05947**	**0.06280**	0.06243
2013	0.04478	-	**0.12354**	0.03785	0.03901	**0.10034**	0.05711	**0.06857**	**0.07893**
2014	**0.06757**	**0.12354**	-	**0.11033**	**0.08222**	**0.17758**	**0.07697**	**0.14566**	**0.15394**
2015	0.04623	0.03785	**0.11033**	-	0.04824	**0.10362**	0.06271	**0.07136**	**0.10174**
2016	0.02918	0.03901	**0.08222**	0.04824	-	**0.07621**	**0.06163**	**0.06466**	**0.06803**
2017	**0.08722**	**0.10034**	**0.17758**	**0.10362**	**0.07621**	-	**0.09710**	**0.06361**	0.08520
2018	**0.05947**	0.05711	**0.07697**	0.06271	**0.06163**	**0.09710**	-	**0.08332**	**0.10082**
2019	**0.06280**	**0.06857**	**0.14566**	**0.07136**	**0.06466**	**0.06361**	**0.08332**	-	0.03011

Values in bolded text indicate significance ($p < 0.05$)

Table 12. Pairwise PERMANOVA R^2 results of fish assemblages grouped by sampling year in Lake Huron. (Dissimilarity index = Bray-Curtis, *n* = 441)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
2011	**0.02355**	0.01115	**0.01578**	**0.01693**	0.01390	**0.03025**	**0.02497**	**0.02341**	**0.02751**
2012	-	**0.02401**	**0.04120**	**0.03179**	0.01687	**0.02216**	0.02663	0.02404	0.03158
2013	**0.02401**	-	**0.01983**	0.01877	0.01288	**0.03051**	0.02036	0.01603	**0.02289**
2014	**0.04120**	**0.01983**	-	**0.01754**	**0.02345**	**0.03965**	**0.02952**	**0.02506**	**0.03309**
2015	**0.03179**	0.01877	**0.01754**	-	0.01607	**0.02334**	**0.01878**	**0.02401**	**0.02259**
2016	0.01687	0.01288	**0.02345**	0.01607	-	0.01661	0.01222	0.00989	0.00887
2017	**0.02216**	**0.03051**	**0.03965**	**0.02334**	0.01661	-	**0.01952**	**0.02722**	0.01987
2018	0.02663	0.02036	**0.02952**	**0.01878**	0.01222	**0.01952**	-	0.01860	0.01519
2019	0.02404	0.01603	**0.02506**	**0.02401**	0.00989	**0.02722**	0.01860	-	0.01089

Values in bolded text indicate significance ($p < 0.05$)

Table 13. Pairwise PERMANOVA R^2 results of fish assemblages grouped by sampling year in Lake Michigan. (Dissimilarity index = Bray-Curtis, *n* = 213)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
2011	0.02141	0.02772	0.04128	**0.03039**	0.01643	0.01515	0.02363	0.03007	**0.07123**
2012	-	0.03470	0.04630	**0.03752**	0.03298	0.02704	0.02380	**0.04638**	**0.07146**
2013	0.03470	-	0.03870	0.02563	0.03242	**0.04020**	**0.04702**	0.03319	**0.06062**
2014	0.04630	0.03870	-	0.03128	**0.04913**	**0.04928**	**0.05173**	0.04722	0.07986
2015	**0.03752**	0.02563	0.03128	-	0.02314	**0.04179**	0.02717	0.01685	**0.04666**
2016	0.03298	0.03242	**0.04913**	0.02314	-	0.01410	0.01640	0.02511	**0.05858**
2017	0.02704	**0.04020**	**0.04928**	**0.04179**	0.01410	-	0.01723	**0.03898**	**0.06999**
2018	0.02380	**0.04702**	**0.05173**	0.02717	0.01640	0.01723	-	0.03230	**0.06410**
2019	**0.04638**	0.03319	0.04722	0.01685	0.02511	**0.03898**	0.03230	-	0.06948

Values in bolded text indicate significance ($p < 0.05$)

Table 14. Pairwise PERMANOVA R^2 results of fish assemblages grouped by monodominant vegetation type in Lake Ontario. (Dissimilarity index = Bray-Curtis, *n* = 277)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
2011	**0.02967**	**0.05883**	**0.07540**	**0.05460**	**0.03804**	**0.09073**	0.00948	**0.06673**	**0.05425**
2012	-	**0.03278**	**0.05376**	**0.04410**	0.02467	**0.05709**	0.01984	**0.04824**	0.02707
2013	**0.03278**	-	0.02544	**0.04308**	0.02979	0.02466	**0.04675**	0.01350	0.01376
2014	**0.05376**	0.02544	-	0.01449	0.03123	0.03398	**0.05014**	0.03073	0.03647
2015	**0.04410**	**0.04308**	0.01449	-	**0.03377**	**0.05949**	0.03017	**0.04909**	**0.05222**
2016	0.02467	0.02979	0.03123	**0.03377**	-	**0.04437**	0.02472	**0.04243**	0.02853
2017	**0.05709**	0.02466	0.03398	**0.05949**	**0.04437**	-	**0.07950**	0.02747	0.04681
2018	0.01984	**0.04675**	**0.05014**	0.03017	0.02472	**0.07950**	-	**0.05234**	**0.04542**
2019	**0.04824**	0.01350	0.03073	**0.04909**	**0.04243**	0.02747	**0.05234**	-	0.02756

Values in bolded text indicate significance ($p < 0.05$)

Table 15. Top five relative contribution of fish species to fish assemblage dissimilarities between basins. Yellow perch, Bluegill or Pumpkinseed, and Black or Brown bullhead are species listed in each comparison indicating they are key drivers of fish assemblage dissimilarity in coastal wetlands across the basin.

Basins	**Common name**	**Scientific name**	**Average A** (catch per sampling event)	**Average B** (catch per sampling event)	**Dissimilarity** (%)	**Cumulative dissimilarity** (%)
Lake Erie (A) and Lake Huron (B)						
	Bluegill or Pumpkinseed	*Lepomis macrochirus/gibbosus*	43.66	30.65	14.96%	14.96%
	Largemouth Bass	*Micropterus salmoides*	23.41	12.34	10.14%	25.09%
	Black or Brown Bullhead	*Ameiurus melas/nebulosus*	15.27	35.78	10.01%	35.10%
	Yellow Perch	*Perca flavescens*	2.20	52.48	7.22%	42.32%
	Mimic Shiner	*Notropis volucellus*	1.90	131.28	6.18%	48.50%
Lake Erie (A) and Lake Michigan (B)						
	Yellow Perch	*Perca flavescens*	2.20	669.76	20.09%	20.09%
	Bluegill or Pumpkinseed	*Lepomis macrochirus/gibbosus*	43.66	39.04	15.06%	35.15%
	Black or Brown Bullhead	*Ameiurus melas/nebulosus*	15.27	109.21	12.61%	47.76%
	Largemouth Bass	*Micropterus salmoides*	23.41	6.89	8.19%	55.95%
	Goldfish	*Carassius auratus*	12.53	0.04	3.55%	59.50%
Lake Erie (A) and Lake Ontario (B)						
	Bluegill or Pumpkinseed	*Lepomis macrochirus/gibbosus*	43.66	37.72	21.33%	21.33%
	Largemouth Bass	*Micropterus salmoides*	23.41	29.25	15.02%	36.35%
	Black or Brown Bullhead	*Ameiurus melas/nebulosus*	15.27	64.02	12.19%	48.54%
	Yellow Perch	*Perca flavescens*	2.20	17.33	7.08%	55.62%
	Goldfish	*Carassius auratus*	12.53	0.33	4.92%	60.54%
Lake Erie (A) and Lake Superior (B)						
	Bluegill or Pumpkinseed	*Lepomis macrochirus/gibbosus*	43.66	101.31	18.34%	18.34%
	Black or Brown Bullhead	*Ameiurus melas/nebulosus*	15.27	131.78	14.46%	32.80%
	Yellow Perch	*Perca flavescens*	2.20	76.69	7.43%	40.23%
	Largemouth Bass	*Micropterus salmoides*	23.41	1.24	6.34%	46.57%
	Black Crappie	*Pomoxis nigromaculatus*	2.25	46.54	5.20%	51.77%
Lake Huron (A) and Lake Michigan (B)						
	Yellow Perch	*Perca flavescens*	52.48	669.76	22.98%	22.98%
	Black or Brown Bullhead	*Ameiurus melas/nebulosus*	35.78	109.21	13.65%	36.63%
	Bluegill or Pumpkinseed	*Lepomis macrochirus/gibbosus*	30.65	39.04	11.46%	48.09%
	Mimic Shiner	*Notropis volucellus*	131.28	2.79	5.54%	53.63%
	Largemouth Bass	*Micropterus salmoides*	12.34	6.89	5.52%	59.15%
Lake Huron (A) and Lake Ontario (B)						
	Bluegill or Pumpkinseed	*Lepomis macrochirus/gibbosus*	30.65	37.72	18.09%	18.09%
	Black or Brown Bullhead	*Ameiurus melas/nebulosus*	35.78	64.02	13.20%	31.29%
	Largemouth Bass	*Micropterus salmoides*	12.34	29.25	11.47%	42.76%
	Yellow Perch	*Perca flavescens*	52.48	17.33	11.43%	54.19%
	Mimic Shiner	*Notropis volucellus*	131.28	0.00	6.03%	60.23%

