WETLAND-NEAR SHORE HABITAT COUPLING IN THE GREAT LAKES: RECONSTRUCTING FISH MOVEMENTS AMONG GREAT LAKES COASTAL WETLANDS

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This is dedicated to my parents Gary and Kathy and my sister Katelan. Your constant encouragement made the completion of this project possible.

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ABSTRACT

WETLAND-NEAR SHORE HABITAT COUPLING IN THE GREAT LAKES: RECONSTRUCTING FISH MOVEMENTS AMONG GREAT LAKES COASTAL WETLANDS

by Lee S. Schoen

Great Lakes coastal wetlands are unique habitats found on the margins of Great Lakes. They may or may not have a surface water connection to the lake itself, but water levels in the wetlands are controlled by Great Lake water levels. This connectivity facilitates the exchange of nutrients, biota and energy between the two habitats in a phenomenon known has habitat coupling. Habitat coupling can be accomplished through chemical cycling as well as physical transport by biota including insects, fish and birds. For those coastal wetlands that do have a surface water connection to the Great Lakes, I predicted that the two habitats may be connected through frequent migrations of forage and predatory fishes. To test this, I utilized otolith transect LA-ICPS to track individual movements across the boundary of wetland and near shore environments. First, I sampled trace element water chemistry from across the Great Lakes to establish a trace element gradient between wetland and near shore environments. At the same time, I collected physical characteristics at each wetland to explore trace element concentrations relationships with at a later time. Next, using the trace element gradient established from water samples, I utilized otolith LA-ICP-MS to reconstruct habitat use for individual yellow perch collected from 13 sites across the Great Lakes. Multivariate statistical analysis of water chemistry revealed that Ba:Ca and Sr:Ca were the two most important elements in discriminating wetlands from the adjacent near shore habitat. Calcium-standardized trace element concentrations were negatively correlated with oxidation reduction potential (ORP) and positively correlated with organic sediment depth. Concentrations of Sr:Ca and Ba:Ca from the

outer margin of otoliths representing the most recent habitat use showed positive linear relationships with the water chemistry in which they were caught. As a result, outer-otolith Sr :Ca and Ba:Ca data from fish caught in wetland and near shore environments were used to regionally generate a trace element threshold for each habitat type using linear discriminant function analysis (LDFA). After developing and verifying the initial model, a predict function was applied to the remaining otolith transect data to reconstruct fish movements between the two habitats. The results indicated three life history strategies were found for yellow perch including (1) wetland residents (2) near shore residents and (3) residents utilizing wetland once per year in the spring. These results suggest that complex life histories of this species may help facilitate habitat coupling and habitat connectivity.

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CHAPTER I

INTRODUCTION

Great Lakes coastal wetlands are distinct habitats found along the margins of Great Lakes. They are differentiated from other wetland types by having a direct hydrologic connection, either surface or subsurface, with the Great Lakes. Of interest to freshwater ecologists, this hydrology facilitates the free exchange of water, energy, trace elements and organisms between wetlands and adjacent off shore areas. This exchange of energy and nutrients across habitat boundaries is known as habitat coupling (Dolson et al., 2009). Habitat coupling can be facilitated by physical forces as well as well as movements of biota between each habitat (Cloerne, 2007; Schindler and Scheuerell 2002 and Dolson et al., 2009).

Cross-habitat connectivity or habitat coupling is a common feature of both aquatic and terrestrial environments. In aquatic habitats, organisms such as fish, plankton and macro-invertebrates are often identified as the primary biological conduits for this connectivity (Gorman et al., 2012). For example, zooplankton such as *Hemimysis anomola* (bloody red shrimp) exhibit diel vertical migrations from the benthic zone to the water column at night (Ives et al., 2013). This behavior couples these two habitats biologically and redirects energy from the benthic zone to consumers in the pelagic zone (Ives et al., 2013). Similarly, in Lake Superior, pelagic and benthic habitats are connected energetically through vertical and horizontal migrations of predator and prey fishes such as Cisco *(Coregonus artedi),* Bloater (*Coregonus hoyi),* kiyi (*Coregonus kiyi),* Rainbow smelt (*Osmerus mordax),* or Lake Trout (Salvelinus namaycush) (Gorman et al., 2012). Moreover, Brazner (2001) directly observed habitat coupling of wetland and near shore habitats by the horizontal emigration of young of year (YOY) forage fishes contributing nutrients and energy to near shore Lake Superior. As a result of these and

other similar studies, large scale exchanges of energy in lentic environments are generally attributed to fish movements such as prey fish migration or direct cross habitat foraging (Schindler and Scheuerell, 2002; Vadeboncoeur et al., 2002; Vander Zanden and Vadeboncoeur, 2002).

Traditionally, research on the habitat connectivity of large lake complexes has placed emphasis on the importance of near shore pelagic habitats as opposed to littoral habitats as an energetic basis (McQueen et al.1989, Hairston and Hairston 1993; Schindler et al., 1996). However, recent research has shifted focus onto the importance of littoral productivity and the connectivity of littoral-pelagic pathways on the structure and function of large lake ecosystems (Vander Zanden and Vadebocoeur, 2002; Gorman et al., 2012 and Dolson et al., 2009). Through stable isotope food web analysis, fish biologists have documented the flow between wetland and near shore food webs of the Great Lakes (Sierszen et al., 2012, Vander Zanden et al., 2002). Fish movements such as YOY larval fish traveling out of wetlands could export wetland carbon whereas fish migrating into wetlands could bring near shore subsidies (Brazner et al., 2001). Since fish biologists believe that wetland visits by adult species are limited to major life history events such as spawning or nursery habitat, detailed individual habitat usage (life history diversity) could be useful in exploring cross-habitat connectivity (Jude et al., 1996). While generalizations have been made about the extent of prey and predator fish movements at early and late life stages, the frequency and duration of horizontal movements are underexplored for species whose range regularly spans littoral and pelagic habitats of the Laurentian Great Lakes. This should be an important consideration to fully understanding littoral-pelagic connectivity.

In addition to explaining a mechanism behind dietary exchanges, knowledge of habitat use for individuals within a population is valuable since it could explain the large variation in

stable isotope dietary reliance seen between individuals from the same predatory population such as in adult northern pike (*Esox luscious)* in Lake Superior wetlands (e.g. Sierszen et al., 2012). The variation in within populations is likely related to the existence of wetland resident and more migratory pelagic sub-populations. This behavior has been suggested in populations of yellow perch *(Perca flavescens)*, white perch (Morone americanas*)* and anadromous freshwater eels (*Anguilla rostrata)* (Parker et al., 2009; Hedger et al., 2009 and Kerr et al., 2009). This phenomenon is likened to a behavior known as partial migrations in which one portion of a given population remains in natal habitats while the other portion migrates out into the near shore environment with changing physical conditions and physiological cues (Kerr et la., 2009). This has been demonstrated by otolith microchemical studies in white perch as well as genetic and morphological studies in yellow perch (Kerr et al., 2009 and Parker et al., 2009). Presumably, these subpopulations would have vastly different dietary reliance based upon this differential habitat use; however, without knowledge regarding individual habitat use, this relationship would remain poorly understood.

To estimate fish movements between habitat types, several methods have evolved including mark-recapture methods (Pangle et al., 2010). While these methods are particularly effective in tracking short-term, small-scale fish movements, these methods have logistical limits in studies exploring large-scale, life history movements such as between wetland and near shore habitats of the Great Lakes. A more practical approach for understanding long-term (i.e. life-long) movements over large spatial scales may involve the use of trace element signatures in fish otoliths.

Otoliths or "ear stones" are internal structures used by fish for hearing and balance. These mineral structures are composed of calcium carbonate ($CaCO_3$) in the approximate form

of 95% aragonite and 5% protein-rich organic matric (Bacon et al., 2004). As fish grow, daily growth rings are formed in the aragonite crystalline matrix of otoliths which are visible through microstructural examination (Kennedy et al., 2002 and Campana and Thorrold, 2001). Although composed mainly of calcium carbonate, a variety of trace elements partition into the aragonite in place of Ca. While there are instances where elements are physiologically regulated by fish (Warner et al., 2005), some specific trace elements are incorporated into the otolith relative to Ba:Ca and Sr:Ca in the water at the time of growth (Zeigler and Whiteledge, 2010; Pangle et al., 2010: Campana et al., 1999; Kalish, 1989).

Therefore, in general fish movements can be reconstructed if the habitats under question have distinct chemistries that are recorded in to otoliths (Kalish, 1990). Otolith chemistry has been used to reconstruct the migration histories of several anadromous fishes since saltwater has a much higher concentration of Sr:Ca than their natal freshwater streams (Volk et al., 2002; Zimmerman and Reeves, 2002 and Kalish, 1990). Using microstructural analysis (similar to dendrochronology), the age at which fish leave and return to their nursery streams can be deduced and migratory individuals can be differentiated from non-migratory counterparts so long as sufficient chemical gradients exist in the trace elements of interest between the habitats being considered (Zimmerman and Reeves, 2000; Zimmerman and Reeves, 2002). However, it must also be noted that temperature, genetics, diet and salinity are confounding factors that may influence trace element concentrations in otoliths (Doubleday et al., 2013; Woodcock et al., 2012; Webb et al., 2012; Walther et al., 2010; Collingsworth et al., 2010; Miller, 2009; and Martin et al., 2004).

Fisheries biologists have further recognized the utility of fish otoliths because, unlike other anatomical elements such as fish scales or spines, otoliths do not reabsorb once they are

formed and are chemically stable throughout the fishes life and after extraction (Campana and Thorrold, 2001; Brazner et al., 2004; Pangle et al., 2010). This characteristic preserves the daily chemistry and chronological order of an individual fish's habitat use (Brazner et al., 2004; Pangle et al., 2010). This can be used to determine the frequency of time spent in different habitats by analyzing trace elements starting at the most recently deposited material (margin) to the oldest (core) via Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS) which chemically analyzes selected areas of the otolith (Fowler et al., 1995; Gemperline et al., 2002).

Objectives and Hypotheses

The main objective of this study was to use trace element otolith microchemistry in habitat reconstruction for yellow perch to determine the extent to which wetland and near shore habitats are used in terms of annual frequency and duration. This information would be vital to the understanding of wetland near shore habitat coupling. In order to accomplish this, our first goal was to determine if trace element gradients exist between wetland and near shore areas of the Great Lakes. Our second goal was to analyze for these elements via otolith microchemistry analysis to show life histories of wetland and near shore habitat use for Great Lakes fishes. We predicted that yellow perch would be tracked back to littoral habitats once per year based upon present knowledge of their littoral spawning behavior; however, we also expected that individual yellow perch might be utilizing wetland more or less frequently within the Great Lakes population.

CHAPTER II

METHODS

Site Description

Sites were selected in lakes Michigan and Huron, including Saginaw Bay (Figure 1). Selections were mainly based upon the availability of collaborators with the Department of Natural Resources (DNR) to sample near shore game fish with beam trawls to examine habitat use by these adults. An example of wetland and near shore sampling stations can be seen in figure 2 for Saginaw Bay sites. All sites were sampled in the wetland and near shore habitats with the exception of Pentwater and Alpena. At these sites, near shore collections were not made. All sites and locations where collections were made can be found in Table 1.

