

**Spatial and Temporal Variation in Lake Huron Yellow Perch (*Perca flavescens*) Life
History Traits**

A Thesis

Submitted to the Faculty of Graduate Studies and Research

In Partial Fulfillment of the Requirements

For the Degree of

Master of Science

in

Biology

University of Regina

by

Ryder Jace Rutko

Regina, Saskatchewan

August 2021

© 2021: R.J. Rutko

UNIVERSITY OF REGINA
FACULTY OF GRADUATE STUDIES AND RESEARCH
SUPERVISORY AND EXAMINING COMMITTEE

Ryder Jace Rutko, candidate for the degree of Master of Science in Biology, has presented a thesis titled, ***Spatial and Temporal Variation in Lake Huron Yellow Perch (*Perca flavescens*) Life History Traits***, in an oral examination held on August 24, 2021. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

External Examiner: *Dr. Caleb Hasler, University of Winnipeg

Supervisor: *Dr. Christopher Somers, Department of Biology

Committee Member: *Dr. Richard Manzon, Department of Biology

Chair of Defense: *Dr. Shaun Fallat, Mathematics & Statistics

*via ZOOM Conferencing

Abstract

Knowledge of fish population structure allows fisheries managers to account for potentially different responses of discrete groups to external stressors. Life history traits are very useful indicators of population structure because they provide information about fish populations that incorporates elements of genetics, environment, and resource use simultaneously. In Lake Huron, the yellow perch (*Perca flavescens*) is managed based on 17 geographic management units; however, it is unknown if management units accurately represent discrete perch groups. Furthermore, it is unclear whether yellow perch population structure changed temporally over the course of the major ecosystem shift in the early 2000s, where invasive mussels decreased zooplankton and benthic invertebrate abundance, altered nutrient and energy distribution, and reduced lake productivity. Here, I used data from the Ontario Ministry of Natural Resources and Forestry's Lake Huron Index Netting Program to derive sex-specific life history traits for yellow perch including size at maturity, age at maturity, maximum size, lifespan, and growth at age 2 from contemporary (2009–2018) and historical (1990–1999) timeframes. In the first part of my study, I examined how yellow perch were spatially structured in Lake Huron. Generalized linear mixed models showed that yellow perch life history traits varied with location and depth, but primarily with latitude. Male maximum size was 1.1-fold greater at southernmost sites (276.3 ± 4.6 mm) compared to northernmost sites (247.7 ± 3.2 mm), while female maximum size was 1.1-fold greater at southernmost sites (318.5 ± 1.3 mm) compared to northernmost sites (293.9 ± 8.1 mm). Longitudinal and depth-based variation existed in fewer life history traits. Female maximum size was 1.2-fold greater at westernmost sites (293.9 ± 8.1 mm) compared to easternmost sites (244.2 ± 12.4 mm).

Male growth at age 2 was 1.2-fold greater at deeper sites (160.0 ± 11.4 mm) compared to shallower sites (131.1 ± 0.3 mm), while female growth at age 2 was 1.2-fold greater at deeper sites (166.1 ± 16.2 mm) compared to shallower sites (139.6 ± 4.0 mm). I found 6 discrete clusters of yellow perch in Lake Huron based on variation in life history trait values, encompassing fish in the (1) South Basin, which were superior in growth, maturity, and lifespan; (2) Main Basin, which grew fast, but died fast; (3) North Channel, which had average growth and maturity, and lived long; (4) northeast Georgian Bay, which were short lived, slow growers; (5) central Georgian Bay, which had slow growth and fast maturity, but died quickly; and (6) south Georgian Bay, which had average growth and maturity, but died quickly. In the second part of my study, I found that yellow perch life history trait values showed no significant temporal variation. The only life history trait that was different before and after the major ecosystem shift was male maximum size, which increased on average 5% from 232.9 ± 23.3 mm to 244.6 ± 30.6 mm. The influence of location and depth varied across timeframes depending on the life history trait analyzed, but did not follow any specific pattern. Clusters of perch identified based on combinations of life history traits were similar in the contemporary and historical datasets. Current management units appear to adequately represent yellow perch population structure in Lake Huron, which suggests that no major change to the spatial arrangement of these management units is necessary. The discovery of no change in life history values over time despite the major ecosystem shift is surprising, and suggests that recent population declines are not via major shifts in the parameters I assessed.

Acknowledgements

First, to my supervisor and good friend Dr. Christopher Somers, thank you for providing me with this incredible opportunity. I am extremely grateful for all of your help, support, and feedback along the way, from when we first met in your Conservation Biology class during my undergrad, to applying for jobs at the conclusion of this degree. I will forever cherish being a member of your lab, and will always remember our talks about fisheries and wildlife management, genetics, research, academia, politics, and life. You are an exceptional role model, and it has been a pleasure to work with you over the last 4 years. To my lab colleagues and co-workers, thank you for creating such a wonderful, funny, and positive working environment in both the field and office. To my committee member, Richard Manzon, thank you for the thoughtful feedback and advice over the course of this study. Finally, and major thank you must go to Chris Davis and the rest of the Lake Huron Office of the Ontario Ministry of Natural Resources and Forestry's Upper Great Lakes Management Unit for providing the extensive database I used in this study.

I would like to thank the organizations that provided financial and in-kind support. Thank you to Bruce Power and the NSERC Collaborate Research and Development Grant Program for the research funding, and to the University of Regina's Faculty of Graduate Studies and Research for a University of Regina Graduate Scholarship and Graduate Teaching Assistantships. Thank you to the University of Regina Department of Biology for the Departmental Teaching Assistantships.

Dedication

I would like to dedicate this thesis to my family and friends, for all of their love and support along this journey. To my mom, Leanne, for showing me the value of education and learning, and for encouraging me to turn my passion of fishing into a career. To my dad, Rob, for taking me fishing when I was young, and for getting me involved in the passion I so dearly enjoy. Thank you both for putting a roof over my head and food on the table when I was younger, and for raising me to have a strong work ethic, chase my goals and dreams, and be a good person. To my brother and sister, Reese and Lorenne, for always being funny, supportive, and encouraging. To my girlfriend Nikita and our beloved pup Bailey, for keeping spirits high and being awesome cheerleaders. Thank you.

Table of Contents

Abstract	i
Acknowledgements	iii
Dedication	iv
Table of Contents	v
List of Tables.....	viii
List of Figures	x
1.0 Introduction	1
1.1 Population delineation in modern fisheries management.....	1
1.2 Characterizing subdivided fish populations.....	3
1.3 Yellow perch importance and status in the Great Lakes and Lake Huron	7
1.4 Yellow perch management in Lake Huron.....	11
1.5 Research Objectives, Hypothesis, and Predictions	16
2.0 Methods and Materials.....	18
2.1 Life History Trait Data	18
2.2 Fish Sampling and Data Collection.....	18
2.3 Location of Sites and Calculation of Site Latitude, Longitude, and Depth for each Dataset.....	20
2.4 Sex-Specific Life History Trait Estimation	27
2.5 Statistical Analysis	28

3.0 Results	30
3.1 Contemporary Dataset (2009–2018)	30
3.1.1 Life History Trait Variation by Location and Water Depth.....	30
3.1.2 Clustering Based on Life History Traits 2009–2018	40
3.2 Historical Dataset (1990–1999)	44
3.2.1 Life History Trait Variation by Location and Water Depth.....	44
3.2.2 Clustering Based on Life History Traits 1990–1999	53
3.3 Temporal Comparison	56
3.3.1 Lake-wide Life History Trait Variation across Timeframes	56
3.3.2 Variation by Location and Depth across Timeframes	60
3.3.3 Variation in Clusters Based on Life History Traits across Timeframes	70
4.0 Discussion	71
4.1 Contemporary Dataset (2009–2018)	71
4.1.1 Life History Trait Variation by Location and Water Depth.....	71
4.1.2 Clustering Based on Life History Traits 2009–2018	76
4.1.3 Management Implications	78
4.2 Temporal Comparison	79
4.2.1 Lake-wide Life History Trait Variation across Timeframes	79
4.2.2 Variation by Location and Depth across Timeframes	80
4.2.3 Variation in Clusters Based on Life History Traits across Timeframes	82

4.2.4 Management Implications	83
4.3 Study Limitations	83
4.3.1 Contemporary and Historical Dataset Limitations	83
4.3.2 Temporal Comparison Limitations	85
4.4 Linking Life History Theory, Yellow Perch Population Ecology, and the Environment	86
References	90
Appendix	111
Supplementary list of tables and figures	112

List of Tables

Table 1: Sites on Lake Huron from OMNRF index netting assessments used to examine life history traits of yellow perch in the contemporary timeframe of 2009–2018. Sites are shown with associated latitude, longitude, depth, years sampled during the timeframe (Time), and sample size for each sex of yellow perch. Latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is an average measured in meters (m). The number of fish sampled and used in the study (n) for each sex at each site is included.22

Table 2: Sites on Lake Huron from OMNRF index netting assessments used to examine life history traits of yellow perch in the historical timeframe of 1990–1999. Sites are shown with associated latitude, longitude, depth, number of years sampled (Time), and sample size for each sex of yellow perch; site numbers represent the same locations as those used in Table 1. Latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is an average measured in meters (m). The number of fish sampled (n) for each sex at each site is also included.25

Table 3: Sex-specific life history trait values at each site for Lake Huron yellow perch sampled in the contemporary timeframe (2009–2018). Length at maturity (L50) measured as fork length in mm, age at maturity (A50) measured as age in years, maximum size (max size) measured as fork length in mm, lifespan measured as age in years, and growth at age 2 (growth rate) measured as fork length in mm are assessed. The lake-wide average with standard deviation ($\bar{x} \pm SD$) for each life history trait is displayed. Male and female growth rate could not be calculated at site 6, while max size and lifespan could not be

calculated at site 13; sites that lack measurement for a particular life history trait are listed as N/A (not available).33

Table 4: Sex-specific life history trait values at each site for Lake Huron yellow perch sampled in the historical timeframe (1990–1999). Length at maturity (L50) measured as fork length in mm, age at maturity (A50) measured as age in years, maximum size (max size) measured as fork length in mm, lifespan measured as age in years, and growth at age 2 (growth rate) measured as fork length in mm are assessed. The mean with standard deviation ($\bar{x} \pm SD$) for each life history trait is displayed. Male max size and lifespan could not be calculated at sites 7, 9, and 18, while male growth rate, female max size, and female lifespan could not be calculated at sites 7 and 9; sites that lack measurement for a particular life history trait are listed as N/A (not available).47

Table 5: Summary table of Generalized Linear Mixed Model results for historical (Hist) and contemporary (Cont) timeframes. Checkmarks (✓) indicate life history traits that were significantly predicted by a geographic predictor and X marks (✗) indicate life history traits that were not significantly predicted by a geographic predictor for each timeframe. Mixed models did not converge for historical female maximum size, male lifespan, and female lifespan, and are listed as N/A (not available).69