Lake Huron (A) and Lake Superior (B)					
Black or Brown Bullhead	*Ameiurus melas/nebulosus*	35.78	131.78	15.20%	15.20%
Bluegill or Pumpkinseed	*Lepomis macrochirus/gibbosus*	30.65	101.31	15.08%	30.28%
Yellow Perch	*Perca flavescens*	52.48	76.69	10.98%	41.26%
Mimic Shiner	*Notropis volucellus*	131.28	46.95	5.98%	47.23%
Black Crappie	*Pomoxis nigromaculatus*	0.53	46.54	4.77%	52.00%
Lake Michigan (A) and Lake Ontario (B)					
Yellow Perch	*Perca flavescens*	669.76	17.33	23.85%	23.85%
Bluegill or Pumpkinseed	*Lepomis macrochirus/gibbosus*	39.04	37.72	17.66%	41.52%
Black or Brown Bullhead	*Ameiurus melas/nebulosus*	109.21	64.02	15.52%	57.03%
Largemouth Bass	*Micropterus salmoides*	6.89	29.25	9.73%	66.77%
Round Goby	*Neogobius melanostomus*	5.38	4.85	3.54%	70.30%
Lake Michigan (A) and Lake Superior (B)					
Yellow Perch	*Perca flavescens*	669.76	76.69	21.64%	21.64%
Black or Brown Bullhead	*Ameiurus melas/nebulosus*	109.21	131.78	16.91%	38.55%
Bluegill or Pumpkinseed	*Lepomis macrochirus/gibbosus*	39.04	101.31	15.04%	53.59%
Black Crappie	*Pomoxis nigromaculatus*	0.43	46.54	4.36%	57.95%
Spottail Shiner	*Notropis hudsonius*	5.23	19.82	3.59%	61.53%
Lake Ontario (A) and Lake Superior (B)					
Bluegill or Pumpkinseed	*Lepomis macrochirus/gibbosus*	37.72	101.31	20.44%	20.44%
Black or Brown Bullhead	*Ameiurus melas/nebulosus*	64.02	131.78	17.31%	37.75%
Yellow Perch	*Perca flavescens*	17.33	76.69	10.60%	48.35%
Largemouth Bass	*Micropterus salmoides*	29.25	1.24	8.13%	56.48%
Black Crappie	*Pomoxis nigromaculatus*	2.83	46.54	5.66%	62.14%

2.9 Figures

Figure 1.

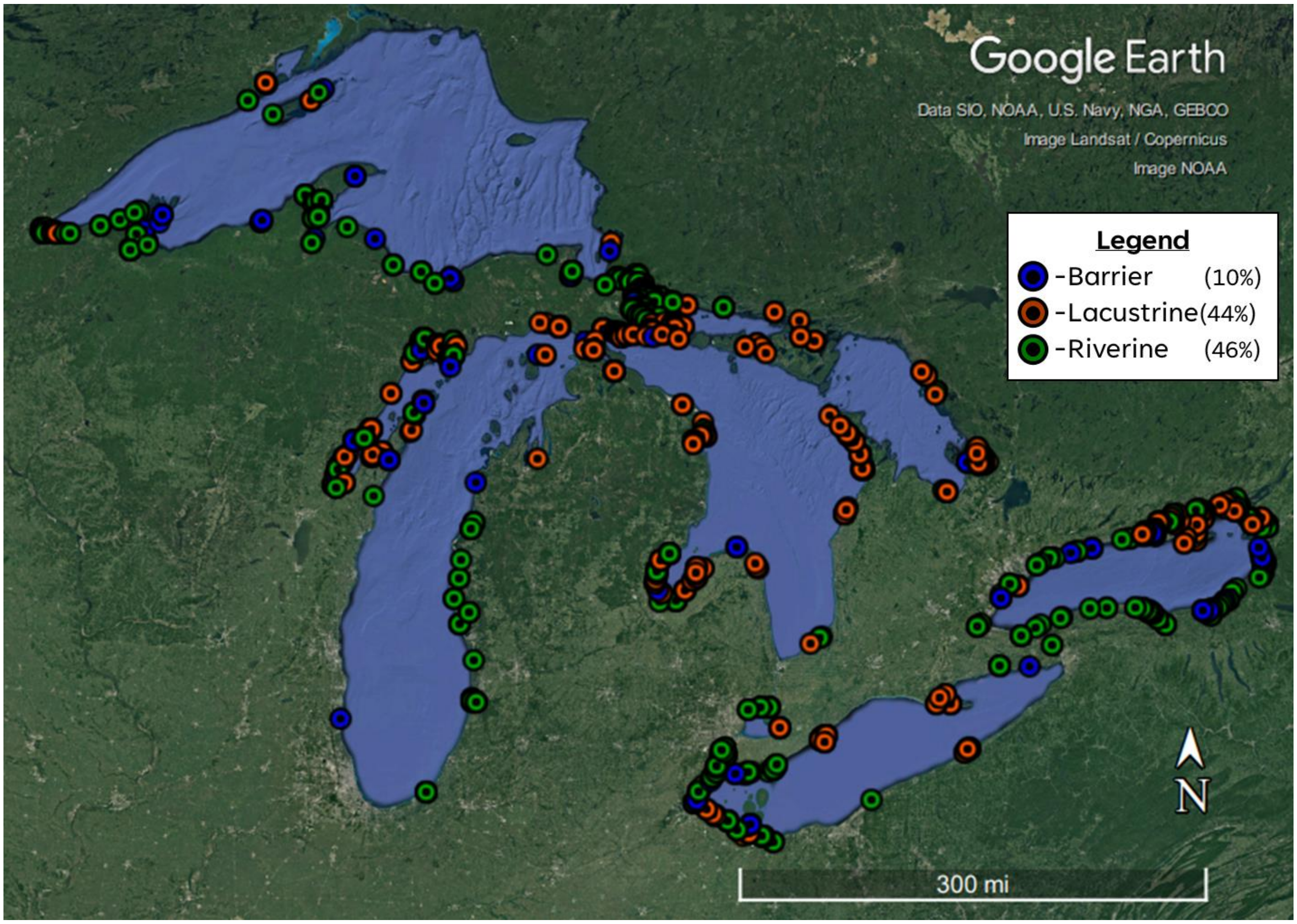


Figure 2.

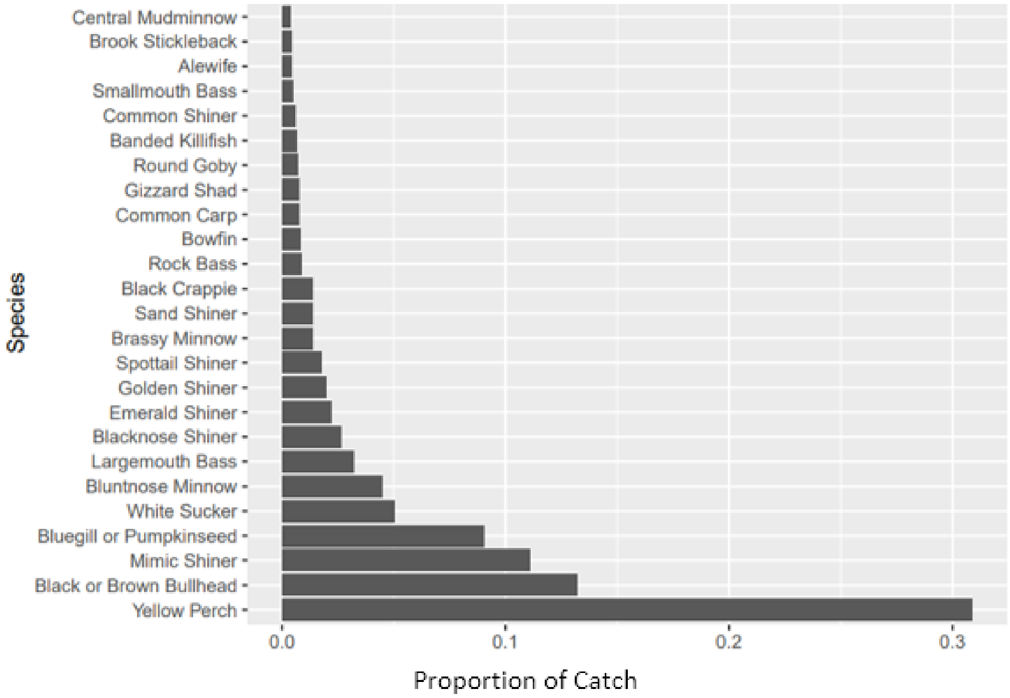


Figure 3.