The minimum wetland size considered was 10 hectares and a total of 13 wetlands from Lakes Huron and Michigan were selected for analysis. Fish community habitat use was compared for multiple locations of the Great Lakes representing two wetland types (i.e., lacustrine and riverine). This included fringing and embayment wetlands in Saginaw Bay and Northern Lake Huron with no direct tributary inputs as well as riverine drowned river mouth wetlands along the east coast of Lake Michigan. These comparisons are important since differences in lake characteristics, hydrologic connection or disturbance have been shown to alter trophic pathways and reduce efficiency and biodiversity in an area (Sierszen et al., 2006). Moreover, by surveying a wide range of wetland types and conditions, we hoped to determine if wetlands are an important to near shore fishes.

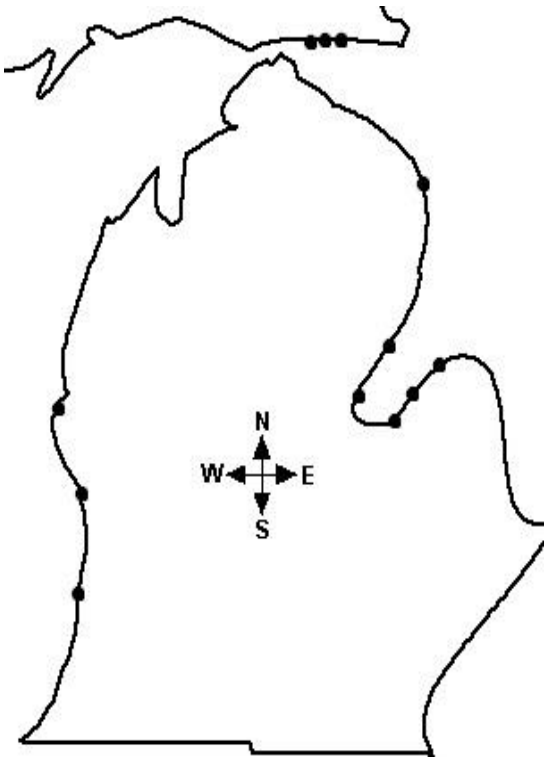

Figure 1. Location of sampling sites from Lakes Michigan and Huron, including Saginaw Bay. Sites marked by black dots.

Table 1. List of all sites with dates of sampling and method of fish sampling.

Region	**Site**	**Date**	**Habitat**	**Gear Type**	**Lat**	**Long**
Lake Huron	Alpena	6/7/2012	Near shore	Gill Net	45.00028333	83.44075
Lake Huron	DuckBay	7/3/2012	Wetland	Fyke net	45.96615833	-84.37646667
Lake Huron	DuckBay	9/7/2012	Wetland	Electrofishing	45.96378889	-84.37753056
Lake Huron	DuckBay	9/24/2012	Near shore	Gill Net	45.96698333	-84.3691
Lake Huron	GovernmentBay	7/4/2012	Wetland	Fyke net	45.97745833	-84.33311944
Lake Huron	GovernmentBay	9/7/2012	Wetland	Electrofishing	45.97745278	-84.33316111
Lake Huron	GovernmentBay	9/24/2012	Near shore	Gill Net	45.97195	-84.31635
Lake Huron	MismerBay	7/2/2012	Wetland	Fyke net	46.00518611	-84.465025
Lake Huron	MismerBay	9/7/2012	Wetland	Electrofishing	46.00429444	-84.46031389
Lake Huron	MismerBay	9/25/2012	Near shore	Gill Net	45.99385	-84.42653333

Lake Michigan	GrandHaven	7/31/2012	Wetland	Fyke net	43.08020556	-86.23752222
Lake Michigan	GrandHaven	8/27/2012	Near shore	Trawl	43.99353333	-86.29213333
Lake Michigan	GrandHaven	9/1/2012	Wetland	Electrofishing	43.07158611	-86.20654167
Lake Michigan	Kalamazoo	7/30/2012	Wetland	Fyke net	42.64467222	-86.19025278
Lake Michigan	Kalamazoo	8/22/2012	Near shore	Trawl	42.35445	-86.3498
Lake Michigan	Kalamazoo	8/31/2012	Wetland	Electrofishing	42.64601944	-86.19621111
Lake Michigan	Pentwater	8/1/2012	Wetland	Fyke net	43.76565556	-86.40808333
Lake Michigan	Pentwater	9/1/2012	Wetland	Electrofishing	43.76333056	-86.41054444
Saginaw Bay	AuGres	6/26/2012	Wetland	Fyke net	44.02873611	-83.67175833
Saginaw Bay	AuGres	9/12/2012	Near shore	Gill Net	44.02683333	83.63033333
Saginaw Bay	AuGres	9/14/2012	Wetland	Electrofishing	44.03686389	-83.67320278
Saginaw Bay	FishPoint	7/12/2012	Wetland	Fyke net	43.71043333	-83.54205833
Saginaw Bay	FishPoint	9/7/2012	Wetland	Electrofishing	43.66788333	-83.58102222
Saginaw Bay	FishPoint	9/10/2012	Near shore	Gill Net	43.71816667	83.58883333
Saginaw Bay	Pinconning	7/1/2012	Wetland	Fyke net	43.847425	-83.91826389
Saginaw Bay	Pinconning	9/11/2012	Near shore	Gill Net	43.79698333	-83.83416667
Saginaw Bay	Pinconning	9/14/2012	Wetland	Electrofishing	43.85469444	-83.92063611
Saginaw Bay	Quanicasee	6/26/2012	Wetland	Fyke net	43.58131944	-83.68215
Saginaw Bay	Quanicasee	9/6/2012	Near shore	Gill Net	43.725	-83.7445
Saginaw Bay	Quanicasee	9/14/2012	Wetland	Electrofishing	43.59210833	-83.67741389
Saginaw Bay	WildfowlBay	6/25/2012	Wetland	Fyke net	43.88030278	-83.33754167
Saginaw Bay	WildfowlBay	9/5/2012	Near shore	Gill Net	43.8896	-83.45868333
Saginaw Bay	WildfowlBay	9/14/2012	Wetland	Electrofishing	43.85936667	-83.35574167

Water and Otolith Collection

Before otoliths were analyzed, paired wetland and near shore waters were sampled at all 13 sites both in the spring and fall of 2012. This was necessary in order to evaluate trace element

variations between paired wetland-near shore habitats regionally. Sampling took place at 3 sites in Lake Michigan and 10 in Lake Huron. All wetland water samples were taken from within the most dominant vegetation type. Near shore sampling occurred just beyond the boundary of the wetland vegetation in areas greater than 1 meter of depth. For Lake Michigan riverine wetlands, the near shore water sample was taken outside of the river plume. In addition, an intermediate water sample was collected at the wetland-near shore interface. This sample was collected to determine if the trace element chemical boundary was diffuse or if a large degree of mixing occurs between the two habitat types.

All trace element water samples were collected and processed using a protocol modified from that described by Shiller (2003). Briefly, all materials used in collection (HDPE syringes and containers) were acid washed with reagent grade nitric acid (HNO_3) diluted to 20% for a total duration of 24hours. From there, containers were triple rinsed with milli-Q ® water and dried under a laminar flow hood. In addition to this step, 0.45um, 25mm polypropylene syringe filters were cleaned and rinsed in the field with optima ® grade HNO_3 (diluted to 20%). This procedure was carried out just prior to use because it avoided any harmful drying of the filters before sampling.

At each site, subsurface water samples were collected in pre-cleaned 250ml HDPE sample bottles. From there, a 26ml aliquot was removed and filtered through a pre-cleaned syringe filter into a pre-cleaned 30ml sample bottle. It is necessary to filter out any particulate matter (since particulate matter can contain elevated trace metal levels), thus sampling only the dissolved solids for analysis (Shiller, 2003). Prior to storage, 4 ml of optima ® grade HNO_3 (diluted to 15% with milli-Q ® water) was added to each filtered site sample. This provided a

final sample volume of 30 ml at 2% HNO_3. This acidification step is necessary so that all trace metals remain in solution during storage. All samples were refrigerated at 4 ºC until analysis.

In this study, habitat use reconstruction via otolith chemistry was limited to yellow perch. This species was chosen because of its economic and ecological importance as a forage fish and a recreational game fish in Canada and 46 U.S. states (Crossman 1991 and Rahel, 2000). In addition, its mobile behavior and abundance in Great Lakes wetlands and near shore habitats was a major reason for its selection (Beletsky et al., 2007, Blackwell et al., 2011 and Brazner et al., 2004 and Becker, 1983).

In addition to its distribution and physical characteristics, the life history of this species is particularly useful in exploring habitat connectivity because of its known wetland and near shore associations (Beletsky et al, 2007). For example, yellow perch are typically hatched from wetland vegetation before absorbing their yolks and dispersing to the near shore as pelagic, planktivorous larvae for 30-75 days (Beletsky et al., 2007). This stage is followed by a movement back in to wetland complexes before moving back off shore to feed on a mixed diet of benthos and prey fishes after age-1 (Wu and Culver, 1992; Fulford et al., 2006; Stevenson et al., 1990 and Brazner et al., 2001; Parker et al. 2009). Presumably, each of these stages has the potential to shuttle energy between the habitats. However, the extent, frequency and relative duration of such movements have not been specifically explored for the species.

An effort was made to sample juveniles and adults in the wetland and the adjacent near shore habitat. A minimum of three and maximum of five fish per habitat (i.e. wetland and near shore) were required for inclusion in final analysis. Wetland fish samples were collected with a combination of modified fyke nets and boat electrofishing. Fyke nets were similar to those being used across the Great Lakes for littoral sampling and are described in Uzarski et al. (2005) and

Breen and Ruetz (2006). Fyke nets were constructed of 4mm mesh and depending upon water depth, nets had box dimensions of 0.5x1 m or 1x1 m with 0.5x7.2 m or 1x7.2 m leads. Nets were set for 24 hours before collection. Electrofishing was completed on a Smith-Root 19' electrofishing boat. The current ranged from 4-6 amps at 240 V using pulsed DC. All electrofishing was completed at night in depths between 0.5 and 2 meters. All fish were euthanized in a solution of excess buffered MS-222 (Tricaine Methanesulfonate) and placed on ice. All samples were frozen within 24 hours of collection. Near shore sampling was conducted by collaborators from the Michigan DNR via gill nets or beam trawls conducted between 0.5 and 2.5 miles from adjacent wetlands (Figure 2). All fish were euthanized in a solution of excess buffered MS-222 and placed on ice. All samples were frozen within 24 hours of collection. All otoliths were removed and analyzed at Central Michigan University within a year of collection.