List of Figures

Figure 1: Management units (MUs) defined for managing fish species in Lake Huron. Management units cover all Canadian waters, encompassing the South Basin (4-5), Main Basin (4-1 to 4-3, and Zone-1), Georgian Bay (5-1 to 5-9, and Zones 2 and 3), and the North Channel (6-1 and 6-3).....	13
Figure 2: Collection sites in Lake Huron for OMNRF index netting that produced the contemporary dataset used to determine yellow perch life history traits. Red circles indicate sample sites and are numerically labelled with an adjacent white circle (0–20). Major basins of Lake Huron are labelled. (Original in colour).....	23
Figure 3: Collection sites in Lake Huron for OMNRF index netting that produced the historical dataset used to calculate yellow perch life history traits. Red circles indicate historical sample sites, which are replicates of contemporary sample sites. Black outlined circles indicate sites sampled in the contemporary dataset, but not replicated in the historical dataset. Sites are numerically labelled with an adjacent white circle (0–20). Major basins of Lake Huron are labelled. (Original in colour).....	26
Figure 4: Relationships between size at maturity (L50) and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 2009–2018. (A) Male size at maturity versus latitude; (B) female size at maturity versus latitude; (C) male size at maturity versus longitude; (D) female size at maturity versus longitude; (E) male size at maturity versus depth; and (F) female size at maturity versus depth. Male and female size at maturity are measured in mm fork length, latitude is measured in decimal degrees north (°N), longitude is measured in decimal degrees west (°W), and depth is measured in	

meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. None of the relationships shown were significant...35

Figure 5: Relationships between age at maturity (A50) and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 2009–2018. (A) Male age at maturity versus latitude; (B) female age at maturity versus latitude; (C) male age at maturity versus longitude; (D) female age at maturity versus longitude; (E) male age at maturity versus depth; and (F) female age at maturity versus depth. Male and female age at maturity are measured in years, latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. Daggers (\dagger) indicate relationships where variables were significant predictors of life history trait values.36

Figure 6: Relationships between maximum size (max size) and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 2009–2018. (A) Male maximum size versus latitude; (B) female maximum size versus latitude; (C) male maximum size versus longitude; (D) female maximum size versus longitude; (E) male maximum size versus depth; and (F) female maximum size versus depth. Male and female maximum size are measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. Daggers (\dagger) indicate relationships where variables were significant predictors of life history trait values.37

Figure 7: Relationships between lifespan and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 2009–2018. (A) Male lifespan versus latitude; (B) female lifespan versus latitude; (C) male lifespan versus longitude; (D) female lifespan versus longitude; (E) male lifespan versus depth; and (F) female lifespan versus depth. Male and female lifespan are measured in years, latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. Daggers (\dagger) indicate relationships where variables were significant predictors of life history trait values.38

Figure 8: Relationships between growth rate at age 2 (growth rate) and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 2009–2018. (A) Male growth at age 2 versus latitude; (B) female growth at age 2 versus latitude; (C) male growth at age 2 versus longitude; (D) female growth at age 2 versus longitude; (E) male growth at age 2 versus depth; and (F) female growth at age 2 versus depth. Male and female growth at age 2 are measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. Daggers (\dagger) indicate relationships where variables were significant predictors of life history trait values.39

Figure 9: K-means cluster plot with site groupings based on similarities in values for the suite of life history traits determined for this study. K-means analysis identified 6 distinct

clusters ranging in size from 1 to 5 sites. Numbers in each cluster correspond with site numbers, and sites belonging to the same cluster are colour coded. Sites 6 and 13 were omitted from k-means clustering. (Original in colour).....42

Figure 10: Map of collection sites in Lake Huron with sites coloured according to K-means clustering based on similarity in the suite of life history traits assessed. Major basins of Lake Huron are labelled, and sites are numerically labelled with an adjacent white circle (0–20). Sites 6 and 13 were omitted from k-means clustering and are indicated by a hollow circle. (Original in colour).43

Figure 11: Relationships between size at maturity and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 1990–1999. (A) Male size at maturity versus latitude; (B) female size at maturity versus latitude; (C) male size at maturity versus longitude; (D) female size at maturity versus longitude; (E) male size at maturity versus depth; and (F) female size at maturity versus depth. Male and female size at maturity are measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. Daggers (†) indicate relationships where variables were significant predictors of life history trait values.48

Figure 12: Relationships between historical age at maturity and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 1990–1999. (A) Male age at maturity versus latitude; (B) female age at maturity versus latitude; (C) male age at maturity versus longitude; (D) female age at maturity versus longitude; (E) male age at maturity versus depth; and (F) female age at maturity versus depth. Male and

female age at maturity are measured in years, latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. None of the relationships shown were significant. ..49

Figure 13: Relationships between historical maximum size and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 1990–1999.

(A) Male maximum size versus latitude; (B) female maximum size versus latitude; (C) male maximum size versus longitude; (D) female maximum size versus longitude; (E) male maximum size versus depth; and (F) female maximum size versus depth. Male maximum size is measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown when models converged. None of the relationships shown were significant.50

Figure 14: Relationships between historical lifespan and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 1990–1999. (A) Male lifespan versus latitude; (B) female lifespan versus latitude; (C) male lifespan versus longitude; (D) female lifespan versus longitude; (E) male lifespan versus depth; and (F) female lifespan versus depth. Male lifespan is measured in years, latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is measured in meters (m). No trendlines with 95% confidence intervals are shown because models did not converge.51

Figure 15: Relationships between historical growth rate at age 2 and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 1990–1999. (A) Male growth rate at age 2 versus latitude; (B) female growth rate at age 2 versus latitude; (C) male growth rate at age 2 versus longitude; (D) female growth rate at age 2 versus longitude; (E) male growth rate at age 2 versus depth; and (F) female growth rate at age 2 versus depth. Male and female growth rate at age 2 are measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. None of the relationships shown were significant.....52

Figure 16: K-means cluster plot with site groupings based on similarities in values for all life history traits in the historical era. K-means analysis identified 4 distinct clusters ranging in size from 1 to 4 sites. Numbers in each cluster correspond with site numbers, and sites belonging to the same cluster are colour coded. Sites 7, 9, and 18 were omitted from historical k-means clustering.54

Figure 17: Map of collection sites in Lake Huron with sites coloured according to K-means clustering based on similarity in all life history traits for the historical era. Major basins of Lake Huron are labelled, and sites are numerically labelled with an adjacent white circle (0–20). Sites 7, 9, and 18 were omitted from historical k-means clustering and are indicated by a hollow circle. Sites 6, 8, and 11–17 were not replicated by the historical dataset are indicated by a hollow circle with an x. (Original in color).55

Figure 18: Box-and-whisker plots of lake-wide Lake Huron yellow perch life history trait values for the historical (Hist) and contemporary (Cont) timeframes. Blue boxes represent

the historical timeframe; yellow boxes represent the contemporary timeframe. (A) male length at maturity between timeframes; (B) female length at maturity between timeframes; (C) male age at maturity between timeframes; (D) female age at maturity between timeframes; (E) male maximum size between timeframes; (F) female maximum size between timeframes; (G) male lifespan between timeframes; (H) female lifespan between timeframes; (I) male growth at age 2 between timeframes; and (J) male growth at age 2 between timeframes. Daggers (†) indicate relationships where life history is significantly different between timeframes. (Original in colour).....58

Figure 19: Relationships between historical (1990–1999) and contemporary (2009–2018) female size at maturity (L50) and latitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical female size at maturity versus latitude; (B) contemporary female size at maturity versus latitude. Female size at maturity is measured in mm fork length, latitude is measured in decimal degrees north (°N). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. A dagger (†) indicates the relationship where latitude was a significant predictor of female size at maturity.....62

Figure 20: Relationships between historical (1990–1999) and contemporary (2009–2018) female age at maturity (A50) and latitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical female age at maturity versus latitude; (B) contemporary female age at maturity versus latitude. Female age at maturity is measured in years, latitude is measured in decimal degrees north (°N). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. A dagger

(†) indicates the relationship where latitude was a significant predictor of female age at maturity.63

Figure 21: Relationships between historical (1990–1999) and contemporary (2009–2018) male maximum size and latitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical male maximum size versus latitude; (B) contemporary male maximum size versus latitude. Male maximum size is measured in mm fork length, latitude is measured in decimal degrees north (°N). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. A dagger

(†) indicates the relationship where latitude was a significant predictors of male maximum size.64

Figure 22: Relationships between historical (1990–1999) and contemporary (2009–2018) female maximum size, latitude and longitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical female maximum size versus latitude; (B) contemporary female maximum size versus latitude; (C) historical female maximum size versus longitude; and (D) contemporary female maximum size versus longitude. Female maximum size is measured in mm fork length, latitude is measured in decimal degrees north (°N), and longitude is measured in decimal degrees west (°W). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown when models converged. Models did not converge for historical female maximum size, and therefore trendlines with confidence intervals are not included. Daggers (†) indicate relationships where variables were significant predictors of life history trait values.65

Figure 23: Relationships between historical (1990–1999) and contemporary (2009–2018) male lifespan, latitude and longitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical male lifespan versus latitude; (B) contemporary male lifespan versus latitude. (C) historical male lifespan versus longitude; and (D) contemporary male lifespan versus longitude. Lifespan is measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}\text{N}$), and longitude is measured in decimal degrees west ($^{\circ}\text{W}$). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown when models converged. Models did not converge for historical male lifespan, and therefore trendlines with confidence intervals are not included. Daggers (\dagger) indicate relationships where variables were significant predictors of life history trait values.66

Figure 24: Relationships between historical (1990–1999) and contemporary (2009–2018) female lifespan, latitude and longitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical female lifespan versus latitude; (B) contemporary female lifespan versus latitude. (C) historical female lifespan versus longitude; and (D) contemporary female lifespan versus longitude. Lifespan is measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}\text{N}$), and longitude is measured in decimal degrees west ($^{\circ}\text{W}$). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown when models converged. Models did not converge for historical male lifespan, and therefore trendlines with confidence intervals are not included. Daggers (\dagger) indicate relationships where variables were significant predictors of life history trait values.67

Figure 25: Relationships between historical (1990–1999) and contemporary (2009–2018) male growth at age 2 (growth rate) and latitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical male growth rate versus latitude; (B) contemporary male growth rate versus latitude. Growth rate is measured in years, latitude is measured in decimal degrees north ($^{\circ}$ N). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. A dagger (\dagger) indicates the relationship where latitude was a significant predictor of male growth rate.

.....68

1.0 Introduction

1.1 Population delineation in modern fisheries management

Understanding how fish populations are spatially and temporally structured is critical for fisheries management. Discrete groups of fish may have different life history traits and demographic parameters, can be more or less sensitive to environmental and anthropogenic influences than others, and respond independently to stressors such as invasive species, commercial harvest, thermal effluent, and habitat degradation (Scheuerell et al., 2006; Cooke et al., 2016). Stressors can lead to regional changes in fish abundance and possibly to local extirpation, depending on how different groups respond (Chaparro-Pedraza & Roos, 2021). Understanding fish population structure allows fisheries managers to apply strategies that account for stressors on each group (Cooke et al., 2016), which is fundamental for preserving fish stock size and diversity, while allowing for sustainable harvest (Hammer et al., 1993; Sterner, 2007). However, before implementing management that accounts for different populations, fisheries managers need a clear understanding of how fish populations are structured within an aquatic ecosystem (Cadrin et al., 2013; Cooke et al., 2016).