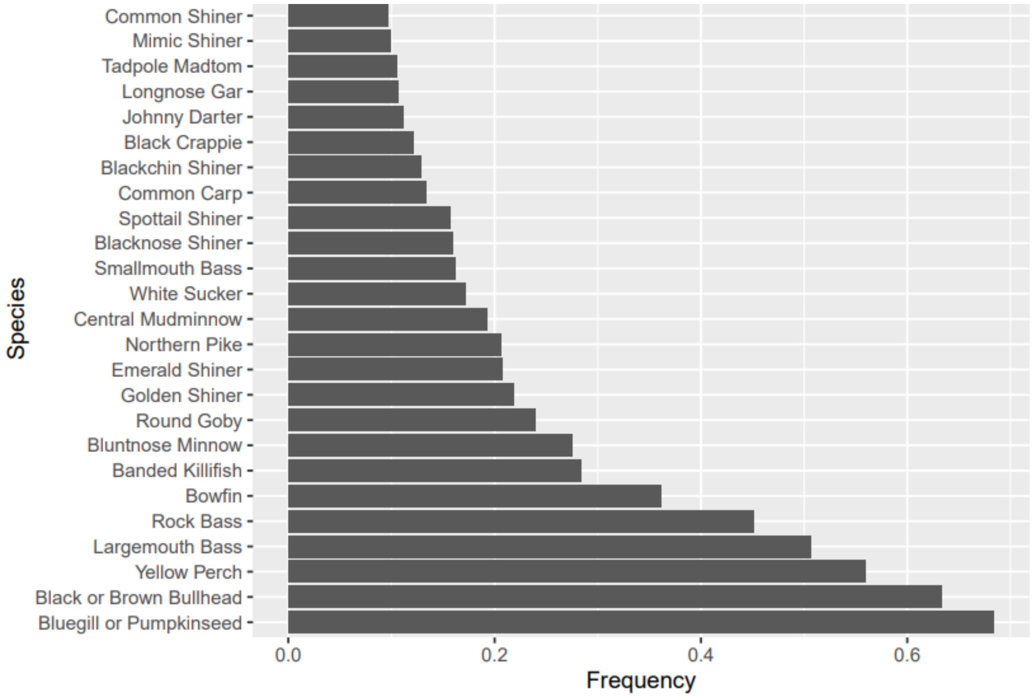
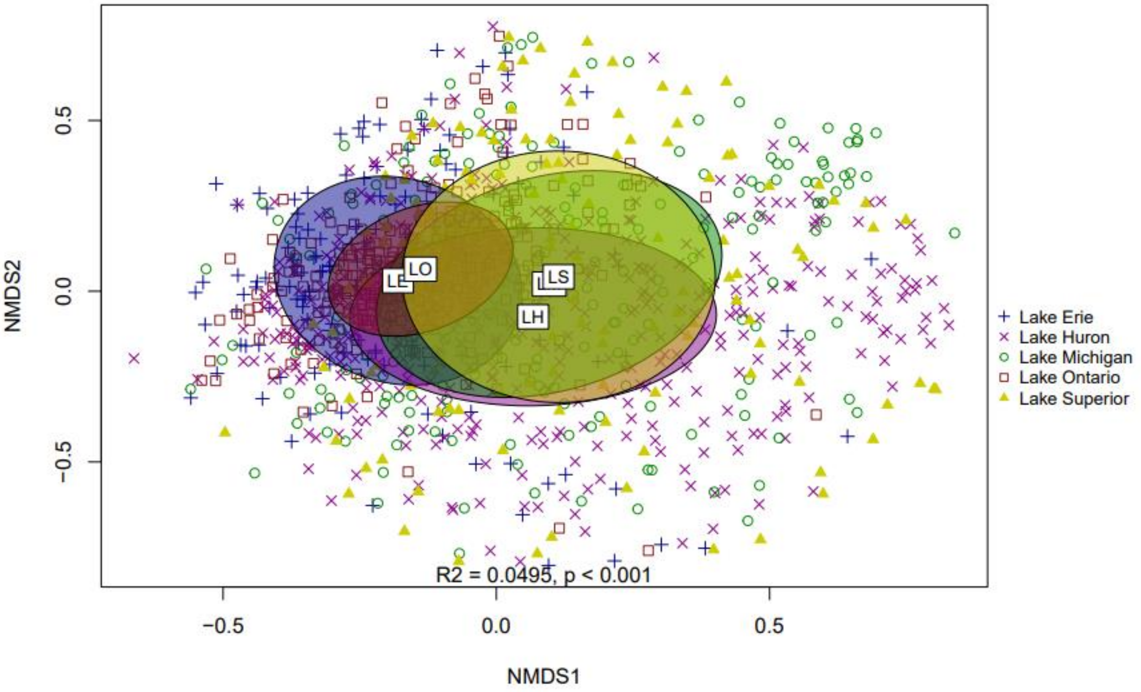


Figure 4.



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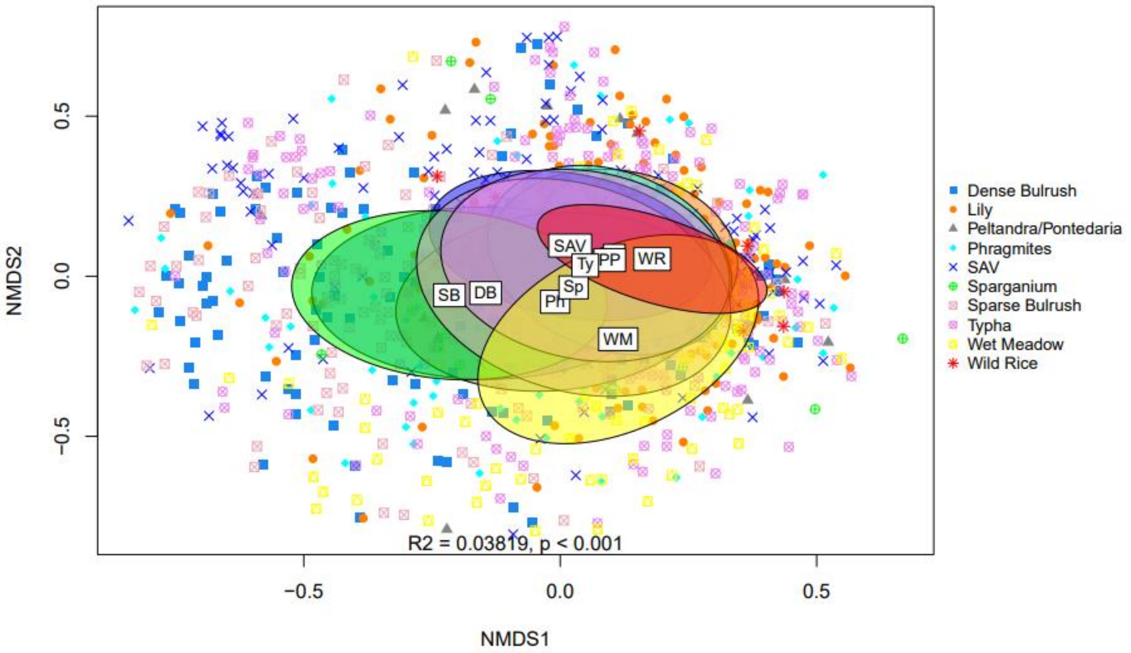


Figure 6.