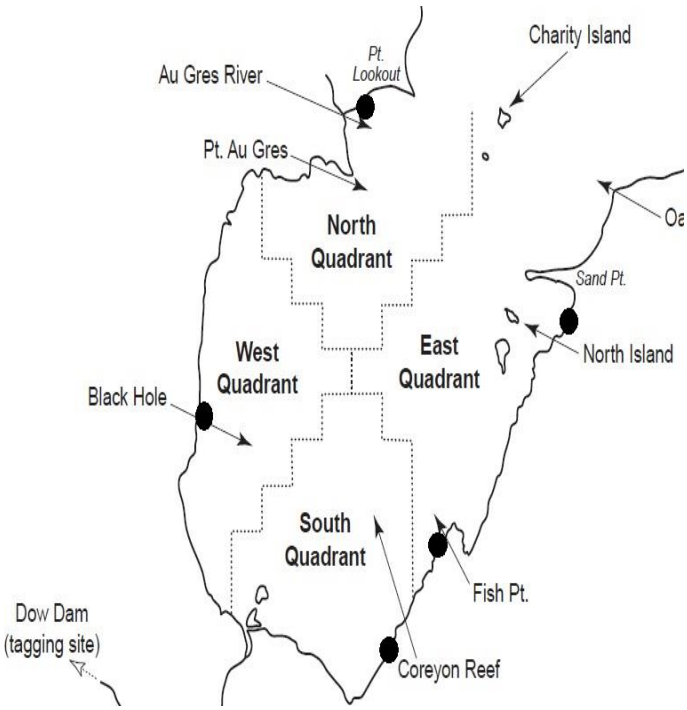

Figure 2. Example of sampling sites for Saginaw Bay**.** Sites included in this project include Fish Point, Black Hole, North Island and Coreyon Reef and Au Gres River. Near shore sampling locations used by the Michigan Department of Natural Resources (MDNR) are indicated by arrows. Wetlands sampling locations are marked by black dots. This map was modified by Fielder and Thomas (2006).

Otolith extraction was conducted in the wetland ecology lab at the Center for Applied Research and Technology with the aid of dissecting microscopes, if necessary. All otoliths were removed from yellow perch collected in near shore habitats within 6 months of collection. Sagittal otoliths were removed and handled according to a protocol modified from that described by Campana et al., (2000). This included cleaning of any connective tissue with milli-Q ® water and storage in new polypropylene micro centrifuge tubes. Otolith sections were prepared by mounting otoliths in Epo-fix ® epoxy resin and subsequent sectioning with an isomet ® low-speed wafering saw to a thickness of 400µm (Zeigler and Whitledge, 2011 and Friedrich and Halden, 2008). After sectioning, otoliths were ground to the plane of the core with 30 and 3

micron lapping paper by hand before polishing with 1 micron polishing paper to expose annuli. Before analysis, otoliths were glued to analysis slides using krazy glue® and sonicated for 10 minutes in 18.2 ohm milli-Q ® water.

Water Sample Analysis

Immediately prior to analysis, 9.8 ml of each preserved water sample collected in this study was aliquoted from the 30ml sample bottle (using sterile 10ml pipette tips and a pipette) and spiked with 0.200ml of an internal standard of In^{115} into sterile 15ml autosampler tubes. All samples analyzed including blanks, project samples and standards contained 2ppb In^{115} to correct for instrumental drift and sample matrix basis during analysis through standardization calibrations. As such, project water samples measured in this study had a dilution factor of 1.1774x. Based upon similar otolith studies, elements of interest included strontium (Sr), barium (Ba), sodium (Na), magnesium (Mg), potassium (K), manganese (Mn), lead (Pb) and calcium (Ca). Similar to other studies, Ca was measured in each water sample to standardize each element to moles of Ca.

Trace element analysis for water chemistry was conducted utilizing a double –focusing single–collector high-resolution sector field inductively coupled plasma mass spectrometrer (SF-ICP-MS) at the Center for Elemental and Isotopic Analysis (CELISA) at Central Michigan University. The analytical setup included a Thermo-Finnigan Element 2 SF-ICP-MS (Thermo-fisher Scientific®, Germany), a CETEC® ASX-520 autosampler, and a Elemental Scientific Instrument ® Peltier chiller (PC^3) and quartz dual cyclonic spray chamber with a Microflow PFA-400 self-aspirating Teflon nebulizer (400µl/min). Table 2 summarizes parameters used to analyze water samples in this study.

Table 2. SF-ICP-MS operating parameters used to analyze water samples in this study.

Forward Power	1275 W
Cool Gas Flow	18L/min Ar
Auxiliary Gas Flow	0.8L/min Ar
Guard Electrode	On
Sample Gas (Ar)	1.153 L/min (tuned for sensitivity)
Data Acquisition	intensity averages
Scanning Mode	Escan
Detector Mode	analog and counting
Resolution	Low and Medium
Isotopes Determined	
Low Resolution (LR)	^{88}Sr, ^{115}In, ^{137}Ba, ^{206}Pb, ^{207}Pb, ^{208}Pb
Medium Resolution (MR)	^{23}Na, ^{24}Mg, ^{39}K, ^{44}Ca, ^{55}Mn, ^{63}Cu, ^{115}In
Dwell Time (segment duration)	0.4-1.25 s depending on isotope
Sample* duration	0.01-0.05 s depending on isotope
Magnet settling time	0.001-0.30 s between various mass settings
Mass Window	80-125% depending on isotope
Samples per Isotope Peak	25-40 depending on isotope
Integration Window	10-12 samples per peak
Analytical time per sample	2min 33 seconds
Runs and Passes	3 and 5
Sensitivity on 115In(LR) during tuning	1,900,000 cps per ppm total In
Sample uptake time	80 seconds
Sample washout	120 seconds
*Note sample is defined as single vertical chord making up part of isotope peak segment.	

Reported concentrations values from this study were determined using calibration with standard solutions prepared using single elements standards (1000ppm in 4% HNO_3) from SCP Science in a final matrix of 2% HNO_3 and 2ppb In. 5 different standard solutions (each containing all the elements of interest) were prepared with a range of concentrations for each element. The highest range was for Ca (50- 100,000 ppb) and the lowest ranges were for Cu, Mn, and Pb (0.010-20 ppb). Minimum detection limits of 0.003ppb (Pb), 0.012ppb (Mn), 0.013ppb (Cu), 0.016ppb (Ba), 0.099ppb (Sr), 14.6ppb (Mg), 16.6ppb (K), 22.6ppb (Na), and

32.5ppb (Ca) were calculated based on 3x the cps of the average laboratory blanks. Concentrations of all measured samples were based on the average of 15 measurements (3 runs, 5 passes) over 2min and 33 seconds for each sample and standardized to calibration samples (quantification and external calibration routine using internal standards in E2 sequence editor routines of the Element software package).

Otolith Analysis

Otolith analysis was conducted utilizing laser ablation sector field inductively coupled plasma mass spectrometry (LA-SF-ICP-MS) at CELISA. The analytical setup included a Thermo-Finnigan Element 2 SF-ICP-MS coupled to a Photon Analyte193nm Excimer laser ablation system. The operating parameters and analytical methods were modified from those described by Friedrich and Halden (2010) mainly due to differences in laser ablation systems and the trace elements of interest (see Table 3 for a full description of operating parameters). Prior to each otolith analysis, an 80µm-wide pre-cleaning ablation raster was conducted (2 pulses per 80 x 80 µm square). Using a 30-µm-diameter-beam traveling at a rate of 2 µm/sec, laser ablation transects(perpendicular to growth annuli) were run across each otolith starting from the outer edge and crossing the otolith core. In some cases, otoliths were analyzed on a line across the entire otolith passing through the core. In other cases, the transect line was angle was changed in order to avoid obvious fractures.

Table 3. SF-ICP-MS operating parameters used to analyze otolith samples in this study.

Forward Power	1300 W
Cool Gas Flow	18L/min Ar
Auxiliary Gas Flow	0.8L/min Ar
Guard Electrode	On
Sample Gas (He/Ar)	1.47/1.34 L/min
Data Acquisition	time resolved
Scanning Mode	Bscan and Escan
Detector Mode	analog and counting
Resolution	Low
Isotopes Determined	^{25}Mg, ^{43}Ca, ^{55}Mn, ^{65}Cu, ^{66}Zn, ^{88}Sr, ^{137}Ba, ^{208}Pb
Dwell Time (segment duration)	0.048 s per isotope
Sample* duration	0.0012 s
Magnet settling time	0.001-0.30 s between various mass settings
Mass Window	80%
Samples per Isotope Peak	40
Integration Window	8 samples per peak
Time/pass	0.986 s across the selected isotope range
Number of passes	varied for laser line length/otolith size
Sensitivity on 88Sr	13,000 cps per ppm total Sr (based on NIST 612)
*Note sample is defined as single vertical chord making up part of an isotope peak.	
Photon193 Laser	
Repetition Rate	12 Hz
Pulse Duration	<4 ns
Power	60%
Laser Stabilization Mode	Energy
Energy	7.5 mJ
Fluence	4.63 J/cm^2 (Calculated)
Spot Size	30 µm
Laser Scan Speed	2 µm/sec
Sample Chamber Flush	He carrier gas (1.47 L/min)

The analyses of 5-6 otoliths (depending on transect lengths) were bracketed by 3 NIST 612 glass standard analyses for trace element concentration determinations. Measured trace element concentrations where processed using the Iolite software Trace Element Internal

Standardization Routine (Woodhead et al., 2007; Hellstrom et al., 2008). Ca was used as an internal standard at 40.0 wt.% as in stoichiometric Ca carbonate relative to NIST 612 glass concentration values reported by Pearce et al., (1997). For every sample and standard analysis, 40-50 seconds of carrier gas background was measured prior to laser ablation. After laser ablation, all otoliths were imaged with imagepro ® software and a compound microscope equipped with a digital camera and high intensity base light. This was necessary to age each individual and to measure and label the core and annuli regions on the resulting trace element spectra. Means limits of detections were prepared using GLITTER software according to Friedrich and Halden (2008). Limits of detection for Mg, Mn, Cu, Zn, Sr, Ba and Pb were 0.364, 0.253, 0.080?, 0.139, 0.061, 0.059 and 0.008 µg/g, respectively.

Data Analysis

Before statistical analysis, all ppm values from water and otolith trace element analysis were converted into molar equivalents and normalized to µmol"X":molCa where "X" is the element of interest. All subsequent data analysis used ratios in this normalized form. Lead was excluded from all statistical analyses because it often fell below detection limits in both water and in the otolith analyses.

Linear discriminate function analysis (LDFA) was used on the remaining 6 dissolved trace elements to determine the most important trace elements discriminating wetland water chemistry from that of the near shore. Six groups were used in the LDFA including Lake Michigan wetland, Lake Michigan near shore, Lake Huron wetland, Lake Huron near shore, Saginaw Bay wetland and Saginaw bay near shore. Wetland samples in all subsequent figures are denoted as 'WL' whereas near shore samples are denoted by 'NS.' The data set was separated this way due to the underlying bedrock geology of the three regions believed to

influence the dissolved trace element fraction. For example, the bedrock geology of sites in northern Lake Huron, Saginaw Bay and Lake Michigan is dominated by Saint Ignace Dolomite, Saginaw Formation and Bois Blac Formation/Coldwater Shale, respectively (Michigan DNR). After the LDFA, a leave-one-out jack-knifing function was used to reclassify each individual water sample to habitat type. In addition to this analysis, a prediction function was used to classify the remaining intermediate water samples taken at the wetland-near shore interface to determine whether the chemical transition boundary between these two habitats was distinct or diffuse based upon the multivariate suite of trace elements analyzed. Multiple response permutation procedure (MRPP) was used to test the significance of the six groups from the LDFA bi-plot. Two-sample t-tests were used to compare the wetland and near shore water chemistry (regionally) for the dominant trace elements from the LDFA.