One way fish population structure is understood is by spatially subdividing a larger fish population into smaller, discrete groups. The delineation of discrete groups is determined based on metrics commonly used in fisheries management, such as genetic lineage, life history traits, or resource use (Cadrin et al., 2013; Buchholz-Sørensen & Vella, 2016; Eberts et al., 2017), and is used to identify areas that may need specific management considerations (Cooke et al., 2016). Knowledge of fish population structure based on spatial variation has been critical in both marine and freshwater management

scenarios. Examining one of the most abused marine fish stocks in the world, the Atlantic cod (*Gadus morhua*), Sterner (2007) showed that managing subdivided populations as one unit lead to over-estimation of growth and harvest potential. If harvest quotas are based on over-estimations, subpopulation diversity is reduced as discrete stocks inevitably collapse. In a freshwater scenario, Larrson et al. (2015) identified northern pike (*Esox lucius*) subpopulations that varied spatially due to natal homing. It was concluded that subpopulation size and diversity should be preserved by managing individual subpopulations and protecting discrete spawning sites. Management approaches that account for spatial variation at the subpopulation level are also being continuously recommended. Cooke et al. (2016) explained that understanding spatial variation allows managers to determine how and when fish and their habitats are exposed to different threats, leading to the development of strategies that protect fish subpopulations over the long term. If spatial variation is ignored, then population assessments may be biased or inaccurate, leading to ineffective management.

Incorporating fish population structure into management regimes is a central theme in modern fisheries science; however, the use of associated terminology is often inconsistent and confusing. Cadrin et al. (2013) provided a set of guidelines that I have adopted here. A fish “population” is defined as a self-sustaining group of individuals from one species, and a “subpopulation” is a single, self-sustaining portion of a population that exhibits a degree of independence in local population dynamics such as life history, genetics, or resource use. The term “subdivision” refers to the delineation of subpopulations within a larger group, and a “management unit” is a geographically delineated fisheries resource based on practical or jurisdictional boundaries for

management (which may or may not reflect population structure). The term “discrete” identifies ecologically or genetically separate or distinct groups, and a “stock” is a fisheries unit (usually in the form of a subpopulation) that is discrete and exploited independently. The term “life history” refers to development and changes undergone by a fish during its lifetime; “spatial/temporal overlap” is the co-occurrence of two or more subpopulations over space and/or time; “contingent” means a group of fish that co-occur in time and space and adhere to the same life history patterns; finally, “connectivity” refers to linkage between two life-history patterns or subpopulations. It is important that these terms be used appropriately both for accuracy, and for proper interpretation of population assessments in a fisheries management framework.

1.2 Characterizing subdivided fish populations

The ultimate goal of assessing fish population structure is to delineate important differences among groups of fish; correspondingly, a variety of tools are available. This includes, but is not limited to: genetic markers, stable isotopes analysis, and life history traits (Begg et al., 1999; Begg & Waldman, 1999; Abaunza et al., 2008a; Cadrin et al., 2013). Genetic markers are commonly used to assess population structure and aid in the development of management regimes (Begg & Waldman, 1999; Cadrin et al., 2013; Buchholz-Sørensen & Vella, 2016; Graham et al., 2016; Morgan et al., 2017). However, these markers are relevant over long time scales (generations), and may lack the resolution necessary to detect short-term population subdivision (Eberts et al., 2017). Stable isotopes of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) can also identify fish subpopulations (Jardine et al., 2003; Eberts et al., 2017). However, stable isotopes analyses are food-web based studies that require extensive sampling from multiple parts

of the ecosystem, resulting in accurate but expensive and time consuming assessment (Layman et al., 2012). One of the most widespread and potentially informative tools for assessing population structure is based on life history traits involving fish size, age, maturity, growth rate, reproduction, fecundity, and mortality (Begg et al., 1999; Begg & Waldman, 1999; Purchase et al., 2005a; Cadrin et al., 2013; Macdonald et al., 2013). Life history traits work well for identifying subpopulations as they can be done over any time scale (Cadrin et al., 2013). Life history traits provide detailed and extensive data on how fish populations respond to elements of genetics, environment, and resource use simultaneously (Cooke et al., 2016).

A number of different life history trait parameters are used for assessment of fish populations. Parameters include, but are not limited to: size at maturity, age at maturity, maximum size, lifespan, and growth rate at a specific age (Begg et al., 1999; Begg & Waldman, 1999; Purchase et al., 2005a; Cadrin et al., 2013; Macdonald et al., 2013). These phenotypic traits are a direct reflection of fish demography and growth, which vary with genetic, environmental, and anthropogenic influences (Begg et al., 1999; Begg & Waldman, 1999; Begg et al., 2005). Genetic influence on life history traits is difficult to quantify and measure (Begg et al., 1999); however, the impact of environmental conditions and anthropogenic factors on life history traits are well characterized. From an environmental standpoint, the environment directly influences fish growth, maturity, and age (Begg et al., 1999; Begg & Waldman, 1999; Begg et al., 2005). As a broad example, average annual water temperature and productivity decrease at increasing latitudes from the equator (New et al., 1999; Vázquez & Stevens, 2004; Lappalainen et al., 2008). Correspondingly, fish populations reflect this environmental change by growing more

slowly (Lobón-Cervia et al., 1993; Belk & Houston, 2002), living longer (Gunderson & Dygert, 1988), and maturing at an older age and larger size (Colby & Nepszy, 1981; Beverton, 1987; Vollestad, 1992; Jonsson & L'Abée-Lund, 1993; Heibo et al., 2005). More locally, the environment varies spatially among and within lakes. Depth and habitat differences result in spatial variance in mean water temperature and productivity (Kurek & Cwynar, 2009), causing plastic responses in life history trait parameters (Wilson et al., 2019). The environment can change in a number of ways and on broad or local scales, but regardless of how the environment changes, fish life history tends to change with it (Begg et al., 1999). Life history traits can therefore be compared spatially to characterize subpopulations based on differences in environmental conditions (Begg et al., 1999; Cadrin et al., 2013). In this case, spatial variation in life history traits is evidence for subpopulations of fish that are different from one another based on existing in a different set of environmental conditions (Begg et al., 1999; Begg & Waldman, 1999).

In addition to variation in the natural environment, fish life history trait parameters respond to both direct and indirect anthropogenic factors. Warm-water thermal effluent from industrial once-through cooling processes alters local productivity and influences growth rate and maturity (Coleman & Koenig, 2010; Prats et al., 2012). Climate change causes ever-shifting effects on fish growth rates, reproductive rates, mortality, maximum size, and lifespan (Wang et al., 2020). In these cases, anthropogenic factors are indirectly altering fish life history by changing the environment, and therefore life history parameters. However, anthropogenic factors can also directly influence fish populations and life history. For example, targeted commercial fishing pressure can alter life history parameters such as mortality, growth rate, maximum size, and lifespan

(Genner et al., 2010; Sharpe et al., 2012; Kolding & Zwieten, 2014; Piou et al., 2015).

Thus, both environmental conditions and anthropogenic pressures influence spatial variation in life history trait parameters.

Life history traits are a popular tool used in fisheries science due to their ability to capture multiple elements influencing fish populations. Consequently, life history traits have become a widely accepted and broadly applicable approach to characterize subdivided populations and determine how they are influenced by environmental gradients (Begg et al., 1999; Begg & Waldman, 1999; Abaunza et al., 2008; Jackson et al., 2010; Ballagh et al., 2012; Cadrin et al., 2013; Macdonald et al., 2013). For example, Jackson et al. (2010) examined spatial variation in snapper (*Pagrus auratus*) in Shark Bay, Australia, using life history traits including age at maturity, maximum age, and growth rate. Spatial variation in snapper life history traits indicated three distinct subpopulations within Shark Bay. Results were consistent with previous studies and supported the idea that snapper should be managed on a finer scale. Borsetti et al. (2018) examined waved whelk (*Buccinum undatum*) populations using life history parameters including sex ratio and size at maturity. Both parameters varied spatially, suggesting local adaptation by whelk. Management of multiple distinct subpopulations of whelk was deemed most appropriate. Life history traits have also been used to determine how subpopulations are influenced by geographic gradients. Macdonald et al. (2013) spatially compared life history traits including size at maturity, sex ratio, and growth rate of the common megrim (*Lepidorhombus whiffiagonis*) between latitudinal extremes. Spatial variation was observed in all life history parameters, suggesting that common megrim should be managed as two separate subpopulations, as opposed to one large population.

In all of these case studies, knowledge of population structure based on life history traits was essential to develop a successful management regime.

Life history trait parameters have also been used extensively in fresh water to understand fish population structure. In the Laurentian Great Lakes, Wang et al. (2008) used size and age at maturity to examine spatial and temporal variation in lake whitefish (*Coregonus clupeaformis*) within and among Lakes Michigan, Huron, and Superior. Maturation schedules varied between sexes and among systems, and age at maturity varied temporally in Lake Michigan and Lake Huron. Kornis et al. (2017) compared life history traits including growth at age 2, lifespan, age at maturity, and fecundity in invasive round goby (*Neogobius melanostomus*) from inshore Lake Michigan to adjacent tributaries. Round gobies from tributaries grew faster, had shorter lifespans, and had lower age at maturity than those in Lake Michigan; however, the cause of life history differences could not be determined. Finally, using yellow perch (*Perca flavescens*) as a study organism, Gislason et al. (2018) examined temporal change in life history traits including age and size at maturity in Lake Erie. Yellow perch age and size at maturity fluctuated widely between 1991 and 2013, with shifts in maturity not explained by harvest. Changes in yellow perch maturity were attributed to other drivers such as harvest of predator fish stocks and ecosystem shifts. Based on the literature, life history traits are an effective tool for characterizing fish populations, and can be used to examine fish populations in the Laurentian Great Lakes.

1.3 Yellow perch importance and status in the Great Lakes and Lake Huron

The yellow perch is one of the most important species in the Laurentian Great Lakes. A freshwater fish in the family Percidae, the yellow perch is native to the Great

Lakes region (Roswell et al., 2014), and is a key commercial and recreational fish species. For example, millions of kilograms of yellow perch are commercially harvested and sold each year, and recreational anglers contribute tens of millions of dollars to local economies while pursuing yellow perch in the Great Lakes (Diana et al., 1987; Fielder & Thomas, 2006; Craig, 2008). As a result, yellow perch life history trait variation based on the environment has been extensively researched in North American fisheries. For example, Weber et al. (2011) found that environmental factors such as water temperature and prey availability increased yellow perch growth rate and survival among lakes. Bachelier et al. (2011) found that regional yellow perch abundance and distribution was influenced among lakes by various environmental factors including predation, water quality, and density dependent effects. Accordingly, high commercial value and increased academic assessment in other waterbodies has resulted in considerable interest in yellow perch in the Laurentian Great Lakes.