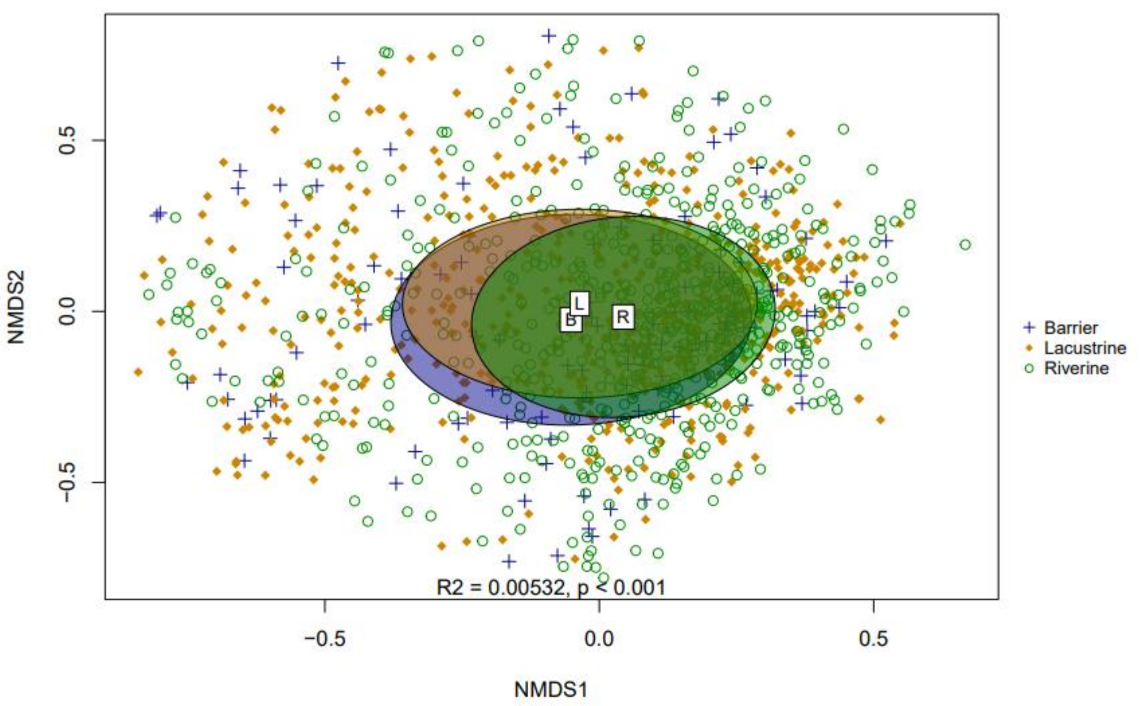
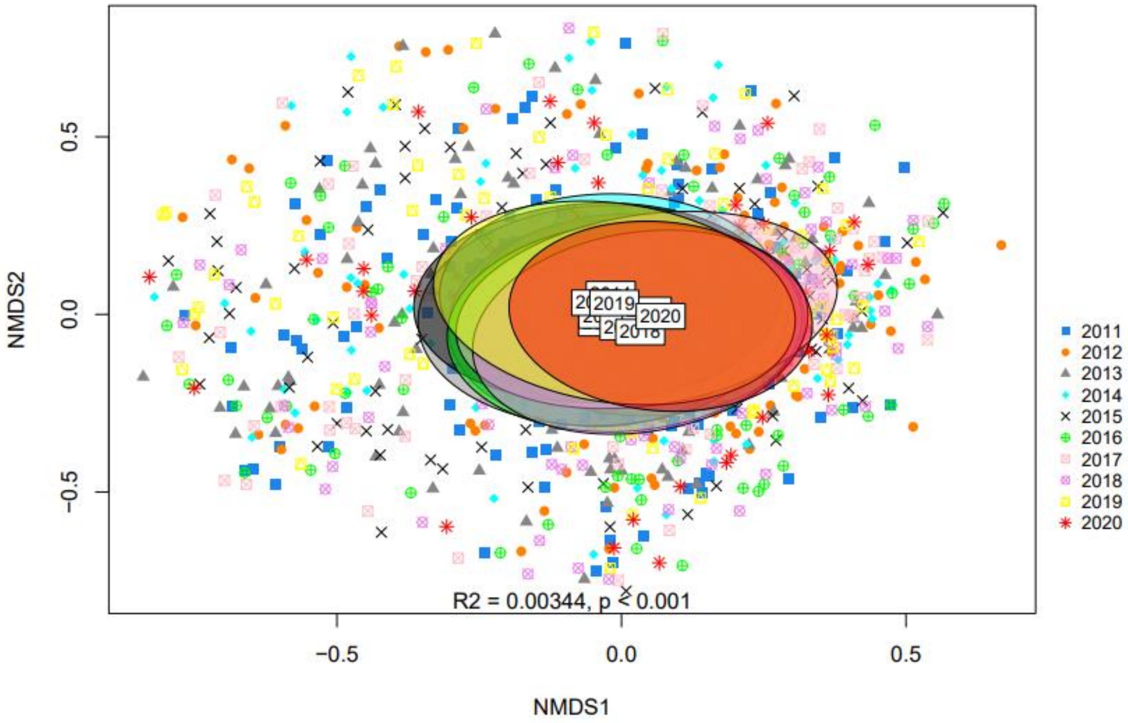


Figure 7.



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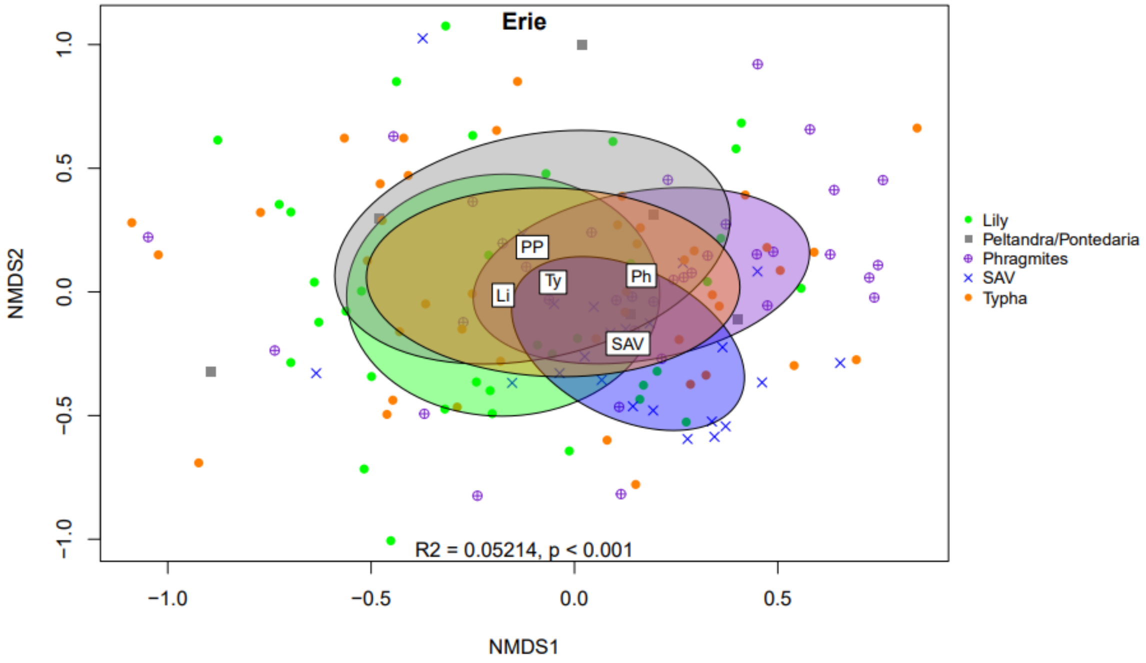


Figure 9.

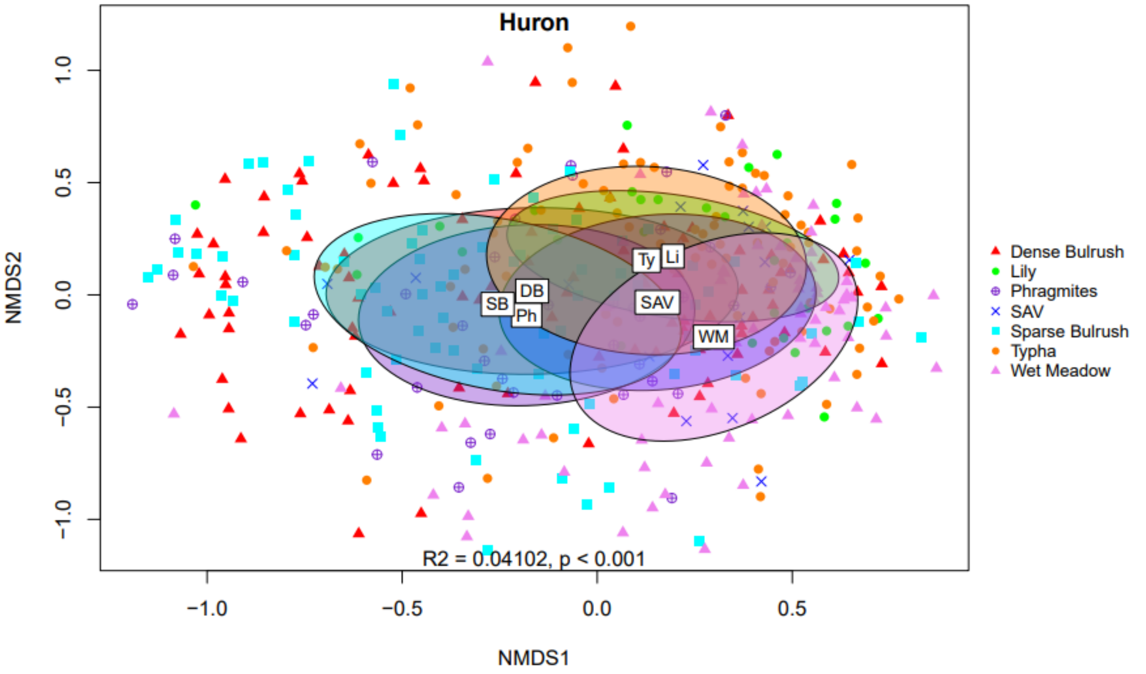


Figure 10.