Next, a principal components analysis (PCA) was conducted on the wetland water chemistry (excluding near shore data) to explore any multivariate groupings or gradients in the trace element chemistry across out 13 wetland sites. Near shore chemistry was excluded so that the wetlands would be ordered from increasing to decreasing µmol"X":molCa molar ratios. Principal component 1 (PC1) and principal component 2 (PC2) were used as synthetic variables with which we explored relationships with. Correlations were explored between PC1/PC2 and wetland characteristics including oxidation reduction potential (ORP) (mV), turbidity (NTU), organic sediment depth (cm) and modified effective fetch (km) which could show a relationship with standardized trace element concentrations. In situ water characteristics were taken using a Yellow Springs Instruments (YSI) model 6600 V2 multi-parameter data sonde including oxidation reduction potential (ORP), turbidity (NTU), dissolved oxygen (mg/L), temperature

(ºC) and pH. Modified effective fetch was calculated using Google-earth® satellite software along with a formula from the British Columbia Estuary Mapping System ®.

Equation 1.

$$Fm = [\cos(45^{\circ}) F45L + \cos(90^{\circ}) F090 + \cos(45^{\circ}) F45R] / [\cos 45^{\circ} + \cos 90^{\circ} + \cos 45^{\circ}]$$

Fm = Modified effective fetch
F = Fetch distance
45L = 45^0 left of perpendicular to the shoreline
45R = 45^0 right of perpendicular to the shoreline

Relationships between mean water and otolith chemical signatures for each habitat were explored across our sampling sites. This was important to determine whether or not water chemistry was controlling trace element content in the otoliths. The outer 20 microns of data from each otolith were used to explore these relationships since this portion reflects the most recent environmental chemistry. Mean water chemistry values for each site were used and plotted in the regressions +/- 1 SE. Mean outer otoliths values for yellow perch caught in each site and each habitat type were used as the dependent variable, +/- 1 SE, regardless of age. Regressions were run separately on wetland and near shore caught fish because of the potential effects cooler pelagic water has on the inclusion of trace elements in near shore fish. Least-squares linear regressions were used to quantify relationships between mean water and mean otolith signatures for each habitat. Trace element otolith data from the outer margins of fish caught from each habitat type (wetland and near shore) were also plotted by site and chemical differences between wetland and near shore caught fish were explored with two-sample t-tests to illustrate the habitat (wetland and near shore) differences in trace elements.

To objectively distinguish between wetland and near shore habitat use in the trace element spectra, it was necessary to determine a threshold value associated with each habitat

type. Traditionally, interpretation of fish movements through spectra has been subjective i.e. peaks are interpreted as movements; however, small scale variation may be the result of other changes in environment such as temperature or salinity since both factors can significantly impact the inclusion of elements into the otolith structure (Collingsworth et al., 2010 and Martin et al., 2004). With the aid of a threshold value, wetland habitat use can be estimated more accurately and objectively. It is not possible to do this with the trace element water chemistry, since otolith ratios do not exactly follow that of the surrounding water due to physiological regulation within the fish (Dorval et al., 2007).

Instead, we used the outer otolith trace element data from fish caught in each habitat type to develop a threshold value on a regional basis (i.e. Lake Michigan, Lake Huron, Saginaw Bay). Since the concentrations of strontium and barium in otoliths broadly followed that of the water chemistry, the outer-otolith concentrations of these two elements were combined in an LDFA to create the wetland and near shore threshold. After running the analysis on the outer otolith data from fish caught in either habitat, we verified the accuracy of the model using a leave-one-out jackknifing procedure to reclassify each data point used in building the model on a regional basis. Wetland/near shore classification accuracies ranged from 79.4-88.7% for wetland-caught fish and 98.3-100% for near shore fish (Table 4). Adding Mg to the analysis did not influence the accuracy, therefore it was excluded from the model even though it was the only other element above detection limits in otolith margins. Next, we utilized the predict function through LDFA to classify the remaining transect data as representing near shore or wetland habitat use.

Table 4. Leave-one-out jackknifing cross-validation results applied to outer otolith data of known-habitat yellow perch, by region.

Saginaw Bay			
	NS	WL	% correctly classified
NS	180	0	**100%**
WL	32	128	**80.0%**
Lake Huron			
	NS	WL	% correctly classified
NS	177	3	**98.3%**
WL	17	133	**88.7%**
Lake Michigan			
	NS	WL	% correctly classified
NS	190	0	**100%**
WL	33	127	**79.4%**

All t-tests and tests of normality were run in minitab 16.0. Principal components analysis and linear discriminate function analysis were run in R 2.15.1. PC-ORD 5 was utilized for the multiple response permutation procedure. Pearson correlations, least squares linear regressions and final figures were completed with Sigmaplot 11.0. Alpha = 0.05 was used for all statistical tests.

CHAPTER III

RESULTS

Water Chemistry

After normalizing each element relative to the molar equivalent of Ca, the LDFA indicated that Ba and Sr were the most important elements discriminating wetlands from the near shore (Figure 3). LD1 and LD2 explained 0.5422 and 0.2292 of the trace, leaving approximately 0.23 of the variation among groups unexplained. Post-hoc leave-one-out jackknifing classified 40/46 sites correctly down to habitat type (i.e wetland or near shore) although several sites were misclassified as the wrong region but correct habitat type. The sites that were misclassified to habitat type included Alpena WL, Government Bay WL, Pentwater WL and Augres WL. All wetland sites were classified as near shore water samples. Using the predict function through the LDFA, all but three of samples taken from the wetland-near shore boundary were classified as near shore water samples (Figure 4). The MRPP based upon the four groups circled in figure 4 resulted in significant groups ($p<0.001$, A= 0.29304, T=-9.40543, observed delta = 334248.34).

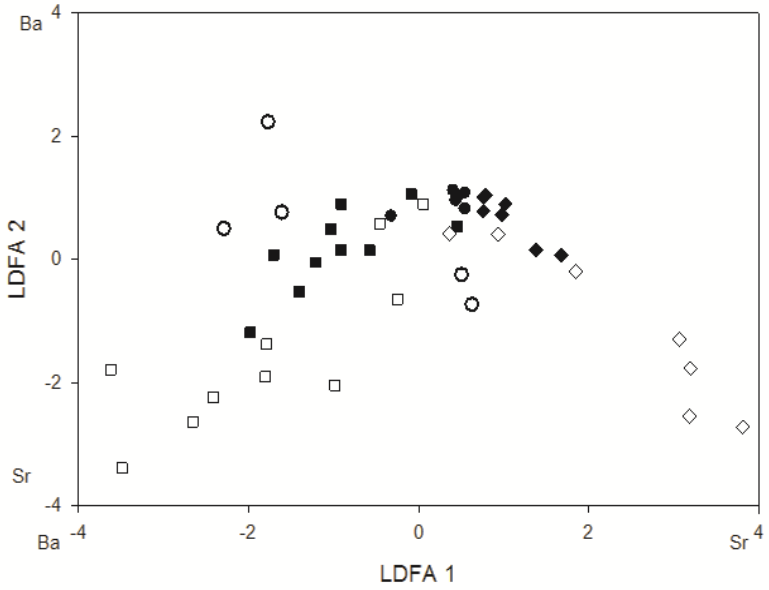

Figure 3. LDFA of trace element data after standardizing to µmol"X":molCa. Shapes indicate region of Great Lakes (circle = Lake Michigan, diamond = Lake Huron, square = Saginaw Bay). Fill indicates habitat type (open = wetland , black = near shore).

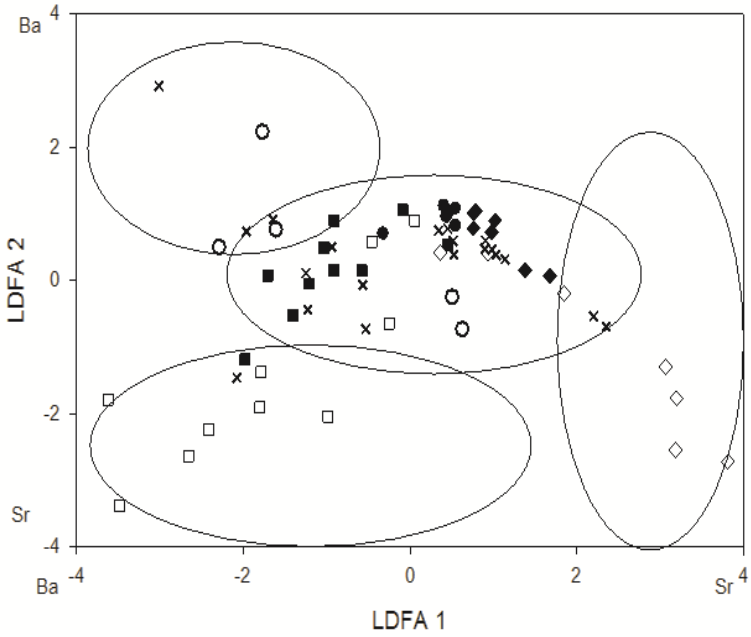

Figure 4. LDFA of trace element data after utilizing the bootstrapping function in R. Intermediate water sample are noted by X. Groups used in the MRPP are indicated by circles.

Graphs of regional wetland and near shore means with deviations and two-sample t-tests among groups are shown in Figures 4 and 5 for Ba and Sr. Ba was more important than for discriminating Lake Michigan wetlands from the near shore chemistry (p=0.013). On average, Lake Huron and Saginaw Bay wetlands were not different from the near shore based upon Ba concentrations (p=0.109 and p=0.105). Sr was most important for discriminating Lake Huron and Saginaw Bay wetlands from the near shore (p=0.029 and p=0001). With respect to Sr, Lake Michigan wetlands were not different from the near shore, on average (p=0.066).

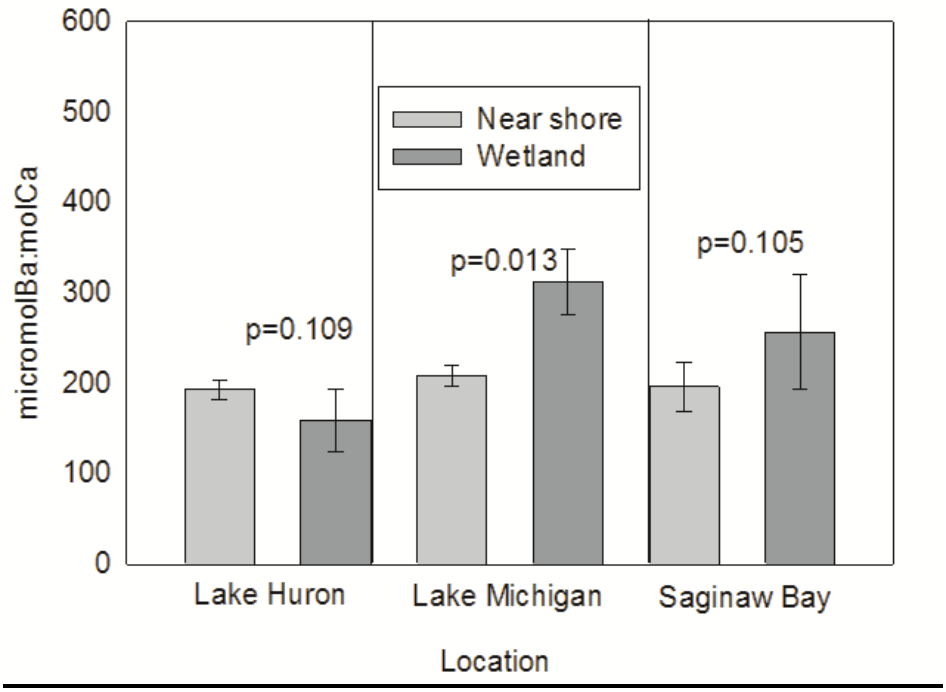

Figure 5. µmolBa:molCa +/- 2 SE for water samples. Results from pairwise two-sample t-tests shown by p-value.