Yellow perch life history has been used to examine spatial variation in population substructure as well. Purchase et al. (2005b) examined sex specific covariation among life history traits of yellow perch from 70 different lakes in North America. Life history traits varied among lakes and across spatial scales. Outside of North America, Heibo et al. (2005) examined latitudinal variation in life history traits of Eurasian perch (*Perca fluviatilis*), a closely related species. Eurasian perch growth rate, mortality, lifespan, age at maturity, and size at maturity were correlated with a gradient of environmental conditions associated with increased latitude among lakes. Clearly, life history traits can be used to characterize yellow perch populations based on spatial variation. However, studies have focused on among-lake variation, and have not been conducted on single,

large bodies of water in the Great Lakes region. Consequently, little is known about spatial variation in yellow perch populations within large waterbodies, such as the Laurentian Great Lakes.

Yellow perch play a vital role in the Lake Huron food web, acting as a mid-trophic level consumer while also being prey for larger predatory fish (Hartman & Margraf, 1993; Fielder & Thomas, 2006; Ivan et al., 2011; Roswell et al., 2014). Yellow perch are economically desirable as well, being the third most commercially harvested species in Lake Huron (Speers, 2018), and a highly sought after sportfish by recreational anglers (Diana et al., 1987; Craig, 2000; Fielder & Thomas, 2006). Despite their importance, yellow perch have declined in abundance over recent decades (Fielder, 2008; Fielder, 2010). Diana et al. (1987) first reported yellow perch declines in the Les Cheneaux Islands of Lake Huron starting in the late-1970s. Lucchesi (1988) confirmed that yellow perch populations were declining in many regions of Lake Huron, but particularly in the Les Cheneaux Islands by the mid-1980s. By the mid-1990s, yellow perch were significantly less abundant in multiple regions of Lake Huron (Diana et al., 1997; Belyea et al., 1997), and in 2000, the yellow perch fishery collapsed (Fielder, 2008; Fielder, 2010). The cause of the collapse is uncertain; however, researchers found a number of environmental and anthropogenic factors were likely at play (Diana et al., 1987; Diana et al., 1997; Belyea et al., 1997; Fielder, 2008; Fielder, 2010; Speers, 2018).

Corresponding with yellow perch population decline, a variety of ecosystem changes occurred in Lake Huron, ultimately resulting in a major ecosystem regime shift by the early 2000s. In 1993, invasive zebra (*Dreissena polymorpha*) and quagga mussels (*D. bugensis*), invaded Lake Huron (Gobin et al., 2015), changing the benthic

invertebrate community (Barbiero et al., 2011a; Barbiero et al., 2011b) and altering nutrient and energy distribution (Hecky et al., 2004; Nalepa et al., 2009; Higgins & Vander Zanden, 2010; Barbiero et al., 2018). Invasive mussels dominated nearshore and offshore benthic habitat, and zooplankton began to decline in response (Nalepa et al., 2007; Barbiero et al., 2009; Barbiero et al., 2011b; Gobin et al., 2015). In 1997, round gobies (*Neogobius melanostomus*) invaded Lake Huron (Schaeffer et al., 2005). By the early 2000s, nearshore and offshore zooplankton populations nearly completely disappeared (Nalepa et al., 2007; Nalepa et al., 2009; Barbiero et al., 2009; Barbiero et al., 2011b; He et al., 2015; Pothoven et al., 2017). In response to zooplankton disappearance, high predator pressure, and extremely cold winter temperatures, alewife (*Alosa pseudoharengus*) populations collapsed in 2003 (Riley et al., 2008; Dunlop et al., 2010; Barbiero et al., 2011a; Dunlop & Riley, 2013; Gobin et al., 2015; He et al. 2016; Riley & Dunlop, 2016). After alewife collapsed, top predators that fed on them, such as chinook salmon (*Oncorhynchus tshawytscha*), began to decline in abundance (Riley et al., 2008; Johnson et al., 2010; Brendan et al., 2012; Clark et al., 2017). Overall, Lake Huron was becoming increasingly oligotrophic (Barbiero et al., 2011a; Cha et al., 2011; Warner & Lesht, 2015; Pothoven et al., 2016; Dai et al., 2019; Stadig et al., 2020), and a major shift in the food web was evident by the early 2000s (Ridgway, 2010; Riley & Adams, 2010; Gobin et al., 2015; Ridgway & Middel, 2015; Barbiero et al., 2018). However, it is unknown how this shift, or the individual components listed, may have affected yellow perch life history traits or population structure.

Since the invasion of dreissenid mussels and the 2003 ecosystem regime shift, productivity has changed significantly in Lake Huron. Shallow nearshore areas continue

to have higher productivity than deeper offshore areas due to dreissenid filtering, nutrient re-suspension, and nutrient loading from tributaries (Stadig et al., 2020). However, algal abundance increased in southern nearshore areas of Lake Huron (Barton et al., 2013) while offshore nutrients and pelagic productivity decreased further north in the lake (Brothers et al., 2016; Stefanoff et al., 2018). Additionally, cold waters in deep areas of Lake Huron, such as the Main Basin, have warmed over past decades, but have not reached temperature averages equivalent to those found in shallower regions, such as the South Basin (Zhong et al., 2019). In Lake Huron, a productivity gradient appears to exist, where productivity is high in shallow nearshore areas located in the south of the lake, and low in deep offshore areas associated with more northern regions of the lake (Brothers et al., 2016; Stefanoff et al., 2018; Dai et al., 2019). In this case, decreasing productivity is associated with increasing latitude, similar to that observed by Vázquez & Stevens (2004) and Lappalainen et al. (2008). Thus, yellow perch life history traits may vary spatially (location in the lake) and temporally (before or after the ecosystem shift) in Lake Huron.

1.4 Yellow perch management in Lake Huron

Managing fish in a system as large as Lake Huron presents a substantial challenge. In Lake Huron, fish populations cover international boundaries and face a wide variety of environmental conditions and anthropogenic stressors over a vast geographic area (Sullivan & Stepien, 2014; Eberts et al., 2017). In attempt to address fish populations that cover multiple jurisdictions, the Canadian side of Lake Huron is managed by division of the lake into 17 distinct management units (**Figure 1**). Management units vary in size, habitat, and fishing pressure (Eberts et al., 2017). Each management unit was created based on life history and genetic patterns, as well as the

location of spawning grounds of native species (Speers, 2018). Individual management units exist as guidelines for index netting and fisheries surveys, but also act as the boundaries in which commercial harvest quotas are allotted (Ontario Ministry of Natural Resources and Forestry, 2019). Commercial harvest quotas vary among management units; each unit is annually assessed, and a set weight or number of fish is allowed to be harvested by commercial fishermen (Ontario Ministry of Natural Resources and Forestry, 2019).

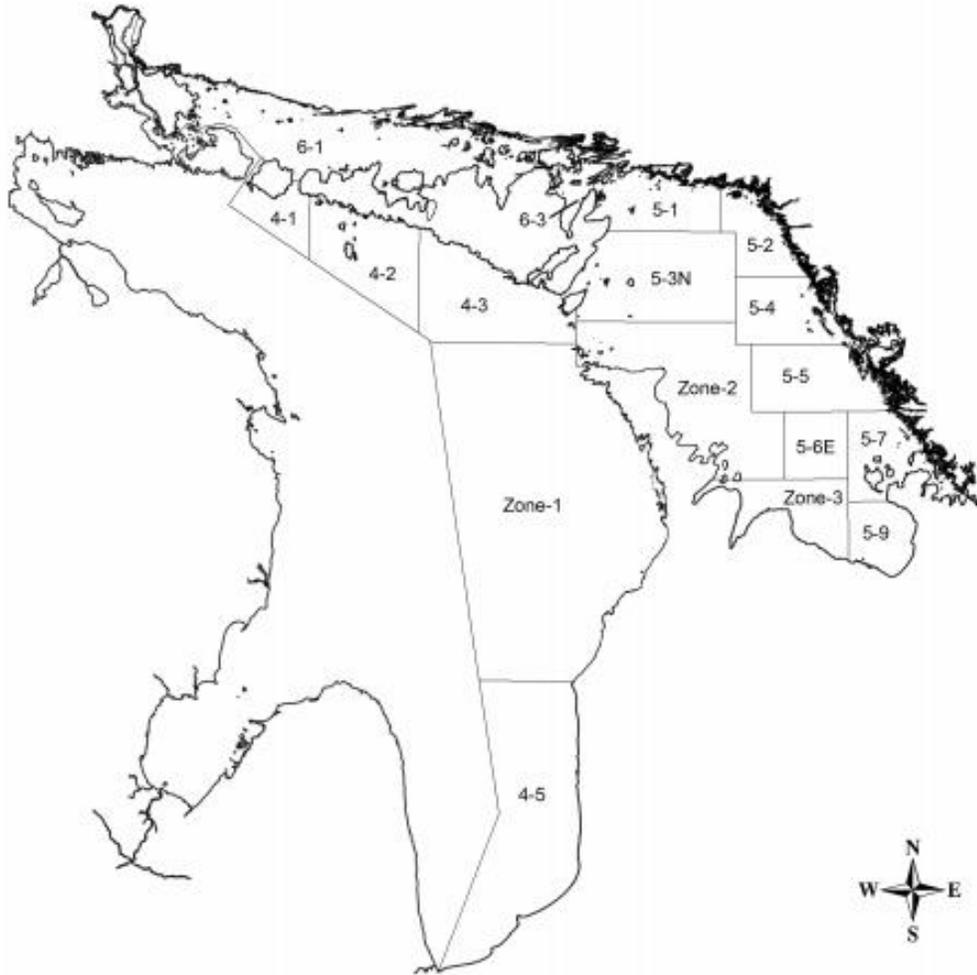


Figure 1: Management units (MUs) defined for managing fish species in Lake Huron. Management units cover all Canadian waters, encompassing the South Basin (4-5), Main Basin (4-1 to 4-3, and Zone-1), Georgian Bay (5-1 to 5-9, and Zones 2 and 3), and the North Channel (6-1 and 6-3).

Different management units experience a variety of different environmental and anthropogenic stressors. For example, different management units cover different habitats, which may be more or less impacted by climate change or habitat degradation (Wang et al., 2020). Each management unit is also subject to different levels of harvest pressure, as commercial and recreational catch quotas vary by management unit (Ontario Ministry of Natural Resources and Forestry, 2019). Certain management units are also continuously affected by thermal discharge from nuclear power generation or altered water chemistry due to runoff or other forms of pollution (Haque et al., 2019). The division of Lake Huron into distinct management units is an attempt to address discrete environmental and anthropogenic stressors, and ultimately reflect fish population structure. However, the accuracy and effectiveness of current management units is unknown. For example, in Lake Huron, yellow perch subpopulations may have modified their location and migration patterns in response to predation, invasive species, commercial harvest pressures, or food web and environmental changes. This is of concern for fisheries managers, as yellow perch populations misrepresented by management zones may be exposed to longer and more extensive periods of harvest than is sustainable (Cadrin et al., 2013; Cooke et al., 2016).