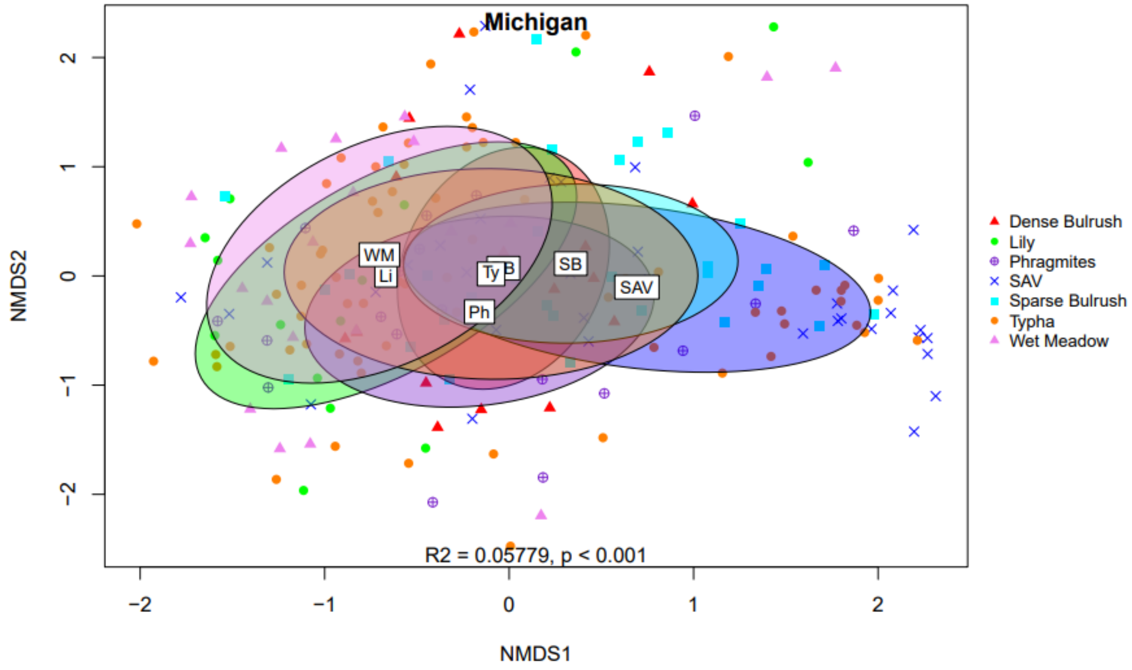


Figure 11.

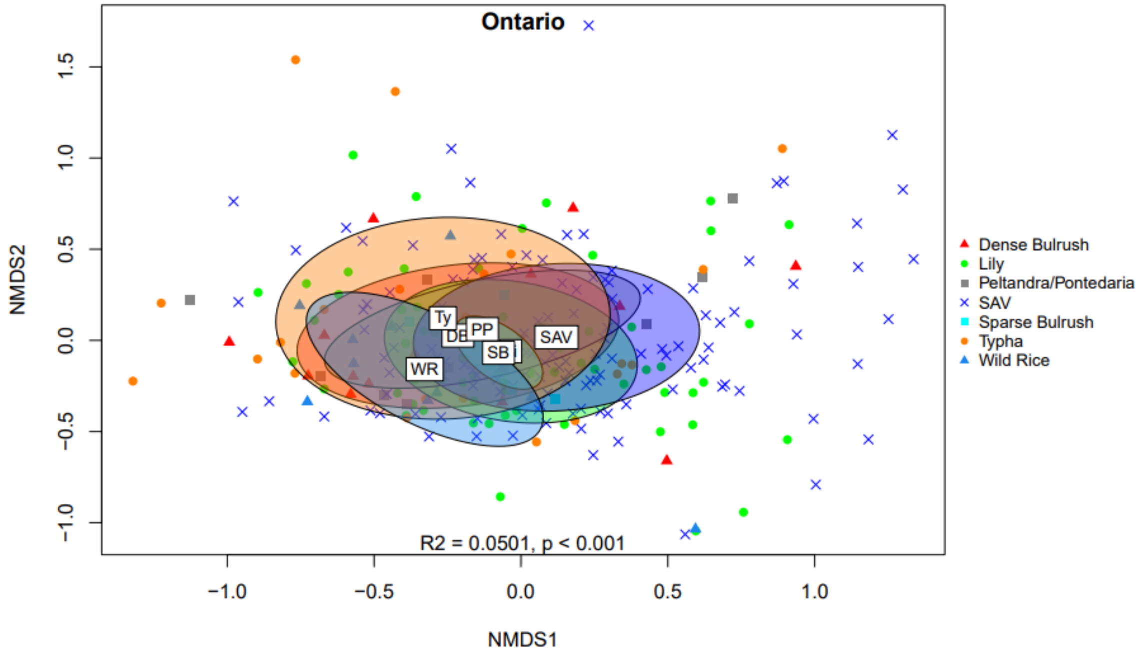


Figure 12.

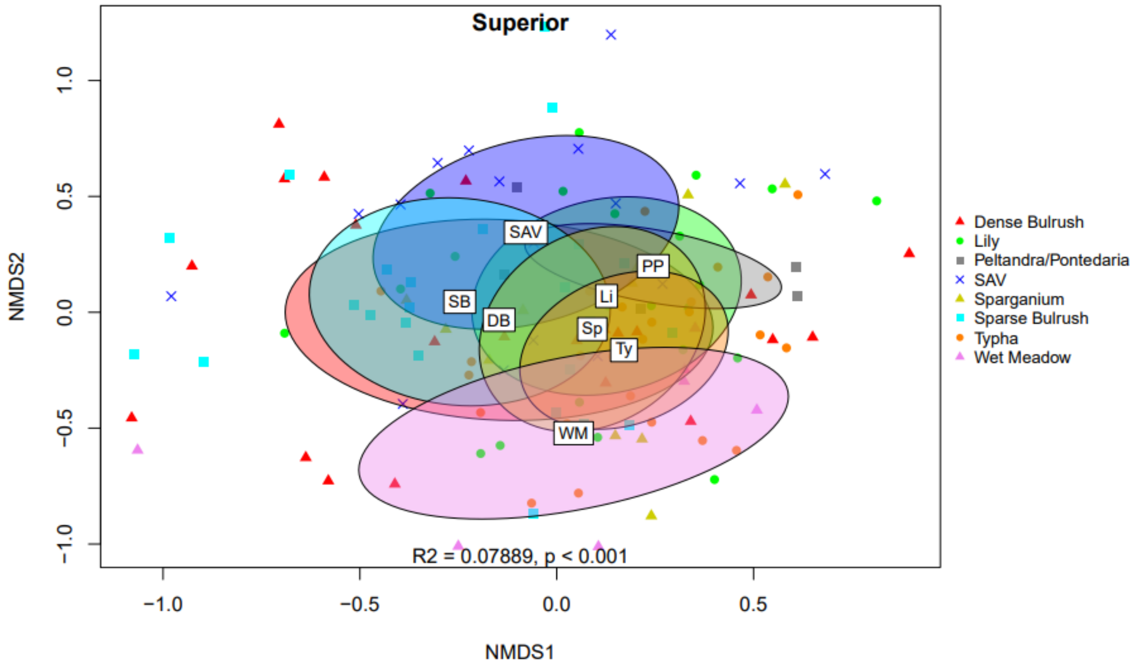


Figure 13.