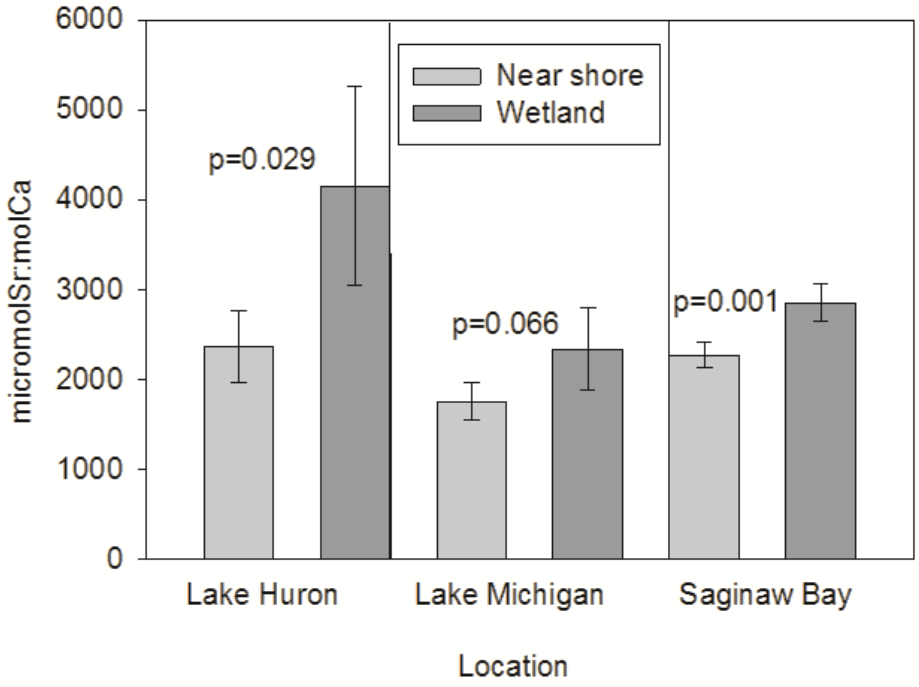

Figure 6. µmolSr:molCa for water samples +/- 2 SE. Results from pairwise two-sample t-tests shown by p-value.

Relationships with Wetland Conditions

In the PCA, PC1 and PC2 explained 49.5% and 20.9% of the variation, respectively. PC1 ordered the wetlands from highest (most concentrated) to lowest (least concentrated) in all trace elements, shown by the distribution of misclassified wetland sites and the directionality of the eigenvectors. Sr and Mg were associated more strongly with PC2 whereas Ba,K and Mg were associated with PC1. Wetlands circled are right were all misclassified by post-hoc jackknifing in the LDFA as near shore samples (Figure 6). Therefore, PC1 and PC2 were used as a synthetic variable representing decreasing µmol"X":molCa with which to run correlations with. Coordinates from synthetic axis PC1 showed positive correlations with organic sediment depth (p=0.028) and a negative correlation with ORP (p=0.0154). There was no correlation

between PC1 and modified effective fetch (p=0.227). This correlation revealed a relationship between higher trace µmoBa, Mg, Mn and K:molCa in sites with higher organic sediment content and lower ORP. Other site-specific field measurements did not show significant relationships with the trace element gradient given by PC1. Principle component 2associated with higher Sr and Magnesium (PC2) did not show correlations with any of the field measurements.

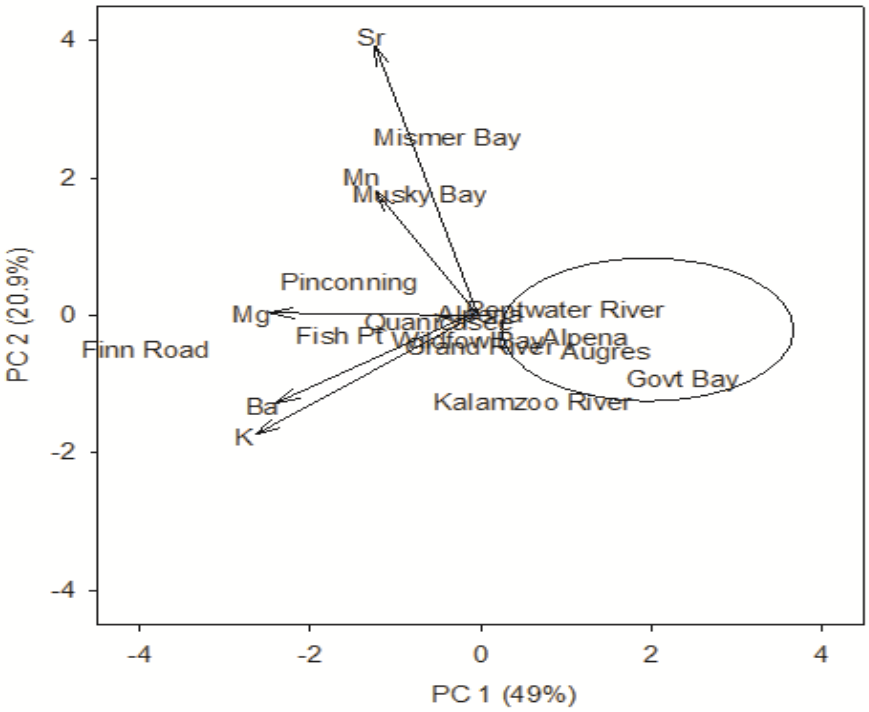

Figure 7. PCA of standardized (µmolX:molCa) spring wetland trace element data. Sites labeled by site names, circle indicates wetland sites misclassified as near shore by the LDFA leave-one-out jackknifing exercise.

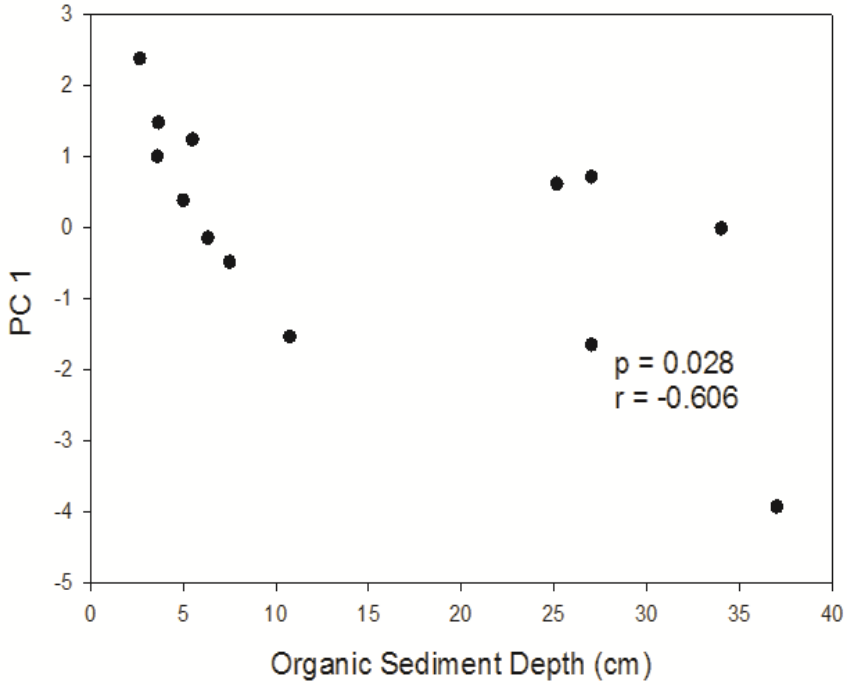

Figure 8. Pearson correlation between PC1 and organic sediment depth in centimeters.

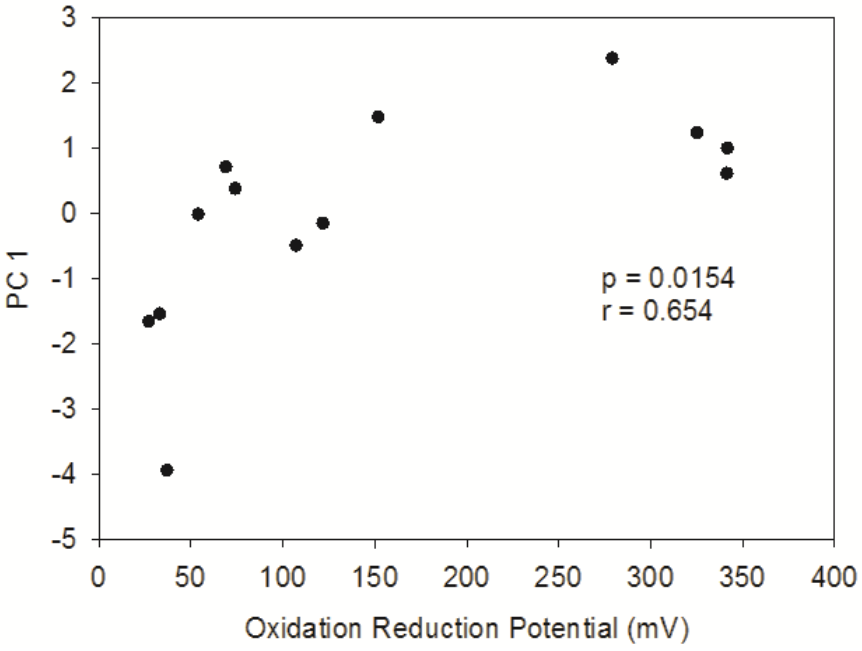

Figure 9. Pearson correlation between PC1 and oxidation reduction potential (ORP) in millivolts.

Otolith Data

Mean otolith Sr:Ca and Ba:Ca showed a positive linear relationship with water Sr:Ca in the near shore and wetland habitats and Ba:Ca in wetland caught fish only. (Figures 10, 11 and 12) ($p = 0.013$, $r^2 = 0.502$ and $p = 0.013$, $r^2 = 0.507$, $p = <0.001$, $r^2 = 0.676$). No relationships were found for Ba:Ca water and Ba:Ca otolith for fish collected from near shore habitats (Figure 13) ($p = 0.706$, $r^2 = 0.000$) or for magnesium or manganese in either habitat type. Other trace elements were not included in this analysis because they frequently fell below detection limits at the outer margin of the otoliths used in analysis although they were elevated in the core region. Therefore, they were not considered in the otolith spectra as indicators of fish movement.