Currently, relatively little is known about yellow perch population structure in Lake Huron. Sullivan & Stepien (2014) performed a population structure assessment of yellow perch using genetic markers (microsatellite loci) to study patterns of spawning aggregations of yellow perch that return annually to the Huron-Erie corridor. Results showed that spawning cohorts were genetically distinct, reflecting reproductive isolation. However, this study did not identify where yellow perch cohorts resided for the

remainder of the year, and did not reflect all yellow perch in Lake Huron, as only fish spawning in the Huron-Erie Corridor were examined. It also lacked the use of life history traits, which should be considered when re-assessing population structure for fish in management zones that were created using life history dynamics. Temporal change in Lake Huron yellow perch is also understudied. Schaeffer et al. (2000) examined the effects of temporal change in the benthic community on yellow perch in Lake Huron, and found that yellow perch were largely prey limited. The decline of large benthic prey, such as mayfly nymphs, resulted in a decline in yellow perch growth rate, maximum size, and lifespan, despite harvest mortality being lower over time. Based on the literature, there is a deficiency of studies on yellow perch population structure and temporal change in Lake Huron.

Although there is a lack of research on yellow perch population structure and whether management units accurately represent subdivided populations, other species within Lake Huron have been more thoroughly investigated. For example, Eberts et al. (2017) used stable isotopes of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) to examine lake whitefish population structure in Lake Huron and determine if subpopulations were accurately represented by management units. Six putative regional groups were found in Lake Huron, with several being highly distinct and ecologically unique from one another. Spatial linkage between spawning-phase and summer fish was identified, indicating that subpopulations of lake whitefish were highly migratory and often overlapping, depending on time of year and life stage. It was concluded that management units were too small and numerous to reflect the true population structure of lake whitefish in Lake Huron.

Imbalances between management units and population substructure exist in lake whitefish in Lake Huron, and could exist for yellow perch as well.

1.5 Research Objectives, Hypothesis, and Predictions

Here, I use life history traits to examine yellow perch population structure and temporal changes across the Canadian portion of Lake Huron. Overall, I had 3 primary research objectives, with a major hypothesis and predictions for each.

1) Determine yellow perch population structure in Lake Huron based on spatial variation in life history traits. My hypothesis for this objective was that yellow perch populations vary spatially in Lake Huron based on differences in environment and anthropogenic influences. I predicted that yellow perch life history would vary spatially along a productivity gradient, in which productivity (based on the environment) decreases from south to north. I predicted that fish in similar areas of Lake Huron would have similar life history trait values because the environment and anthropogenic influences will be the same on a local scale.

2) Determine the influence of latitude, longitude, and depth on yellow perch life history traits and population structure. My hypothesis was that variables that influence environmental conditions would be significant predictors of most life history traits. I predicted that latitude and depth would be the most important predictor variables. This is based on latitude and depth directly influencing productivity, and correspondingly age at maturity, size at maturity, and lifespan (Heibo et al. 2005). I predicted that longitude would not be a significant predictor of yellow perch life history traits, because productivity and the environment does not vary as much on a longitudinal scale.

3) Determine if yellow perch life history, geographic influence, or population structure have changed over time. My hypothesis was that yellow perch life history values would vary temporally based on the major ecosystem shift in Lake Huron during the early 2000s. Specifically, I predicted that measures of growth rates and size would decrease, reflecting a more oligotrophic Lake Huron. However, I predicted that the importance of geography and the influence of latitude, longitude, and depth would remain consistent over time. Correspondingly, I did not expect population structure based on groups of fish with similar life history trait values to change over time.

2.0 Methods and Materials

2.1 Life History Trait Data

My study used data from the Ontario Ministry of Natural Resources and Forestry's (OMNRF) Lake Huron offshore index netting program. This program is used to assess fish population status and trends in the Canadian portions of Lake Huron, and is based on standardized gill net sets (see Fish Sampling and Data Collection below) (Speers, 2018). I separated the data from the OMNRF assessments into two relevant timeframe datasets: (1) contemporary—spanning the years 2009–2018; and, (2) historical—spanning the years 1990–1999. Timeframe datasets were chosen to reflect periods before and after a major ecosystem shift that occurred in Lake Huron in the early 2000s (Ridgway, 2010; Riley & Adams, 2010; Gobin et al., 2015; Ridgway & Middel, 2015; Barbiero et al., 2018). Dividing yellow perch samples into contemporary and historical datasets allowed me to address all three objectives. Contemporary data enabled me to address modern population structure and geographic influence on life history, while historical data provided a snapshot of population structure and geographic influence before perch populations collapsed. Both datasets were needed to examine temporal change in yellow perch life history, geographic influence, and population structure.

2.2 Fish Sampling and Data Collection

All fish used in my study were sampled by fisheries biologists from the Lake Huron division of the Ontario Ministry of Natural Resources and Forestry's Upper Great Lakes Management Unit, as part of the Offshore Index Assessment Program. The Offshore Index Program has remained nearly unchanged since the early 1970s, and has consisted of both a fixed and random component in each year of sampling;

correspondingly, most index nets were set in approximately the same place every year (Speers, 2018).

Index netting standards are described in the Lake Huron Offshore Index Assessment Program 2018 Summary Report (Speers, 2018). Fish were collected from 2009 to 2018 and 1990 to 1999 using multi-mesh monofilament gill nets set on the lake bottom at various locations throughout Lake Huron. Nets contained a 15-m panel of 32 mm (1.25") mesh, a 25-m panel of 38 mm (1.5") mesh, and 50-m panels of 51 mm (2.0"), 64 mm (2.5"), 76 mm (3.0"), 89 mm (3.5"), 102 mm (4.0"), 114 mm (4.5"), 127 mm (5.0"), 140 mm (5.5"), and 153 mm (6.0") mesh arranged in a standardized random order. Nets were set perpendicular to depth contours and distributed across the lake from June to September to prevent seasonal bias. All netting was conducted from the OMNRF research vessel, the *Huron Explorer I*. Latitude, longitude, lake depth, Secchi depth, weather, and water temperature were recorded at each set, with set duration lasting 20 – 24 hours.

When net sets were pulled, catch was divided by mesh size into containers, with individual fish fork length, total length, and round weight recorded. Aging structures were collected for up to 20 randomly selected individuals of each species in each mesh size. For yellow perch, scales were taken as aging structures. Scales were collected from below the lateral line in the center of the body, folded in wax paper, and placed in envelopes for transport to the lab. At the lab, scales from each fish were pressed onto acetate slides and viewed with a dissecting microscope or microfiche projector (Speers, 2018). Annuli of each scale were counted with the age of each fish recorded, similar to that described in Lucchesi & Bruce (2006). Fish were dissected and assessed for maturity

(mature or immature) based on the presence or absence of gonads, then further assessed for sex based on the presence of thread-like testes (male) or fused ovaries (female) (Speers, 2018). All data were archived in a permanent database.

2.3 Location of Sites and Calculation of Site Latitude, Longitude, and Depth for each Dataset

I used data from each site that was part of the Offshore Index Netting Program for each year where possible, and replicated sample sites across time periods where possible. Sites were grouped by rounding the recorded sampling location to the nearest 0.1 decimal degree of latitude and longitude. Therefore, nets set within a 5 km radius of the initial site from the first year of recorded data for each timeframe were considered the same site across multiple years. Depth was measured as the average lake depth in metres for each site; however, due to the nature of the 0.1 decimal degree buffer used to group sites, depth at each site was determined by calculating the mean lake depth from all years in both datasets. Thus, sites replicated across the contemporary and historical timeframes have measurements of latitude, longitude, and depth that are consistent over time. In each dataset, the minimum number of years that qualified a site for inclusion in this study was two. Given the variable number of years incorporated across sites, the number of years contributing was always included in statistical analysis.

Contemporary Dataset (2009–2018)

The above approach led to a total of 20 sites for the contemporary timeframe, that span major basins and regions of the Canadian portion of Lake Huron. Sites were numerically ordered to increase with increased latitude, which ranged from 43.3 to 46.1 °N (**Table 1**). Thus, sites 1 – 6 were located in the South Basin; sites 7, 8, and 10 were

located in the Main Basin; sites 9 and 11 – 17 were located in Georgian Bay, and sites 18 – 20 were located in the North Channel (**Figure 2**). Site longitude ranged two full decimal degrees from -82.0 to -80.0 °W. A wide range of depths were sampled, with site depth ranging from 5.8 to 28.4 m. The contemporary dataset included a total of 16,332 individual yellow perch, with 7,068 male and 9,264 female fish used in the calculation of life history traits (**Table 1**).

Table 1: Sites on Lake Huron from OMNRF index netting assessments used to examine life history traits of yellow perch in the contemporary timeframe of 2009–2018. Sites are shown with associated latitude, longitude, depth, years sampled during the timeframe (Time), and sample size for each sex of yellow perch. Latitude is measured in decimal degrees north (°N), longitude is measured in decimal degrees west (°W), and depth is an average measured in meters (m). The number of fish sampled and used in the study (n) for each sex at each site is included.

Site	LAT (°N)	LON (°W)	Depth (m)	Time (years)	# Fish Sampled at Each Site	
					Male (n)	Female (n)
1	43.3	-81.9	14.7	10	1812	1366
2	43.3	-82.0	26.3	7	499	69
3	43.4	-81.8	24.5	3	184	156
4	43.5	-81.8	12.2	7	610	340
5	43.6	-81.8	18.5	10	1148	1014
6	43.8	-81.8	9.0	5	221	173
7	44.5	-81.4	19.4	9	354	392
8	44.6	-81.4	28.4	3	145	101
9	44.7	-80.6	21.0	4	82	140
10	44.7	-81.3	13.8	7	228	312
11	44.8	-80.1	19.5	5	101	602
12	44.9	-80.0	18.2	9	104	664
13	45	-80.1	16.5	2	13	57
14	45.3	-80.3	7.3	5	177	512
15	45.6	-80.4	8.0	2	212	857
16	45.7	-80.7	5.8	4	135	305
17	45.9	-81.0	10.4	5	205	324
18	46	-82.1	11.7	9	444	960
19	46	-82.3	10.6	9	312	749
20	46.1	-82.2	13.3	6	82	171
<u>TOTAL</u>					7068	9264