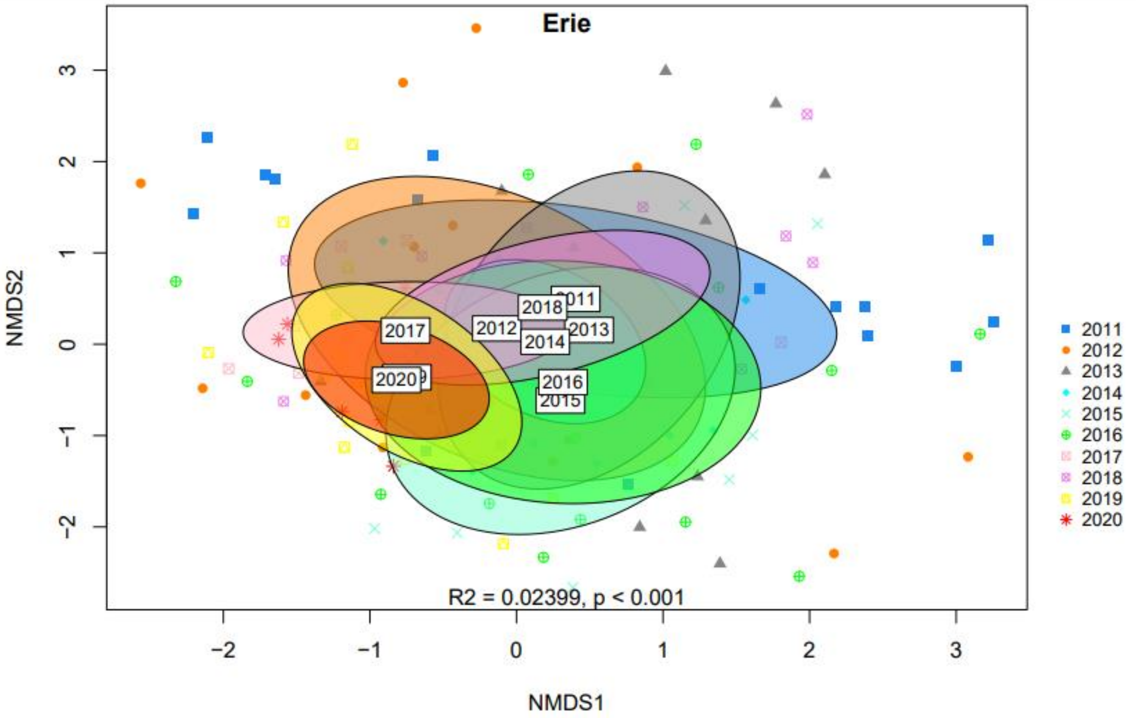


Figure 14.

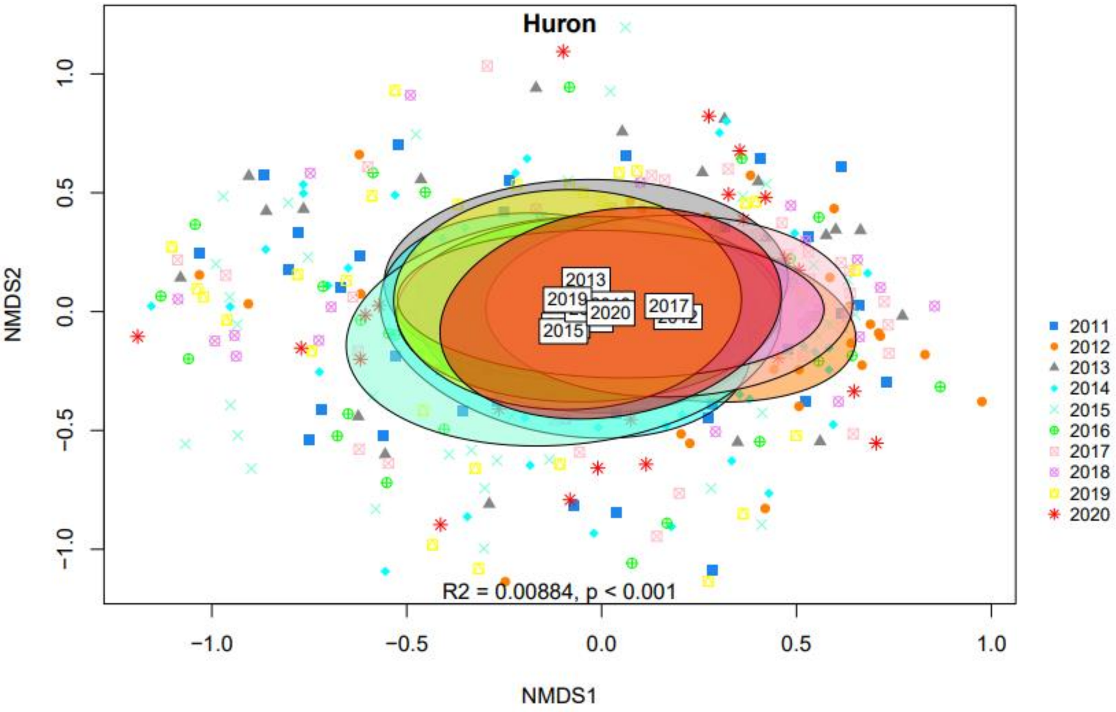


Figure 15.

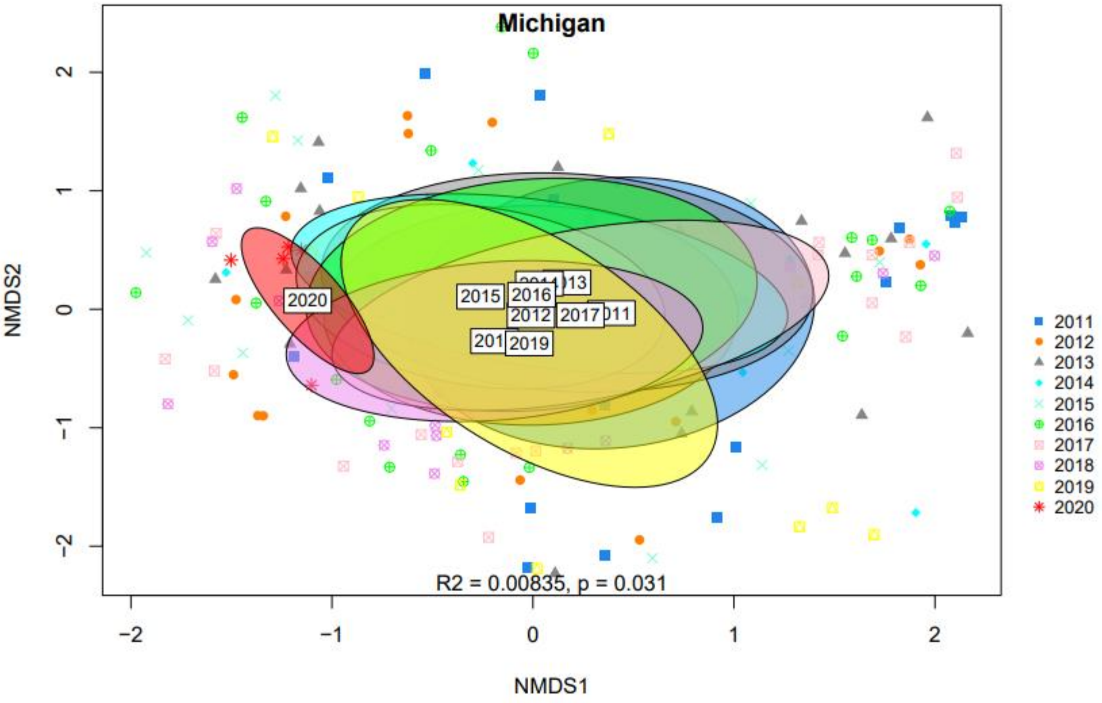


Figure 16.

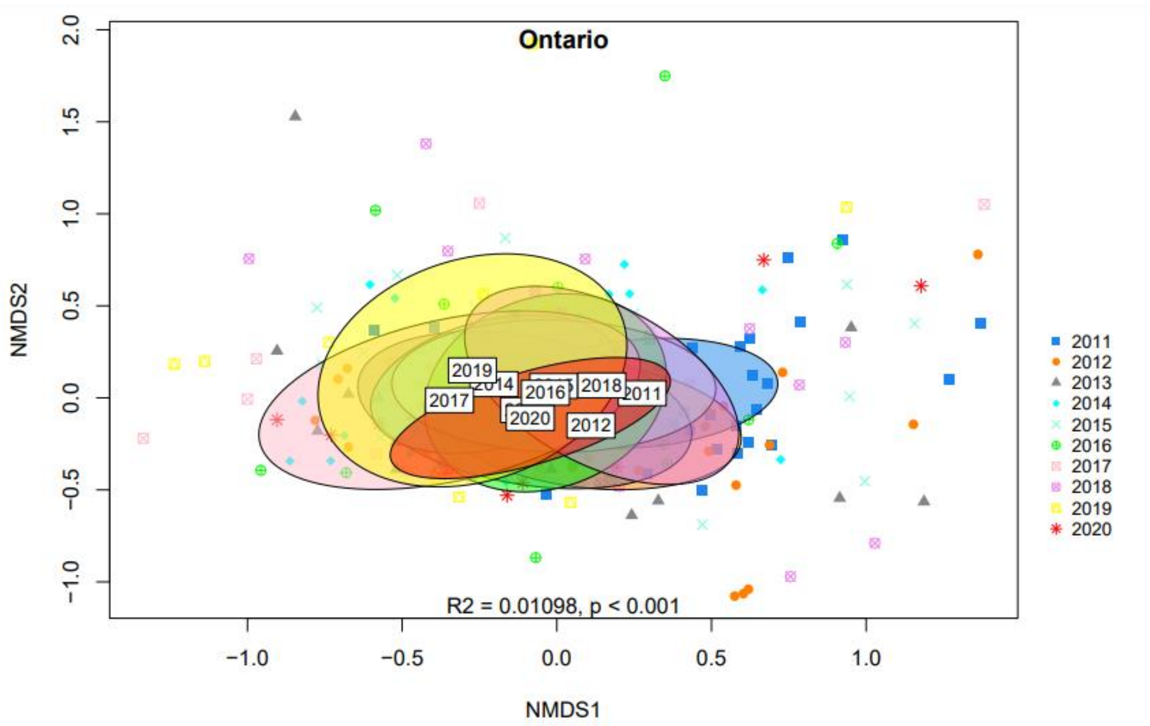


Figure 17.