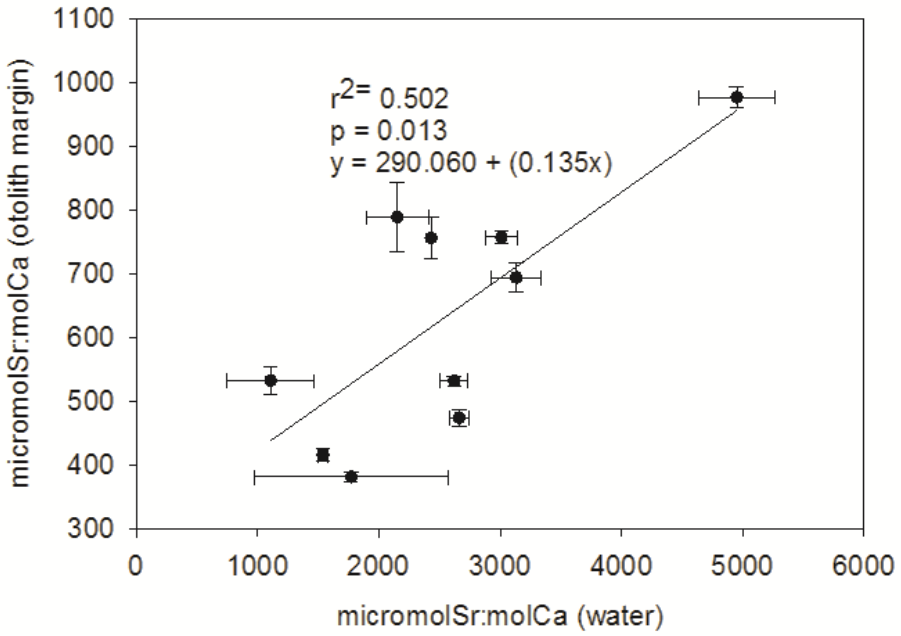

Figure 10. Least squares regression between wetland shore water and otolith Sr:Ca. Data points are sample means +/- 1 SE.

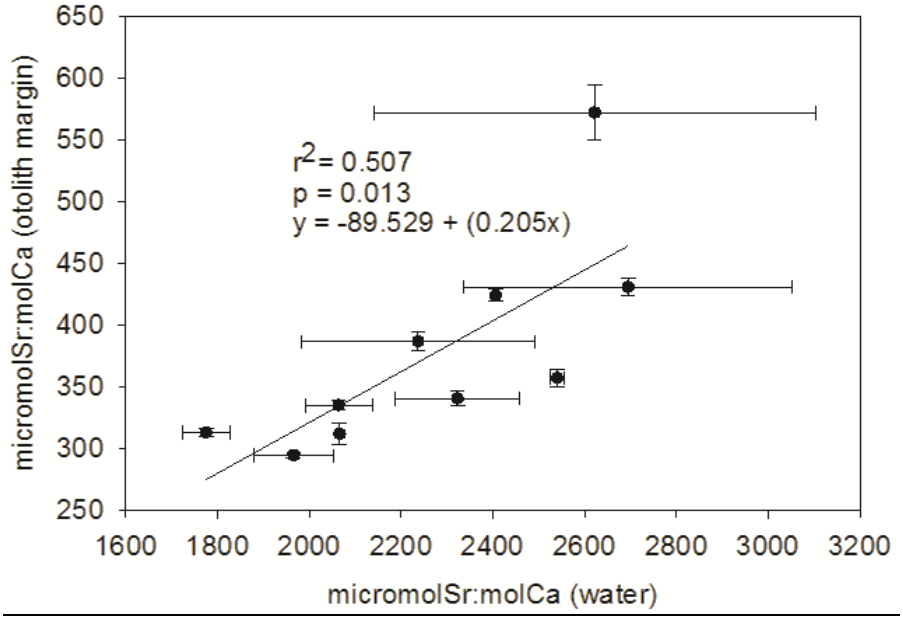

Figure 11. Least squares regression between near shore water and otolith Sr:Ca. Data points are sample means +/- 1 SE.

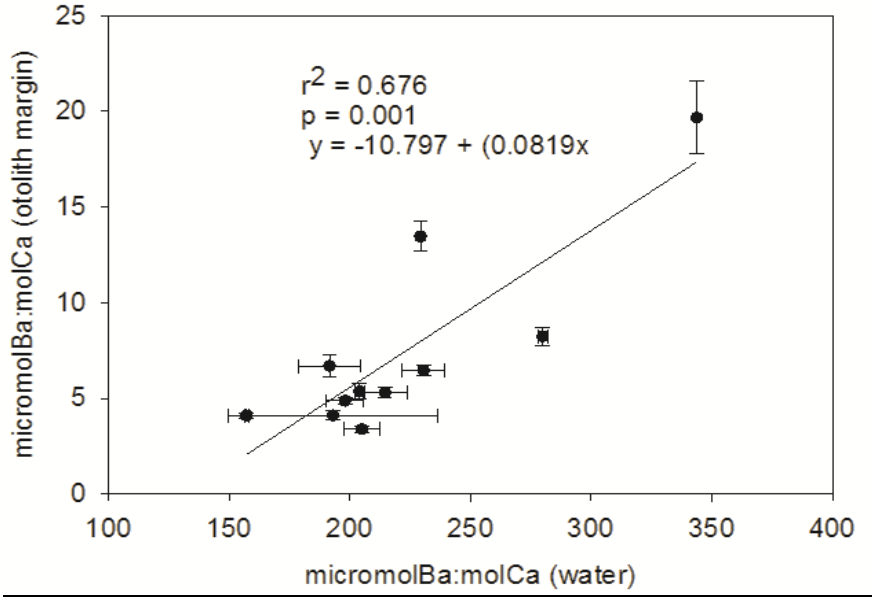

Figure 12. Least squares regression between wetland water and otolith Ba:Ca. Data points are sample means +/- 1 SE.

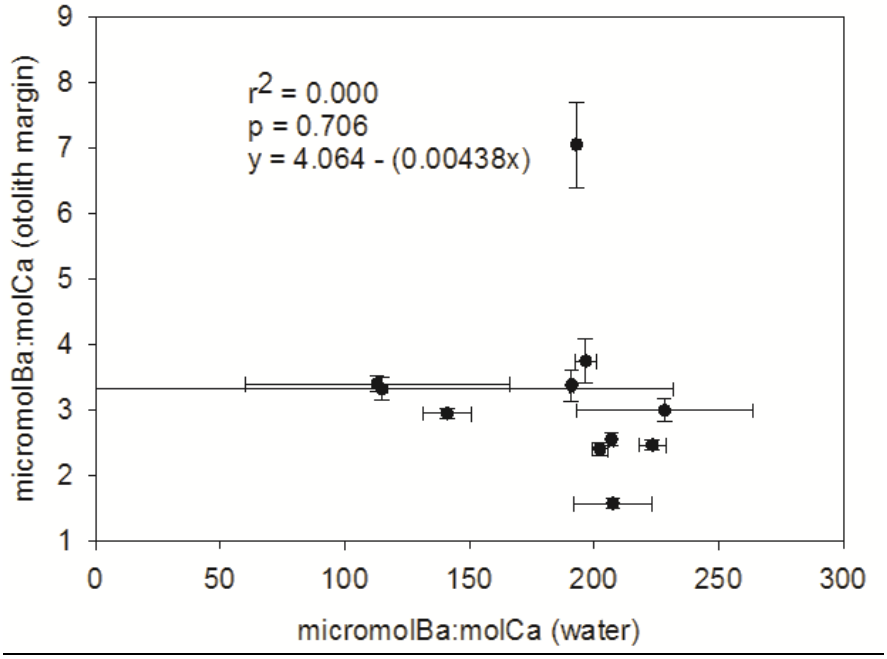

Figure 13. Least squares regression between near shore water and otolith Ba:Ca. Data points are sample means +/- 1 SE.

Pairwise comparisons of the mean otolith margin Sr:Ca for fish caught in wetland and near shore environments were significant (figure 14) at all sites ($p<0.05$). The same comparisons for Ba:Ca in wetland and near shore caught fish was significant for all sites except for Government and Mismer bays (figure 15). For these two sites, fish caught in wetland and near shore habitats had statistically similar Ba:Ca ($p>0.05$).

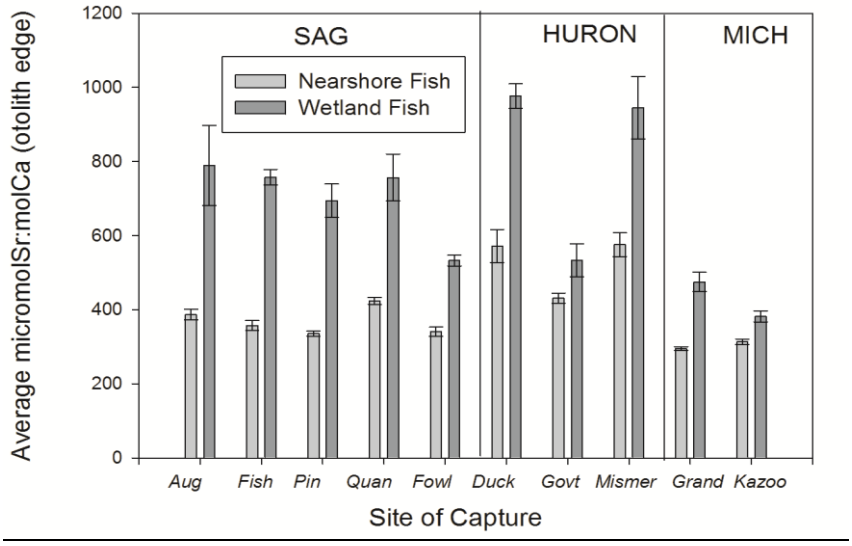

Figure 14. Comparison of otolith outer margin µmolSr:molCa for fish caught at different sites and different habitats +/- 2 SE. All pairwise WL-NS comparisons significant unless otherwise noted.

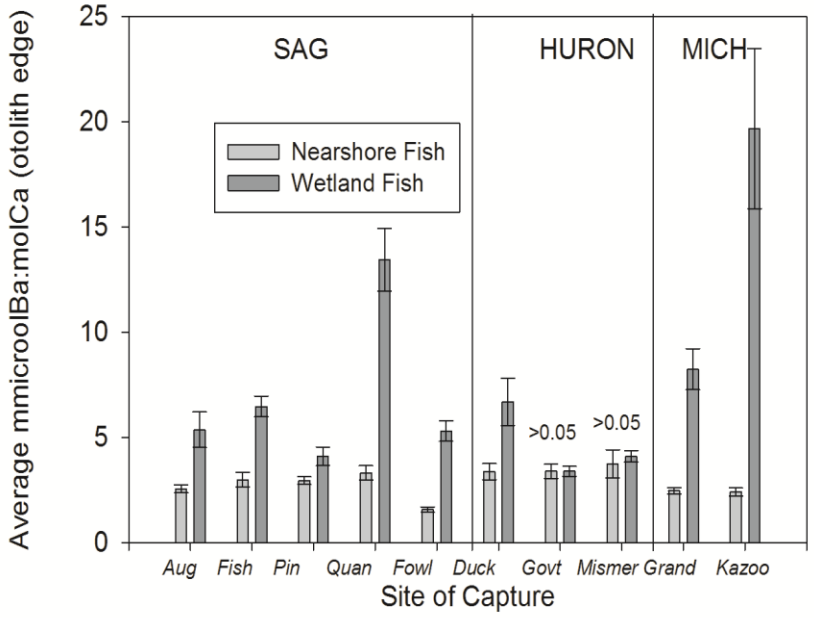

Figure 15. Comparison of otolith outer margin µmolBa:molCa for fish caught at different sites and different habitats +/- 2 SE. All pairwise WL-NS comparisons significant unless otherwise noted.