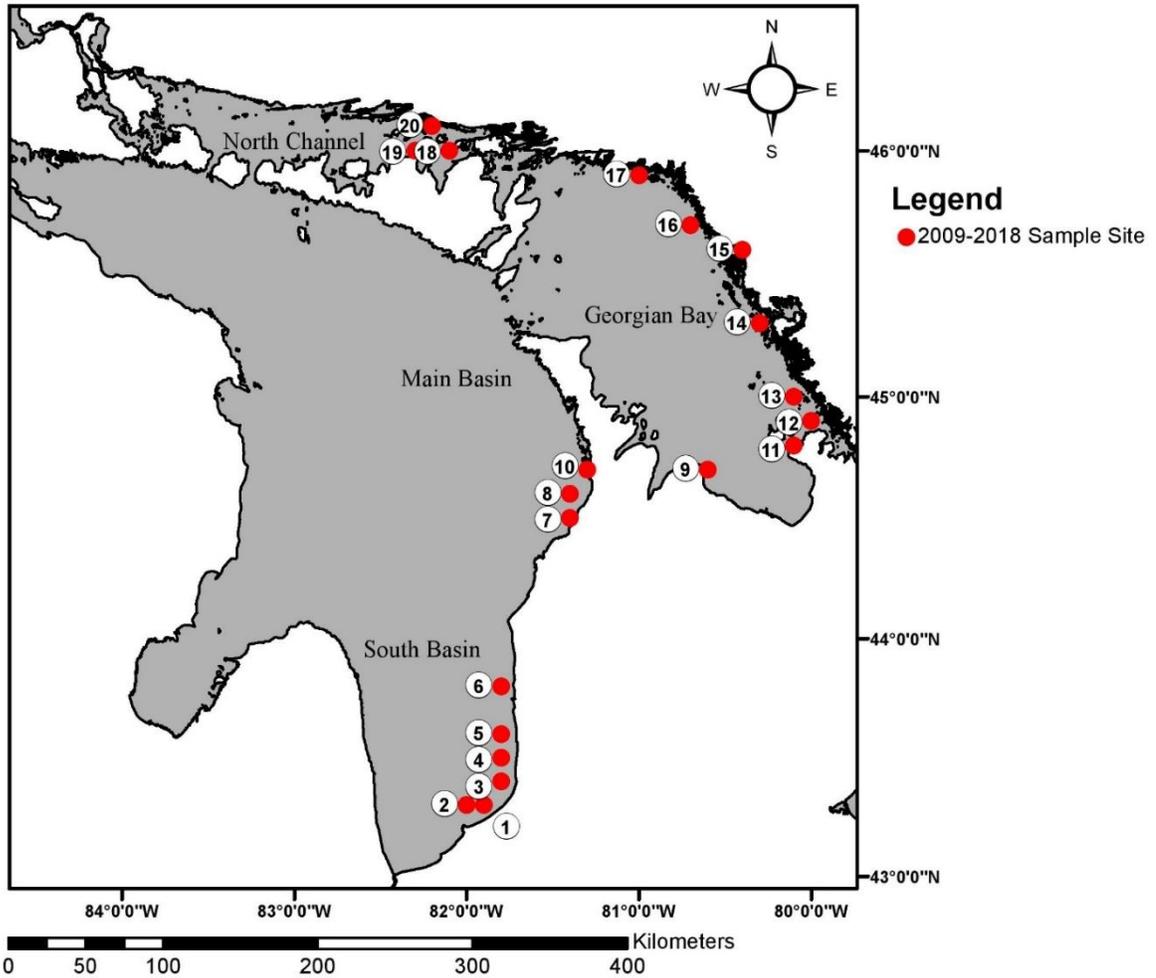


Figure 2: Collection sites in Lake Huron for OMNRF index netting that produced the contemporary dataset used to determine yellow perch life history traits. Red circles indicate sample sites and are numerically labelled with an adjacent white circle (0–20). Major basins of Lake Huron are labelled. (Original in colour).

Historical Dataset (1990–1999)

A total of 11 sites were used for the historical timeframe (**Table 2**), all of which were also represented in the contemporary timeframe to enable temporal comparison. Sites replicated in the historical dataset included 1, 2, 3, 4 and 5 in the South Basin, 7 and 10 in the Main Basin, 9 in southern Georgian Bay, and 18, 19 and 20 in the North Channel (**Figure 3**). Site 6 in the South Basin, 8 in the Main Basin, and 11 – 17 in Georgian Bay were not replicated by the historical dataset due to a lack of yellow perch sampled in the index netting program in those areas from 1990–1999. Sites replicated by the historical dataset ranged in latitude from 43.3 to 46.1 °N, but only covered a longitudinal range of -82.0 to -80.6 °W (**Table 2**). As a result of this, certain regions of Lake Huron, particularly Georgian Bay, were not well represented in the historical dataset (**Figure 3**). Depth ranged from 10.6 to 26.3 m. Sites replicated in the historical dataset included a total of 8,296 individuals, with 4,729 male and 3,567 female fish used in the calculation of life history trait values (**Table 2**).

Table 2: Sites on Lake Huron from OMNRF index netting assessments used to examine life history traits of yellow perch in the historical timeframe of 1990–1999. Sites are shown with associated latitude, longitude, depth, number of years sampled (Time), and sample size for each sex of yellow perch; site numbers represent the same locations as those used in Table 1. Latitude is measured in decimal degrees north (°N), longitude is measured in decimal degrees west (°W), and depth is an average measured in meters (m). The number of fish sampled (n) for each sex at each site is also included.

Site	LAT (°N)	LON (°W)	Depth (m)	Time (years)	# Fish Sampled at Each Site	
					Male (n)	Female (n)
1	43.3	-81.9	14.7	8	1260	300
2	43.3	-82.0	26.3	9	1490	525
3	43.4	-81.8	24.5	3	118	160
4	43.5	-81.8	12.2	5	264	172
5	43.6	-81.8	18.5	9	326	308
7	44.5	-81.4	19.4	2	19	27
9	44.7	-80.6	21	4	20	21
10	44.7	-81.3	13.8	7	703	1309
18	46	-82.1	11.7	2	43	161
19	46	-82.3	10.6	7	428	490
20	46.1	-82.2	13.3	3	58	94
<u>TOTAL</u>					4729	3567

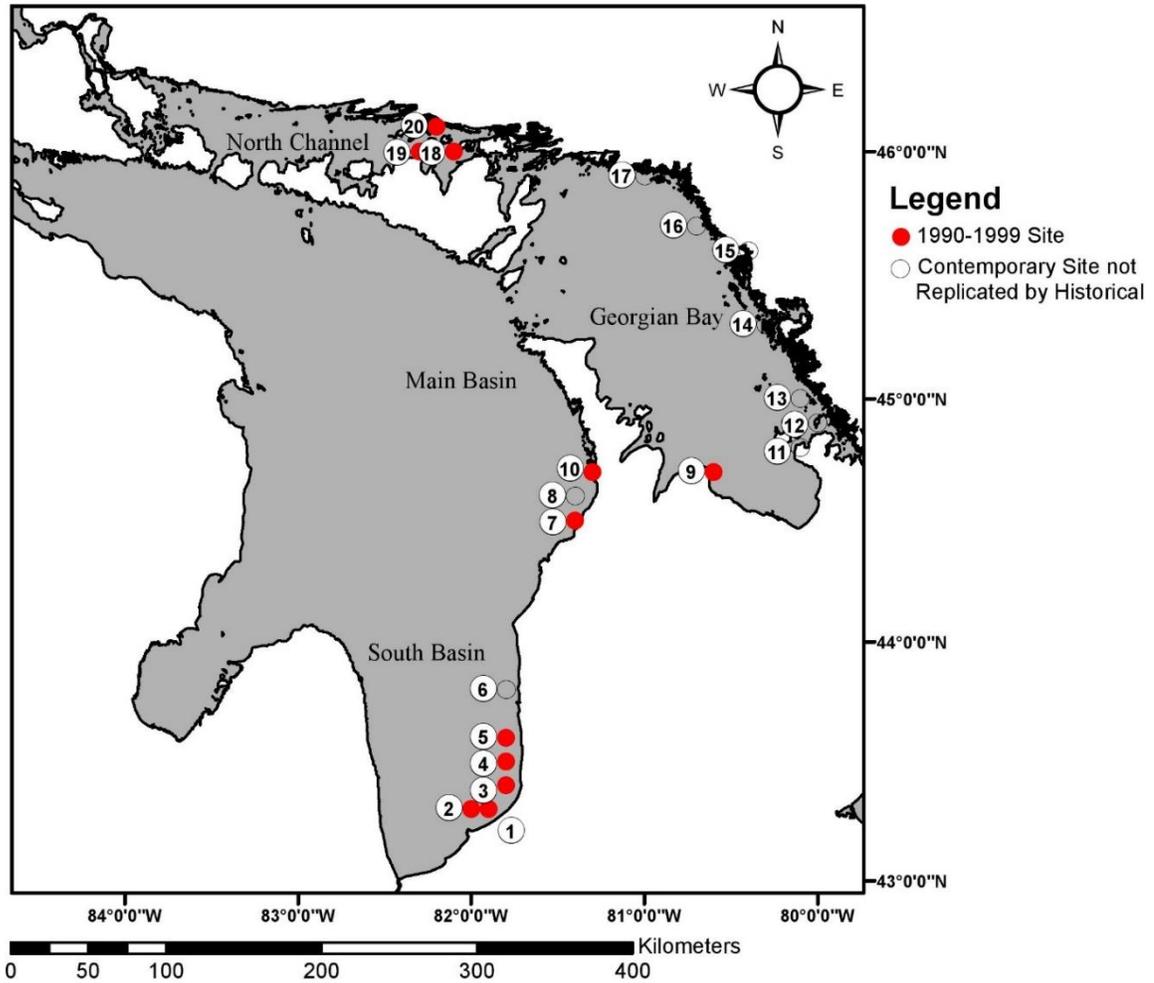


Figure 3: Collection sites in Lake Huron for OMNRF index netting that produced the historical dataset used to calculate yellow perch life history traits. Red circles indicate historical sample sites, which are replicates of contemporary sample sites. Black outlined circles indicate sites sampled in the contemporary dataset, but not replicated in the historical dataset. Sites are numerically labelled with an adjacent white circle (0–20). Major basins of Lake Huron are labelled. (Original in colour).

2.4 Sex-Specific Life History Trait Estimation

Sex specific measurement of life history traits is important, as fish size, growth rate, maturity, and lifespan may differ between sexes (Purchase et al., 2005a). Thus, I assessed fish separately for each site based on sex. Only fish that had measurements of size in fork length, age in years, sex, maturity, and location/date caught were used to estimate life history traits. Life history traits were estimated using methods described in Purchase et al. 2005a and Purchase et al. 2005b. I derived five major life history trait metrics for male and female yellow perch in Lake Huron: (1) size at maturity (L50); (2) age at maturity (A50); (3) maximum size; (4) lifespan; and (5) growth rate. I defined size and age at maturity as the size and age when 50% of the population (sex-specific) reached sexual maturity where at least 50 individuals were sampled, similar to that of Purchase et al. (2005a). Both size at maturity (fork length, mm) and age at maturity (years) were estimated via logistic regression in R (R Core Team, 2017). I estimated maximum size as the mean fork length (mm) of the largest 5% of fish sampled, where at least 50 yellow perch were collected. Using the largest 5% of fish is an underestimate of maximum size; however, it provides an index of maximum size that is repeatable among sites and timeframes (Purchase et al., 2005a). I estimated lifespan as the mean age (years) of the oldest 5% of fish at sites where at least 50 yellow perch were sampled. Similar to maximum size, using the largest 5% of fish is an underestimate of lifespan, but provides an index that is repeatable among sites and timeframes. I defined growth rate as early age growth, in this case as mean fork length (mm) at age 2. Fork length at age 2 was used as the index for early growth rate due to young of the year catch being highly variable among sites. Sample size was limited to a minimum of at least five individuals at age 2

per site. Only sites that provided data to calculate at least four sex-specific life history traits were used for this study. All life history trait estimations were calculated the same way across contemporary and historical datasets.