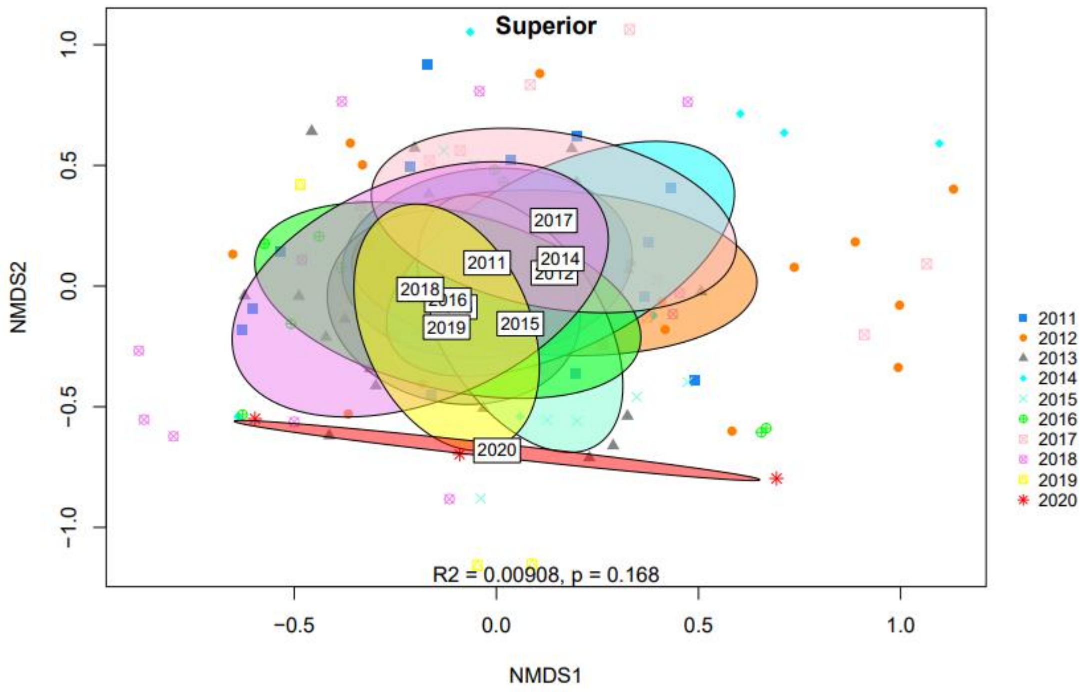
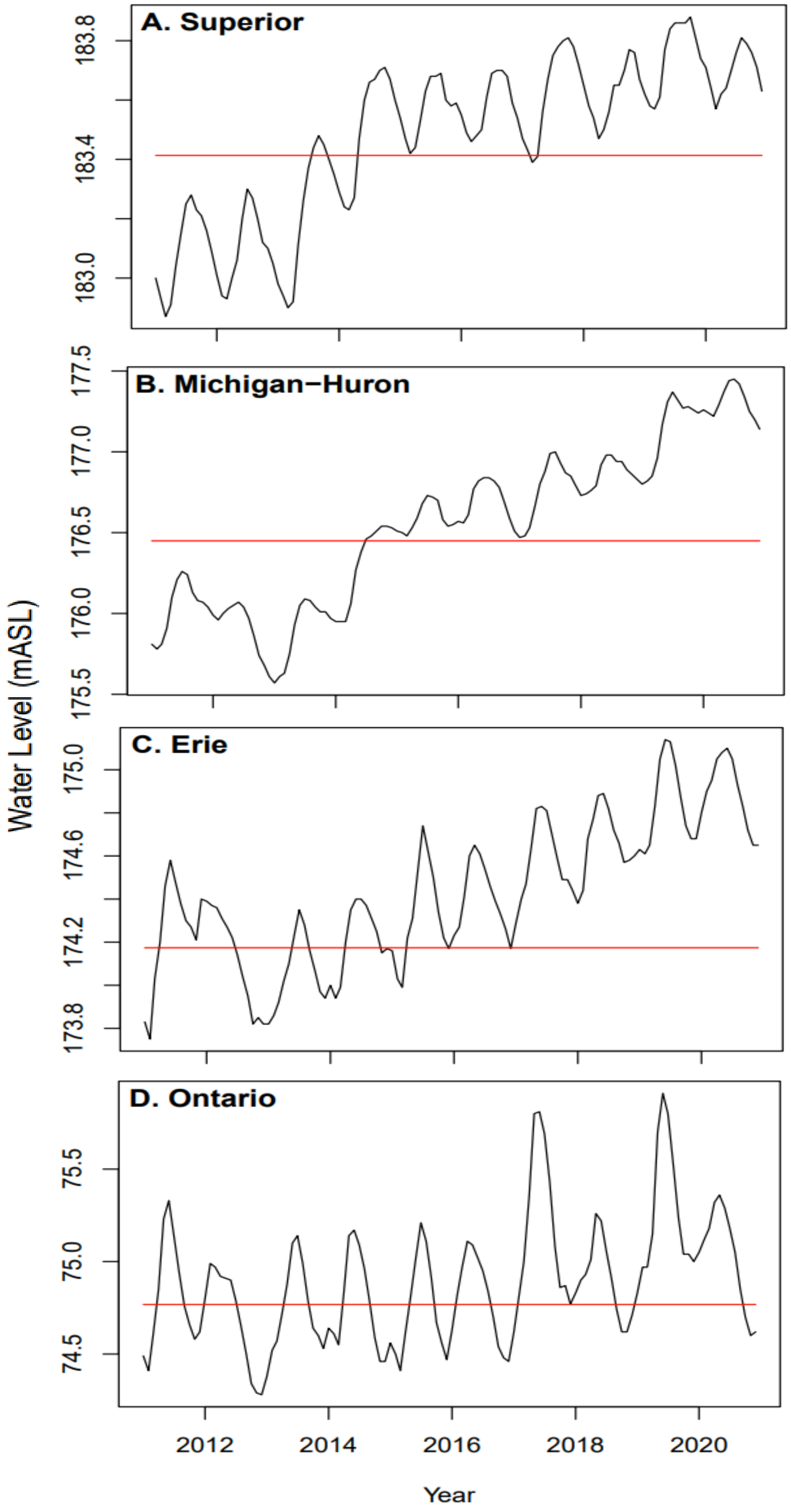


Figure 18.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183.4
183.0
B. Michigan−Huron
177.5
177.0
176.5
176.0
175.5
C. Erie
175.0
174.6
174.2
173.8
D. Ontario
75.5
75.0
74.5
Water Level (mASL)
2012
2014
2016
2018
2020
Year

Chapter 3: Extended Review of Literature and Extended Methodology

3.1 Extended Review of Literature

The Laurentian Great Lakes basin holds most of the surface freshwater in North America and provides both environmental and economic services (Melstrom & Lupi, 2013; Mitsch & Gosselink, 2000; Sierszen *et al*., 2012). Coastal wetlands historically covered more of the lakeshore of the Great Lakes than they currently do, defined as nearshore wetlands influenced by fluctuations in Great Lakes water levels (Albert *et al*., 2005; Gronewold *et al*., 2013; Larson & Schaetzl, 2001; Quinn, 2002). The environmental services provided by coastal wetlands are essential to the overall functioning of the Great Lakes ecosystem (Sierszen *et al*., 2012, 2019). Abiotic conditions across the Laurentian Great Lakes basin causes changes in coastal wetland structure, broadly ranging between lacustrine, hydrogeomorphic, and barrier (Albert *et al*., 2005; Kovalenko *et al*., 2018). The various abiotic conditions of coastal wetlands influence the biotic characteristics taking place within (Brazner, 1997; Brazner *et al*., 2005, 2007a, 2007b; Keough *et al*., 1999; Lemein *et al*., 2017; Midwood & Chow-Fraser, 2012; Trebitz *et al*., 2007b). Obligate wetland vegetation is influenced by the abiotic environmental characteristics and is often used to define areas within Great Lakes coastal wetlands, providing habitat for fish species in the Laurentian Great Lakes basin (Fracz & Chow-Fraser, 2013; Kovalenko *et al*., 2018; Lemein *et al*., 2017; Midwood & Chow-Fraser, 2012; Trebitz *et al*., 2009b). Various fish species use Great Lakes coastal wetlands for different life stages and purposes (Jude & Pappas, 1992; Uzarski *et al*., 2005). These uses include, but are not limited to, nursery habitat, feeding grounds, permanent residence, and migratory habitat (Jude & Pappas, 1992; Uzarski *et al*., 2005). As with flora inhabiting coastal wetlands, fish assemblages respond to the abiotic and biotic characteristics defining each coastal wetland (Bhagat *et al*., 2007; Brazner *et al*., 2005, 2007a; Jacobus & Ivan, 2005; Trebitz *et al*., 2007b, 2009a, 2009b). Fish assemblage response to abiotic and biotic characteristics make them a particularly useful tool for reflecting the overall health of different watersheds (Bhagat *et al*., 2007; Cooper *et al*., 2018). The presence/absence and abundance of various fish species coincide with the abiotic and biotic characteristics they can tolerate (Trebitz *et al*., 2007a). Understanding how fish assemblages vary across Great Lakes coastal wetlands can provide key insights into the status and trends of the Great Lakes basin.