All final otolith spectra used in habitat construction were created by plotting µmolSr:molCa along the laser transect. Interpretation and reconstruction of habitat use within these spectra was accomplished combining µmolSr:molCa and µmolBa:molCa in the LDFA because of the difference in wetland and near shore habitat chemistry (Figures 5, 6, 14 and 15) and because of the strong relationship between Sr/Ba:Ca water Sr/Ba:Ca otolith chemistry in wetland and near shore habitats (Figures 10, 11,12 and13). Ba was plotted in Figure 16 alone for the sole purpose of displaying the occurrence and extent of the core region in each spectra.

After plotting the data, all yellow perch otolith spectra displayed a common pattern in early life otolith chemistry before the first annuli (Figure 16). First, the core area of all yellow perch was marked by an elevated level of Ba. A peak of this magnitude was not observed outside of this region of the otolith. Conversely, the core region was marked by depleted levels of Sr. Between the core and annuli one, each spectra showed a peak in Sr:Ca. This was followed by a decrease in Sr:Ca and Ba:Ca and another peak near the first annuli. When applying the LDFA predict function to this spectra, the intermediate peak between the core and annuli 1 is classified as wetland habitat use and the peak after annuli 1 is also classified as wetland habitat use (Figure 17).

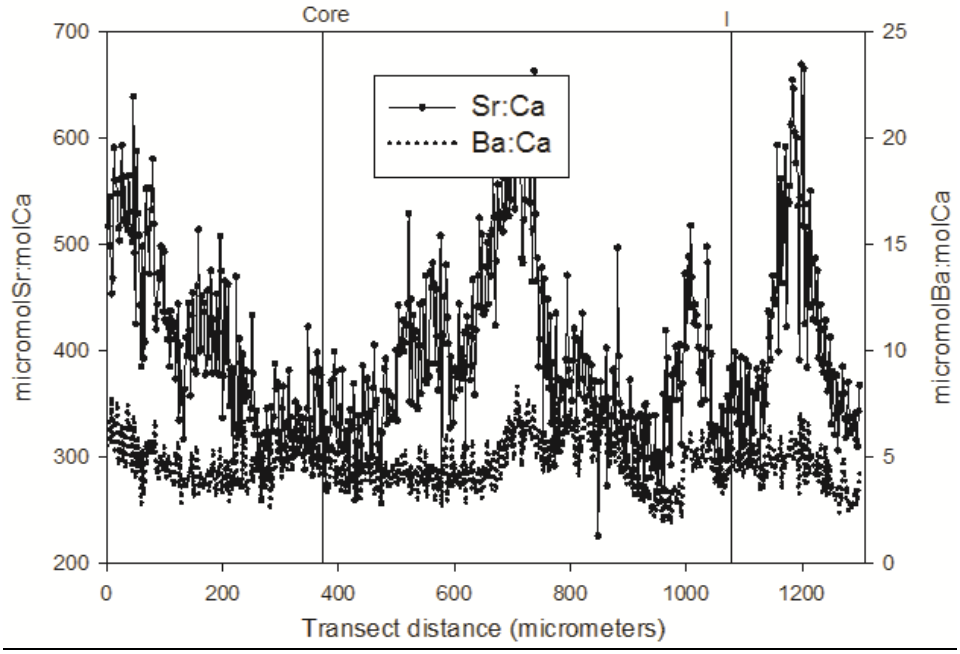

Figure 16. µmolSr:molCa and µmolBa:molCa for an age 1+ yellow perch from Alpena. Raw data plotted, unsmoothed.

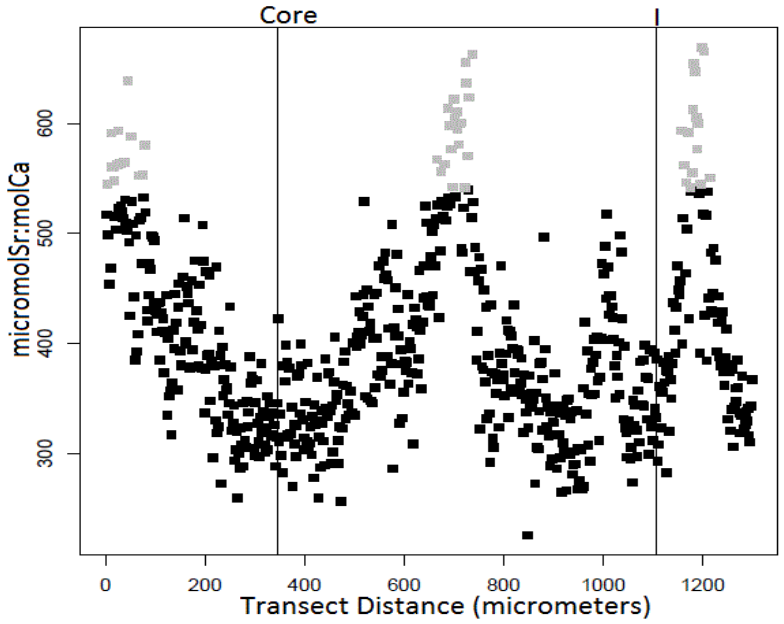

Figure 17. Classification of wetland and near shore habitat from Figure 16 based upon the LDFA model using Sr and Ba. Data points represent the strontium profile, wetland habitat use is indicated by dark squares, near shore habitat use is indicated by dark squares. Core and annuli indicated by vertical bars.

Any fish greater than two years of age was classified as an adult. As a result, 51 yellow perch were included in the adult habitat reconstruction analysis. After applying the model to these adult spectra, adult yellow perch displayed at least three distinct Sr profiles outside of the first annuli (Figures 18, 19 and 20). In life history 1, element values increase above the wetland-near shore cutoff value once per year when the annuli are deposited (Figure 18, n=33). In scenario 2, values remain below the wetland-near shore for several years while increasing above the threshold other years (Figure 19, n=10). In scenario 3, values increase and remain above near shore levels for year round and/or increase above near shore levels twice per year (Figure 20, n=8).

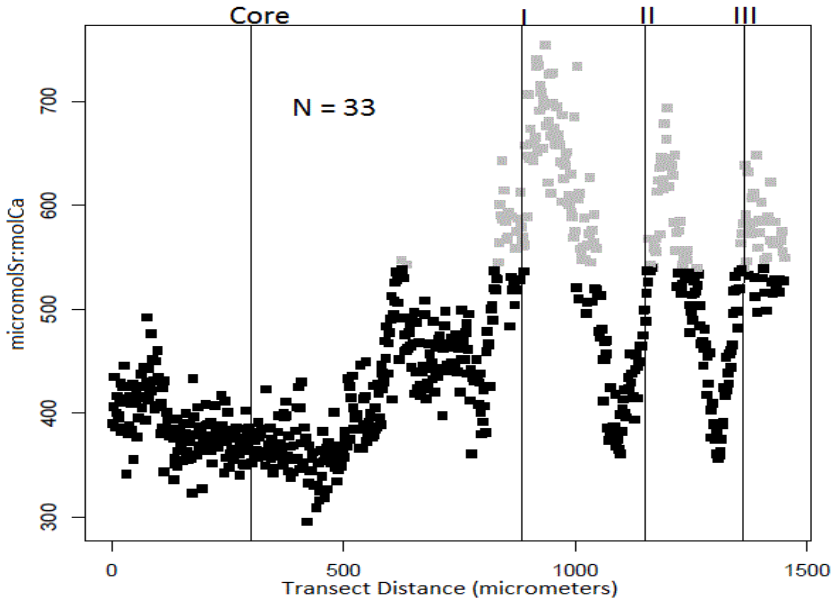

Figure 18. Classification of wetland and near shore habitat based upon the LDFA model using Sr and Ba. Data points represent the strontium profile, wetland habitat use is indicated by dark squares, near shore habitat use is indicated by dark squares. Core and annuli indicated by vertical bars.

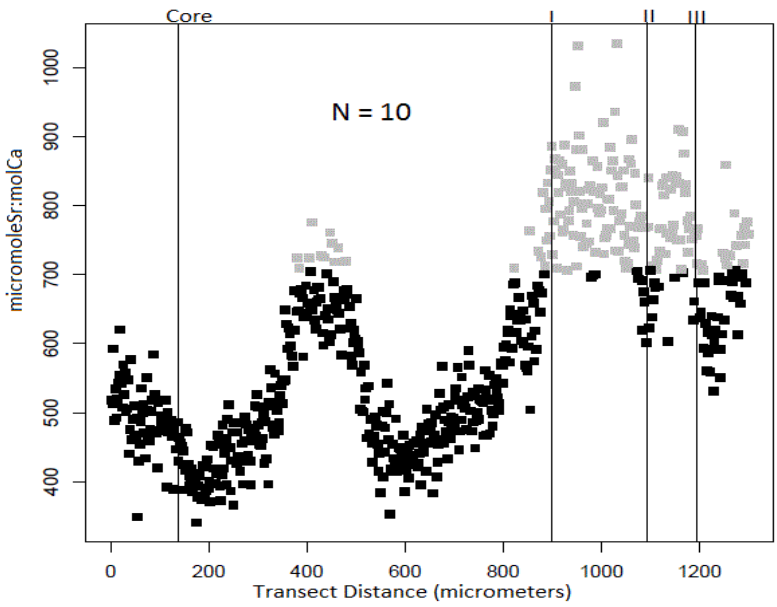

Figure 19. Classification of wetland and near shore habitat based upon the LDFA model using Sr and Ba. Data points represent the strontium profile, wetland habitat use is indicated by dark squares, near shore habitat use is indicated by dark squares. Core and annuli indicated by vertical bars.

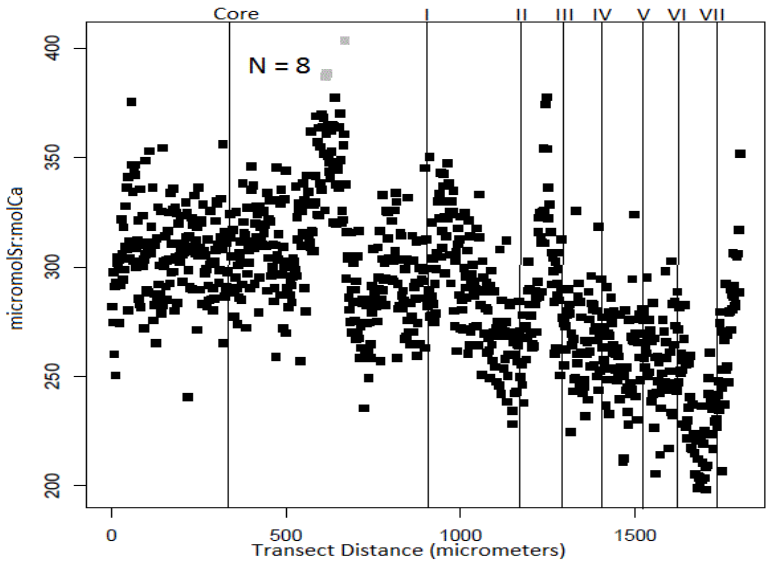

Figure 20. Classification of wetland and near shore habitat based upon the LDFA model using Sr and Ba. Data points represent the strontium profile, wetland habitat use is indicated by dark squares, near shore habitat use is indicated by dark squares. Core and annuli indicated by vertical bars.