2.5 Statistical Analysis

I used generalized linear mixed models (GLMMs) to examine the influence of location and depth on mean, population-level life history traits. I built individual GLMMs for each life history metric listed above for each sex. The fixed effects included were latitude, longitude, and depth, with the number of years sampled as a random effect. The random term was included to account for variation in the number of years sampled at each site. In the contemporary dataset, life history trait values for all 20 sites were calculated and used in mixed model analysis. In the historical dataset and temporal comparisons, the 11 sites that were replicated across datasets were used. However, due to limited sample numbers in the historical dataset, female maximum size, male lifespan, and female lifespan were omitted from analysis. All GLMMs were built in R (R Core Team, 2017) using the “lme4” package (Bates et al., 2015) with P-values generated using the add-on package “lmerTest” (Kuznetsova et al., 2017). Marginal and conditional R^2 values for each GLMM were generated using the “MuMIn” package (Barton, 2020).

To group sites based on similarities in all life history traits combined, I used K-means clustering via the “FactoMineR” (Husson et al., 2008) and “factoextra” (Kassambara, 2020) packages in R for each dataset. I used the elbow method via “factoextra” and “NbClust” (Charrad et al., 2014) to determine the appropriate number of clusters for each dataset. Eighteen of the original 20 sites from the contemporary timeframe were used for K-means clustering; sites 6 and 13 were omitted because

lifespan and growth rate could not be calculated for either sex due to small sample size. Eight of the 11 sites from the historical dataset were used for K-means clustering; sites 7, 9, and 18 were omitted because male and female maximum size, male and female lifespan, and male growth rate could not be calculated due to small sample size.

To compare life history trait values between timeframes, I used a mix of practical statistical tests in R. I used Shapiro-Wilk tests to first check if data were normally distributed in each timeframe for each sex-specific life history trait. When data met the assumption of normality for both timeframes, I used an F-test to check for homogeneity in variances in each life history trait. If variance between timeframes was equal (F-test p-value > 0.05), a classic Student's t-test was used to determine if the means were significantly different between timeframes. If variance was unequal between timeframes (F-test p-value < 0.05), a Welch t-test was used to examine differences in the means. If data did not meet the assumption of normality across both timeframes for a sex-specific life history trait, a non-parametric two-sample Wilcoxon rank-sum test was used. Thus, a combination of parametric and non-parametric tests was used to determine whether life history trait values differed between timeframes on a lake-wide scale.

3.0 Results

3.1 Contemporary Dataset (2009–2018)

3.1.1 Life History Trait Variation by Location and Water Depth

Size and Age at Maturity

Male size at maturity (L50) ranged 5-fold from 31.8 mm at site 4 in the South Basin to 165.9 mm at site 16 in northern Georgian Bay, with a lake-wide average of 122.7 ± 28.8 mm. In contrast, female L50 was less variable, ranging 1.4-fold from 140.8 mm to 193.3 mm at sites 17 and 16 in northern Georgian Bay, with an average of 167.0 ± 12.6 mm lake-wide (**Table 3**). Latitude, longitude, and depth were not significant predictors of male or female yellow perch L50 in Lake Huron (**Figure 4**; Appendix **Table S1A** and **Table S1B**).

Male age at maturity (A50) ranged more than 4-fold from 1.2 years at site 2 in the South Basin to 4.8 years at site 15 in northeast Georgian Bay, with a lake-wide average of 1.2 ± 1.4 years. Female A50 also ranged approximately 4-fold from 0.8 years to 4.1 years at sites 17 and 16 in northern Georgian Bay. The lake-wide average for female A50 was 2.6 ± 0.7 years (**Table 3**). Male A50 varied significantly with latitude, increasing from south to north, and longitude, increasing from west to east (**Figure 5A** and **Figure 5C**). Depth was not a significant predictor of male A50 (Appendix **Table S1C**). Latitude was a significant predictor of female A50, but age decreased from south to north, opposite to the trend observed for males (**Figure 5B**). Longitude and depth were not significant predictors of Female A50 (Appendix **Table S1D**).

Maximum Size

Male maximum size ranged 1.6-fold from 181.0 mm at site 15 in northeast Georgian Bay to 285.3 mm at site 3 in the South Basin, with a lake-wide average of 244.6 ± 30.6 mm. Females were generally larger than males, and maximum size also ranged 1.6-fold from 214.4 mm at site 16 in northern Georgian Bay to 346.2 mm at site 5 in the South Basin. The lake-wide average maximum size for females was 278.64 ± 40.1 mm. Male maximum size could not be calculated at site 13 due to a shortage of old-age male fish samples (**Table 3**). Male maximum size varied significantly with latitude, decreasing from south to north (**Figure 6A**). Longitude and depth were not significant predictors of male maximum size (Appendix **Table S1E**). Female maximum size varied significantly with latitude, decreasing from south to north, and longitude, decreasing from west to east (**Figure 6B** and **Figure 6D**). Depth was not a significant predictor of female maximum size (Appendix **Table S1F**).

Lifespan

For male perch, lifespan ranged 1.8-fold from 4.0 years at site 10 in the Main Basin to 7.1 years at site 2 in the South Basin, and averaged 5.7 ± 0.9 years lake-wide. Female lifespan ranged 2.5-fold from 3.7 years at site 13 in southern Georgian Bay to 9.3 years at site 2 in the South Basin and averaged 6.54 ± 1.4 years lake-wide. Similar to male maximum size, male lifespan could not be calculated at site 13 due to a shortage of old-age male fish samples (**Table 3**). Latitude, longitude, and depth were not significant predictors of male yellow perch lifespan, while latitude and depth were not significant predictors of female yellow perch lifespan (Appendix **Table S1G** and **Table S1H**).

Longitude was a significant predictor of female lifespan; female lifespan increased from east to west (**Figure 7D**).

Growth Rate

Male growth at age 2 (growth rate) ranged only 1.3-fold from 130.8 mm at site 14 in southern Georgian Bay to 176.2 mm at site 8 in the Main Basin, with a lake-wide average of 149.7 ± 13.8 mm. Female growth at age 2 ranged 1.4-fold from 131.7 mm at site 16 in northern Georgian Bay to 188.9 mm at site 8 in the Main Basin, averaging 155.9 ± 15.5 mm lake-wide. Male and female growth rate at age 2 could not be determined at site 6 due to a shortage of sampled age-2 fish in both sexes (**Table 3**).

Depth was the only significant predictor of male and female growth rate; both male and female yellow perch had increased growth at greater depths (**Figure 8E** and **Figure 8F**).

Growth rate was not significantly predictor by latitude or longitude in either sex (Appendix **Table S1I** and **Table S1J**).

Table 3: Sex-specific life history trait values at each site for Lake Huron yellow perch sampled in the contemporary timeframe (2009–2018). Length at maturity (L50) measured as fork length in mm, age at maturity (A50) measured as age in years, maximum size (max size) measured as fork length in mm, lifespan measured as age in years, and growth at age 2 (growth rate) measured as fork length in mm are assessed. The lake-wide average with standard deviation ($\bar{x} \pm SD$) for each life history trait is displayed. Male and female growth rate could not be calculated at site 6, while max size and lifespan could not be calculated at site 13; sites that lack measurement for a particular life history trait are listed as N/A (not available).

Site	Life History Traits									
	Male					Female				
	L50	A50	Max Size	Lifespan	Growth Rate	L50	A50	Max Size	Lifespan	Growth Rate
1	111.0	-0.2	270.6	6.7	143.4	174.6	3.2	316.6	7.2	153.0
2	68.1	-1.2	273.0	7.1	138.0	172.3	3.5	321.0	9.3	134.9
3	141.9	1.6	285.3	6.6	165.8	179.4	2.6	318.0	7.5	174.6
4	31.8	-0.4	276.7	6.5	142.6	169.3	3.0	332.2	8.4	143.2
5	112.1	0.6	269.2	6.2	147.8	183.8	2.8	346.2	7.7	151.9
6	160.2	-0.7	271.9	6.3	N/A	175.2	2.8	315.3	7.4	N/A
7	120.7	-0.2	265.5	5.1	164.3	177.7	1.9	320.4	6.1	182.8
8	122.2	0.4	227.3	5.4	176.3	165.0	1.8	260.8	5.8	188.9
9	124.7	0.8	224.0	4.3	159.7	165.0	2.3	256.7	5.1	163.8
10	125.0	-0.1	238.2	4.0	172.4	168.5	2.2	245.4	4.1	181.6
11	121.6	1.4	257.2	5.4	158.7	151.7	2.5	249.0	6.5	153.7
12	145.9	2.0	264.6	7.2	164.2	162.0	2.7	262.8	6.3	151.2
13	140.7	2.0	N/A	N/A	143.0	169.2	2.9	220.7	3.7	147.2

14	109.8	1.9	217.0	5.2	130.8	148.3	2.9	244.5	6.7	141.9
15	126.3	4.8	181.0	5.3	130.9	149.0	2.4	234.0	5.5	145.1
16	165.9	3.5	186.6	4.6	131.6	193.3	4.1	214.4	5.5	131.7
17	124.9	1.6	196.7	5.3	138.3	140.8	0.8	232.9	6.8	147.7
18	136.0	1.8	247.5	6.0	147.9	159.7	2.1	301.2	6.9	156.1
19	139.0	1.9	242.3	6.1	143.7	174.4	2.6	302.9	8.2	157.9
20	126.0	1.5	253.3	5.5	144.2	160.8	2.2	277.7	6.1	154.8
	122.7 ±	1.2 ±	244.6 ±			167.0 ±	2.6 ±			155.9 ±
$\bar{x} \pm SD$	28.8	1.4	30.6	5.7 ± 0.9	149.7 ± 13.8	12.6	0.7	278.6 ± 40.1	6.5 ± 1.4	15.5

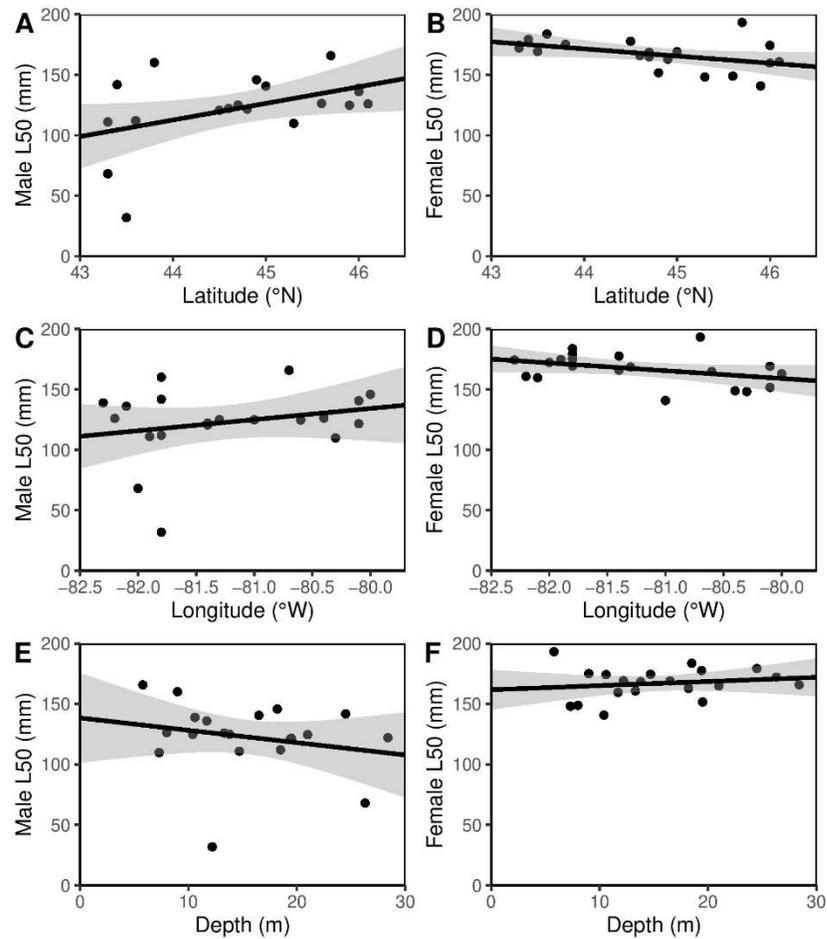


Figure 4: Relationships between size at maturity (L50) and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 2009–2018. (A) Male size at maturity versus latitude; (B) female size at maturity versus latitude; (C) male size at maturity versus longitude; (D) female size at maturity versus longitude; (E) male size at maturity versus depth; and (F) female size at maturity versus depth. Male and female size at maturity are measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}\text{N}$), longitude is measured in decimal degrees west ($^{\circ}\text{W}$), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. None of the relationships shown were significant.