A strong argument for the importance of Great Lakes coastal wetlands is the heavy use of this unique ecosystem by fish populations and their contributions to the overall fishery of the Great Lakes (Jude & Pappas, 1992; Sierszen *et al*., 2019). One of the most comprehensive pieces of literature describing fish use of coastal wetlands is a study conducted by Jude & Papas (1992). During this study, coastal wetlands across the entire basin were sampled to evaluate the abundance of fish species in the Great Lakes basin utilizing coastal wetlands (Jude & Pappas, 1992). It was concluded that there were two groupings of fish-use in Great Lakes coastal wetlands: permanent residents, and migratory species (Jude & Pappas, 1992). The species categorized as migratory were subcategorized into three groups; those that are born there and leave, those that use it as nursery habitat, and those that move into the wetland from other locations (Jude & Pappas, 1992). Contributions of coastal wetlands to the overall Great Lakes fishery are dependent on maintaining connectedness to the Great Lakes, even if the wetland is degraded (Jude & Pappas, 1992).

While the importance of fish use of Great Lakes coastal wetlands has been documented, additional research has focused on how fish assemblages are changing across coastal wetlands in the basin (Brazner *et al*., 2005; Cvetkovic *et al*., 2010; Fracz & Chow-Fraser, 2013; Jacobus &

Ivan, 2005; Jude & Pappas, 1992; Midwood & Chow-Fraser, 2012; Trebitz *et al*., 2007b, 2009b). Most importantly, it has been shown that fish assemblages in Great Lakes coastal wetlands change in response to abiotic and biotic conditions surrounding them (Brazner *et al*., 2005, 2007a; Cvetkovic *et al*., 2010; Jacobus & Ivan, 2005; Jude & Pappas, 1992; Midwood & Chow-Fraser, 2012; Trebitz *et al*., 2007b, 2009a). One of the most notable large-scale changes across the Great Lakes basin that has been recorded is the variation in water levels (Quinn, 2002). This change in water levels happens on long- and short-term temporal scales, ranging from seasonal water-level changes to influences by wind causing seiche events (Gronewold *et al*., 2013; Quinn, 2002). Fluctuations in water levels have been reported to influence coastal wetland fish assemblages (Fracz & Chow-Fraser, 2013; Langer *et al*., 2018; Midwood & Chow-Fraser, 2012; Montocchio & Chow-Fraser, 2021). This influence can impact the abundance of fish species as well as the diversity present (Langer *et al*., 2018). One shortcoming of these studies has been the limited scope at which they are able to assess patterns. Often, researchers are only able to sample a limited range or type of vegetation, leading to conclusions only applicable to those areas rather than across the Great Lakes basin. One of the hypothesized reasonings for temporal influence on fish assemblages in Great Lakes coastal wetlands is the impact of water levels on fish habitat in the form of wetland vegetation (Fracz & Chow-Fraser, 2013; Montocchio & Chow-Fraser, 2021).

Wetland vegetation has been shown to be a more effective indicator of fish assemblages than water quality (Cvetkovic *et al*., 2010). This is why many studies choose to focus on fish assemblages within Great Lakes vegetation zones, as they can be more reflective of fish assemblages that are either permanent residents or migrants using coastal wetland (Cvetkovic *et al*., 2010; Jacobus & Ivan, 2005; Midwood & Chow-Fraser, 2012; Trebitz *et al*., 2009b).

Vegetation in this ecosystem are significantly influenced by the surrounding abiotic conditions, often defining the extent of the habitat present (Burgmer *et al*., 2007; Fracz & Chow-Fraser, 2013; Lemein *et al*., 2017; Trebitz *et al*., 2009a). As a result of fish assemblages being strongly associated with vegetation where they reside and vegetation being influenced by abiotic characteristics, it can be inferred that fish assemblages are influenced by surrounding abiotic conditions. Some studies have shown that invasive vegetation has had negative impacts on the abundance and diversity of fish in assemblages of coastal wetlands (Schrank & Lishawa, 2019). As these habitats continue to be influenced by anthropogenic stressors and be degraded, continued study into the relationship between vegetation and fish assemblages is important to understanding how to best manage these ecosystems and the Great Lakes fishery.

As a result of fish assemblages reflecting the biotic and abiotic characteristics of the surrounding environment, they have been used as a measure of the overall health of the coastal wetland where they reside (Bhagat *et al*., 2007; Brazner *et al*., 2007a, 2007b; Cooper *et al*., 2018; Cvetkovic & Chow-Fraser, 2011; Montocchio & Chow-Fraser, 2021; Seilheimer & Chow-Fraser, 2006; Uzarski *et al*., 2005). While many indices of biotic integrity (IBIs) contain metrics consisting of multiple biotic variables, an important component is often a fish index (Bhagat *et al*., 2007; Cooper *et al*., 2018; Seilheimer & Chow-Fraser, 2006; Uzarski *et al*., 2005). With fish utilizing coastal wetlands having different tolerances to abiotic influences dependent on species, they can give insight to more long-term water quality conditions than a simple water quality test as that provides only a brief snapshot of the current conditions (Cooper *et al*., 2018; Seilheimer & Chow-Fraser, 2006; Trebitz *et al*., 2007b). Results of studies using these indices show that as more long-term data are available using consistent sampling methods, the more accurate these indices can be.

While there is extensive research in Great Lakes coastal wetlands regarding fish assemblages and how they vary, there are few studies that address fish assemblages on the scale of the entire Great Lakes basin. By using consistent sampling methodology and sampling over both large spatial and temporal scales, observations can be made and applied to larger scales, such as the Laurentian Great Lakes basin. This can lead to more effective and informed management of these important but degraded ecosystems and the fisheries that they support.

3.2 Extended Methodology

Dataset Acquisition

The dataset used in this analysis was acquired from the Great Lakes Coastal Wetland Monitoring Program (GLCWMP) main website (https://www.greatlakeswetlands.org). This included all data collected from related water quality and vegetation sampling that took place simultaneously. All data not related to fyke netting was excluded for this analysis. Sampling methodology is detailed in section 2.3.2 of this thesis, which is summarized from the methods described in detail in Uzarski *et al*., (2017) and Cooper *et al*., (2018).

Dataset Manipulation

The fish dataset (based on fyke netting) acquired from the GLCWMP needed to be manipulated from its original form to be used for analysis. The first step in this process was to remove any of the benchmark sampling sites that were not scheduled as part of the regular panel sampling. Benchmark sampling sites were defined as coastal wetlands specially requested to be sampled as part of the GLCWMP due to special circumstances or an ongoing restoration project. As a result of this, all benchmark site sampling needed to be removed from the dataset as they did not reflect the goal of this study. This was to remove any bias there would be towards those sites due to their higher sampling frequency. Monodominant vegetation types were simplified into 10 distinct categories from the original 21 types. Much of this was because of removing vegetation types that were associated with non-panel benchmark samplings (open water and within diked areas) or combining descriptive forms of the same type (*Polygonum* spp. combined into submerged aquatic vegetation). All fyke net data from a vegetation type collected on a single day were combined to create a sampling point for the dataset. In some cases, only two fyke nets were successfully fished at a vegetation type within a site. For these instances, catch was adjusted by effort (i.e., expressed as catch per unit effort) and expressed as the number of fish captured per three fyke nets.

As a result of conducting fish identification in the field, many of the young-of-year (YOY) *Lepomis* could not be differentiated between Bluegill (*Lepomis macrochirus*) or Pumpkinseed (*Lepomis gibbosus*). This led to all species listed as Bluegill or Pumpkinseed being combined into a single taxonomic group “Bluegill or Pumpkinseed” for the analysis. A similar case was exhibited with members of the *Ameiurus* genus. YOY Black Bullhead (*Ameiurus melas*) and Brown Bullhead (*Ameiurus nebulosus*) were difficult to reliably identify in the field early on in the project until reliable characteristics were assessed (Dumke *et al*., 2020), so all records of Black Bullhead and Brown Bullhead were combined for analysis.

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