CHAPTER IV

DISCUSSION

Otolith chemistry is a rapidly evolving tool used to reconstruct environmental histories and fish movements across areas with different chemical signatures (Elsdon et al., 2008). This technology is commonly applied to explore fish movements across coarse spatial boundaries with distinct chemical boundaries such as freshwater-saltwater movements of pacific salmon or freshwater eels (Hedger et al., 2008, Jessop et al., 2002, Volk et al., 2000, Zimmerman and Reeves, 2000), Zimmerman and Reeves, 2002, Bacon et al., 2004 and Kalish et al., 1990). However, this research is one of the first of its kind to attempt reconstructing movements of non-migratory fish across freshwater habitat types at fine spatial and temporal scales. This included movements between Great Lakes coastal wetlands and near shore zones including riverine wetlands as well as fringing wetlands.

The results of our exploratory trace element water chemistry data indicated that, in general, wetland areas of the Great Lakes can be distinguished from the near shore based upon the suite of trace elements we utilized. After normalizing to molar equivalents of Ca, the most important elements for this discrimination are the elements Ba and Sr. However, there were wetlands whose chemistry could not be distinguished from the near shore. The water chemistry of four wetland samples were misidentified as near shore samples in the post-hoc jackknifing procedure based upon the elements analyzed. These sites included Government Bay, Augres, Alpena and Pentwater. Three of these samples were fringing wetlands, characterized by high wave energy windswept habitats which results in low organic matter and high amounts of mixing with the pelagic zone. The last wetland, Pentwater, is a low order river of Lake Michigan with low discharge. This site has a history of low discharge where it is not uncommon for seiches

from Lake Michigan to force pelagic water upstream from our sampling location. These conditions could explain the observed dilution in trace elements at these wetland sites.

When placing the water samples taken at the interface of the wetland-near shore transition with the LDFA boot strapping function, all but three were classified as near shore samples. This indicates that the chemical transition from wetland to near shore is relatively quick. However, three samples were misclassified as wetland water samples, indicating that the chemistry of these three samples was more similar to that of the wetland. These samples included the intermediate water sample taken at the Pinconning wetland and the Wildfowl Bay wetland. Since both of these wetlands are protected embayments in Saginaw Bay, the water samples were taken well within the limits of embayment which may explain why their water chemistry was so similar to that of the wetland. The last misclassified intermediate sample was taken from the Grand River mouth, which suggests that the chemical boundary between major river plumes and the near shore zone may be fairly diffuse and that the boundary may move in response to increased river discharge during flood events or seiche events when pelagic water is forced up river. As a result, more research needs to be done to determine the spatial variation in trace element water chemistry in complex wetland environments of the Great Lakes.

After constructing a PCA with the wetland trace element data, the wetlands were roughly ordered from highest to least concentrated in trace elements μmolBa, Mg, Mn and K:molCa along PC1. Consequently, the wetland samples misclassified in the jackknifing procedure as near shore samples were found furthest to the right in the PCA. All four of these wetland sites were characterized by characterized by low organic sediment content (i.e. sandy substrates), high conductivity and high ORP (Figures 7, and 8). There was no relationship between wave action (fetch) and trace element concentrations across the samples sites. This was likely because

modified effective fetch does not account for bathymetry which plays a role in moderating wave action where fetch is high. PC2 was strongly associated with μmolMn and Sr:molCa and site characteristics were found; however, no relationships were found by synthetic axis 2 and site-specific characteristics indicating that these variables may not be related to local wetland conditions.

Otolith elemental compositions were correlated with the water chemistry of the corresponding water fish were caught in for Sr and Ba. Interestingly, otoliths from wetlands that had statistically similar water chemistry to the near shore had statistically different concentrations of trace elements indicating that other factors may be influencing trace element inclusion. However, while Ba:Ca of otoliths from fish caught in wetlands followed wetland water chemistry across the wetland sites, there was no relationship between Ba:Ca (water) and Ba:Ca (otolith) for fish caught in the near shore. This may be the result of relatively low variance in Ba across the near shore sites. Additionally, no evidence was found suggesting that water concentrations influences the levels of manganese or magnesium found in fish otoliths. These conclusions are consistent with similar studies that have found that otolith Ba and Sr are influenced mainly by water chemistry as opposed to diet or temperature whereas other elements may be influenced by factors outside of water chemistry including physiological regulation or diet (Zeigler and Whiteledge, 2010 and Gibson-Reinemer et al., 2009, Fowler et al., 1995 and Kalish 1989).

The early life yellow perch habitat reconstruction agrees with what has already been established by fish biologists studying the larval stage of this species. For example, our data suggests elevated levels of Ba, manganese (not pictured) and magnesium (not pictured) in the core of yellow perch. This has been explained by biologists as a relic of the initial calcification

of otoliths which may require larger amounts of protein, therefore integrating higher levels of minor trace elements (Ruttenberg et al., 2005 and Zhang and Runham 1992). Therefore, the elevated levels of these elements do not necessarily indicate wetland habitat use in the core region. Moreover, yellow perch are known to commonly spawn amongst wetland vegetation while undergoing a pelagic larval stage within days of hatching which may last upwards of 80 days (Beletsky et al., 2007). Their return to littoral habitats is documented in every yellow perch otolith that was analyzed in this project by a spike in Sr above the near shore threshold between the core and annuli one.

The results from the LDFA model constructed from the outer 20 microns of otolith chemistry from fish caught in wetland and near shore habitats had accuracy based upon the cross validation table; however, the classification accuracy of wetland fish was lower than that of near shore fish. This is likely because wetland classifications were mostly based upon juvenile young of year individuals. Because of the timing of our sampling, it is likely that these young fish had recently returned to wetland habitats after their pelagic phase. Therefore, their outer otolith material may have not equilibrated with the wetland chemistry and instead reflected the chemistry of the near shore environment they had just migrated from. In addition, based upon our results, there was much more variation among wetland chemistries than near shore chemistries which would result in higher variation in wetland otolith chemistry. Both cases could have limited the accuracy of the LDFA in predicting wetland habitat use.

Outside of this early life history (i.e. annuli 1 and beyond), yellow perch were quantitatively classified into three unique life histories based upon our analysis. The first and most common history is single, annual use of wetland habitats. The purpose of this visit is likely the result of late spring spawning in which adults broadcast strands of eggs amongst structure

including wetland vegetation or woody debris (Kolkolvski and Dabrowski, 1998, Robillard and Marsden 2001 and Thorpe, 1997.) In addition, the location and timing of the Sr spike before annulus formation is consistent with early spring spawning behavior of this species since annuli are typically deposited by June or July of each year in the northern hemisphere, just after peaks in Sr occur (Blackwell et al., 2012).

The second history revealed by our analysis is bi-annual or year-round utilization of wetland habitats of the Great Lakes. Although yellow perch are known to show some flexibility in spawning time from March through rare occasions in October (Kolkovlvski and Dabrowski, 1998), it is generally accepted that the species spawns once per year. Therefore, it would seem that these species may be staying in wetland habitats for reasons such as predator avoidance and/or foraging (Thorpe, 1997). Throughout the Great Lakes, yellow perch are an important forage fish since they connect the base of the food chain to larger piscivorous fish. In the Great Lakes, the diet of yellow perch is dominated by crustaceans and insects such as chironomids or odonate naids from larval phase until a juvenile size of 150mm (Age2-3) after which the fish switch to a mix of insects and piscivory (Clady, 1974 and Thorpe, 1997). Moreover, many species of fish in the Great Lakes use low-oxygen areas such as wetlands as refuge from predators because of the lower aerobic demands on prey species in addition to the high structural complexity offered by macrophyte vegetation (Robb and Abrahams, 2002). Therefore, the utilization of coastal wetlands for long periods of time in to the juvenile stage could be explained by either the need for refuge or simple foraging behavior in wetlands.

The third and final life history that was revealed in this study was the non-use of wetland habitats, exemplified by uniformly low Sr profiles. Although yellow perch traditionally spawn in wetland habitats amongst vegetation, there has been a growing body of work regarding this

species spawning in off shore areas. In fact, some research has demonstrated yellow perch spawning behavior and the presence of eggs in near shore waters of Lake Michigan at depths greater than 5 meters with sufficient cobble substrate (Robillard and Marsden 2001). Therefore, it appears that this third category may be explained by such behavior. Moreover, research by Parker (2009) demonstrated a genetic, morphological and dietary difference in yellow perch inhabiting deep near shore habitats and shallow wetland areas of the Great Lakes. The conclusion of separate yellow perch populations seems well supported by the presence of this third life history category evident in the data collected in this study, although it must be noted that particularly quick wetland visits (i.e. <20 days) may go unnoticed in our data due to technological limits of transect-based LA-ICP-MS methodology. Therefore, these fish may be using wetland so quickly that their presence is not detected by our analysis. Potentially higher resolution LA-SF-ICP-MS studies could be conducted where Sr, Ba, and Ca where the only elements of interest.

In general, these results suggest three specific and complex life histories for yellow perch within the Great Lakes. These histories include individuals that exhibit (1) prolonged wetland-residence (2) prolonged near shore-residence and (3) individuals that visit wetland temporarily each spring for spawning purposes only. This complex set of behaviors has not previously been described for yellow perch and it provides direct evidence of fish-mediated connectivity of Great Lakes coastal wetlands and near shore food webs. This is significant since this fish moves between these habitats and it is known to be an important forage species for many other economically important predatory fish.

Future Directions

The results of this study bring up several important questions for future research. With respect to Great Lakes coastal wetland water chemistry, our research found broad concentrations of Sr and other trace elements with respect to organic sediment depth and ORP with higher trace element concentrations in protected wetland areas with high organic content and low ORP. While we suspect that this relationship may be the result of microbial pathways resulting in a release of elements from the sediments, the research on this topic is limited. In fact, research suggests that the release of metals may be promoted by the dissolution of bacteriogenic iron oxides (Ferris et al., 2000, Fortin and Langley 2005) or reduction of sulfur-metal complexes under reducing conditions (Gadd, 2000 and Negrel and Pauwels, 2003) while other research indicates that the presence of Sr and other metals may be the result of chemical weathering of common minerals and rock materials such as apatite (Blum et al., 2002), plagioclase, celestite, and limestone or via anthropogenic pollution through atmospheric deposition or landscape runoff of materials with heavy metal associations (Negrel and Pauwels, 2003). Additionally it should be noted that apatite is a primary component used in the manufacturing of many commercial fertilizers.

In addition, on several of the spectra small spikes in Sr were apparent below the wetland-near shore threshold value established by the LDFA. While this may have been a quick visit to a wetland, another possibility could be a change in temperate that influence the partitioning coefficient of Sr into the calcium carbonate matrix, although the effects of temperature have been under explored with few lab manipulations with inconsistent results (Collingsworth et al., 2010 and Elsdon ad Gillanders, 2004). Therefore, more research is needed on the thermal regime of

the near shore Great Lakes and the impacts this change has on trace element chemistry before we can determine what these peaks mean for fish habitat use.

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