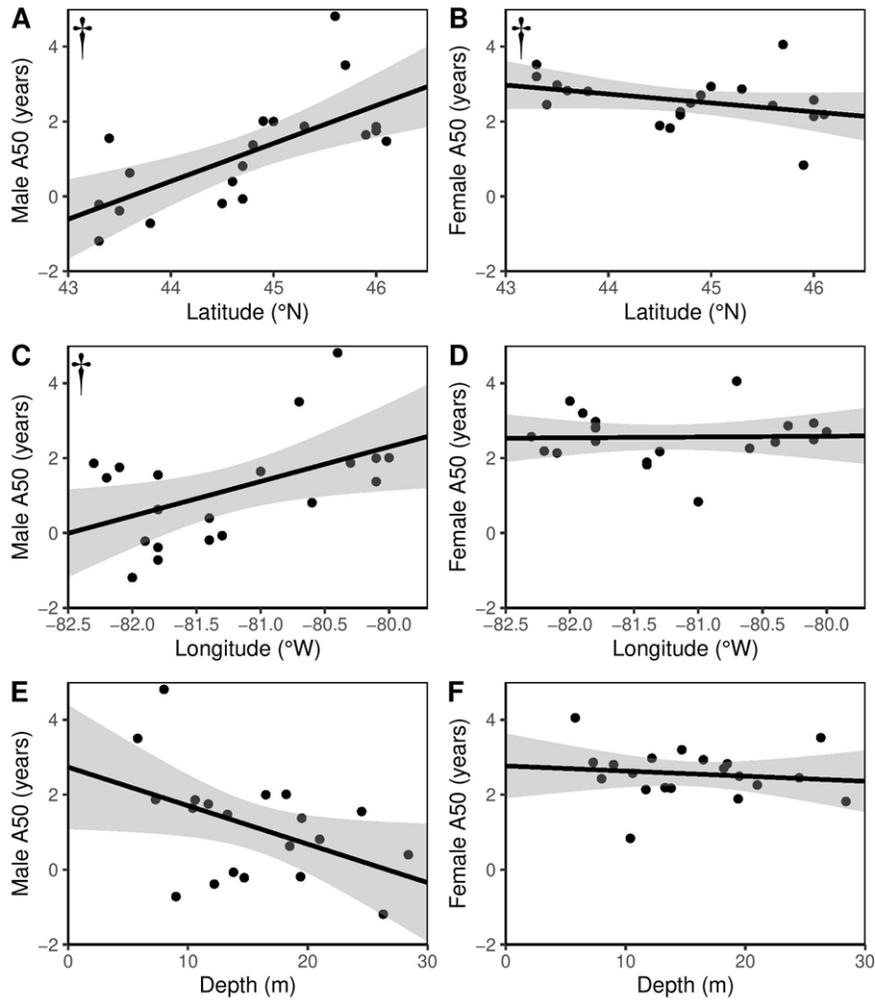


Figure 5: Relationships between age at maturity (A50) and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 2009–2018. (A) Male age at maturity versus latitude; (B) female age at maturity versus latitude; (C) male age at maturity versus longitude; (D) female age at maturity versus longitude; (E) male age at maturity versus depth; and (F) female age at maturity versus depth. Male and female age at maturity are measured in years, latitude is measured in decimal degrees north ($^{\circ}\text{N}$), longitude is measured in decimal degrees west ($^{\circ}\text{W}$), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. Daggers (\dagger) indicate relationships where variables were significant predictors of life history trait values.

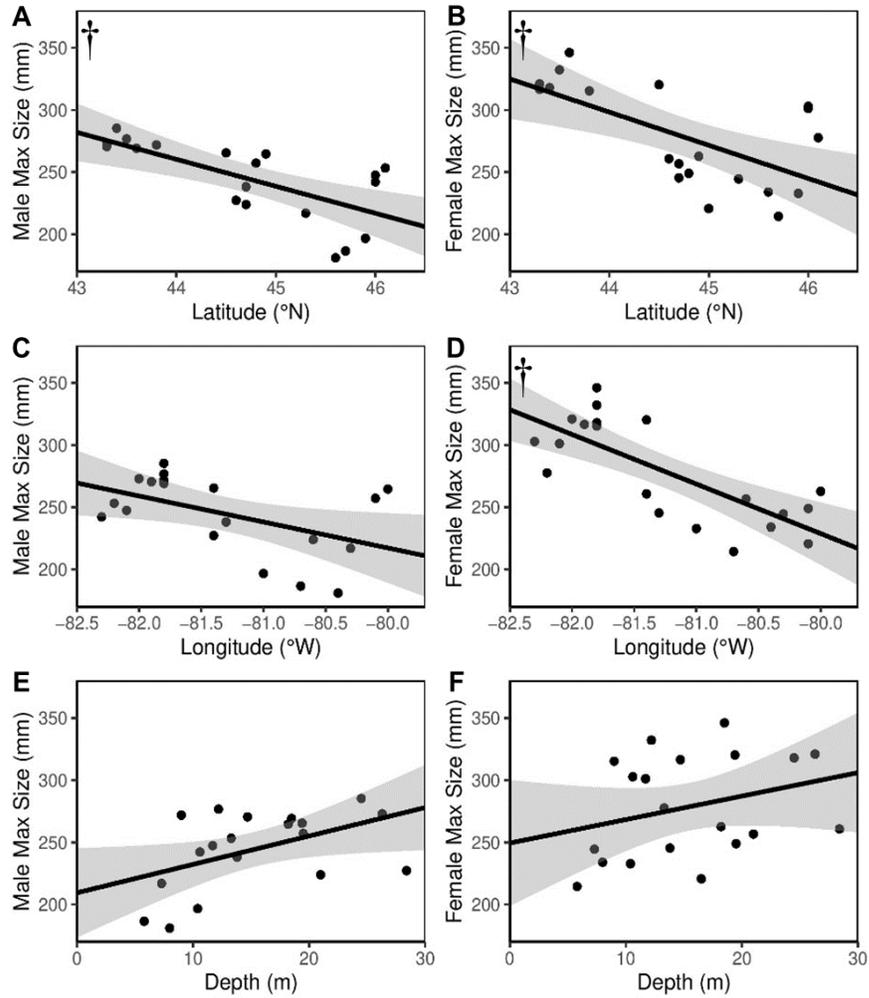


Figure 6: Relationships between maximum size (max size) and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 2009–2018. (A) Male maximum size versus latitude; (B) female maximum size versus latitude; (C) male maximum size versus longitude; (D) female maximum size versus longitude; (E) male maximum size versus depth; and (F) female maximum size versus depth. Male and female maximum size are measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. Dagggers (†) indicate relationships where variables were significant predictors of life history trait values.

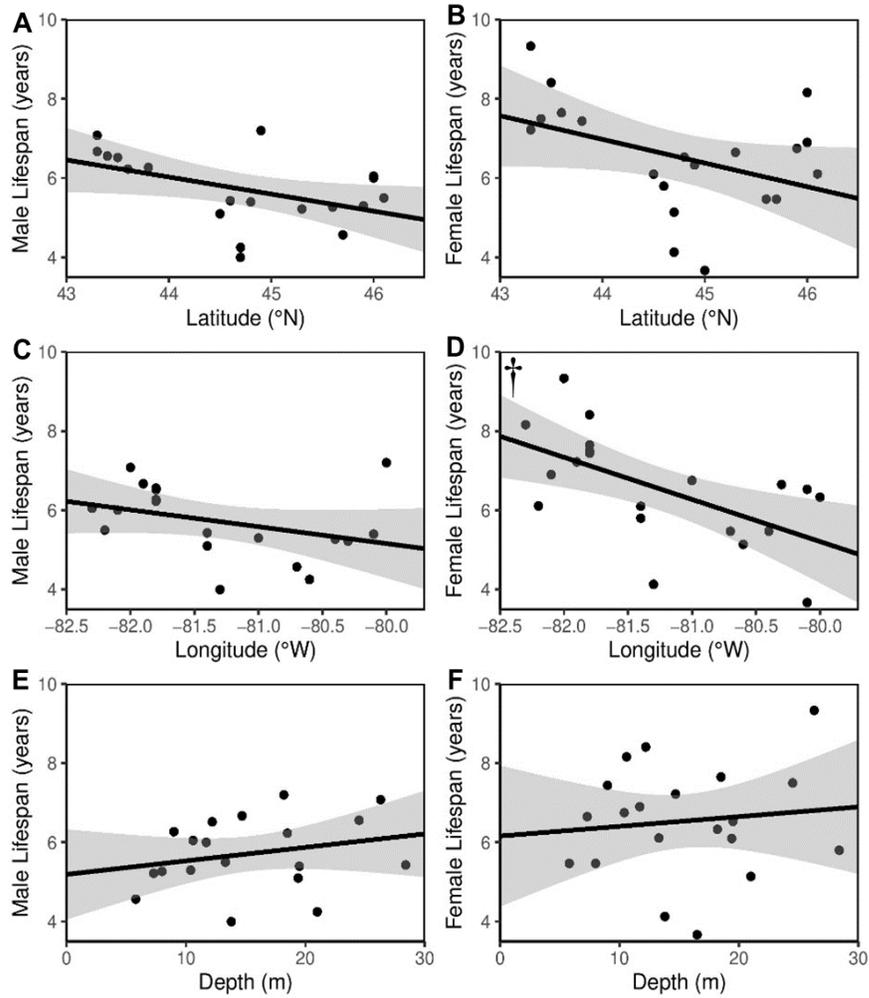


Figure 7: Relationships between lifespan and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 2009–2018. (A) Male lifespan versus latitude; (B) female lifespan versus latitude; (C) male lifespan versus longitude; (D) female lifespan versus longitude; (E) male lifespan versus depth; and (F) female lifespan versus depth. Male and female lifespan are measured in years, latitude is measured in decimal degrees north ($^{\circ}\text{N}$), longitude is measured in decimal degrees west ($^{\circ}\text{W}$), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. Daggers (\dagger) indicate relationships where variables were significant predictors of life history trait values.

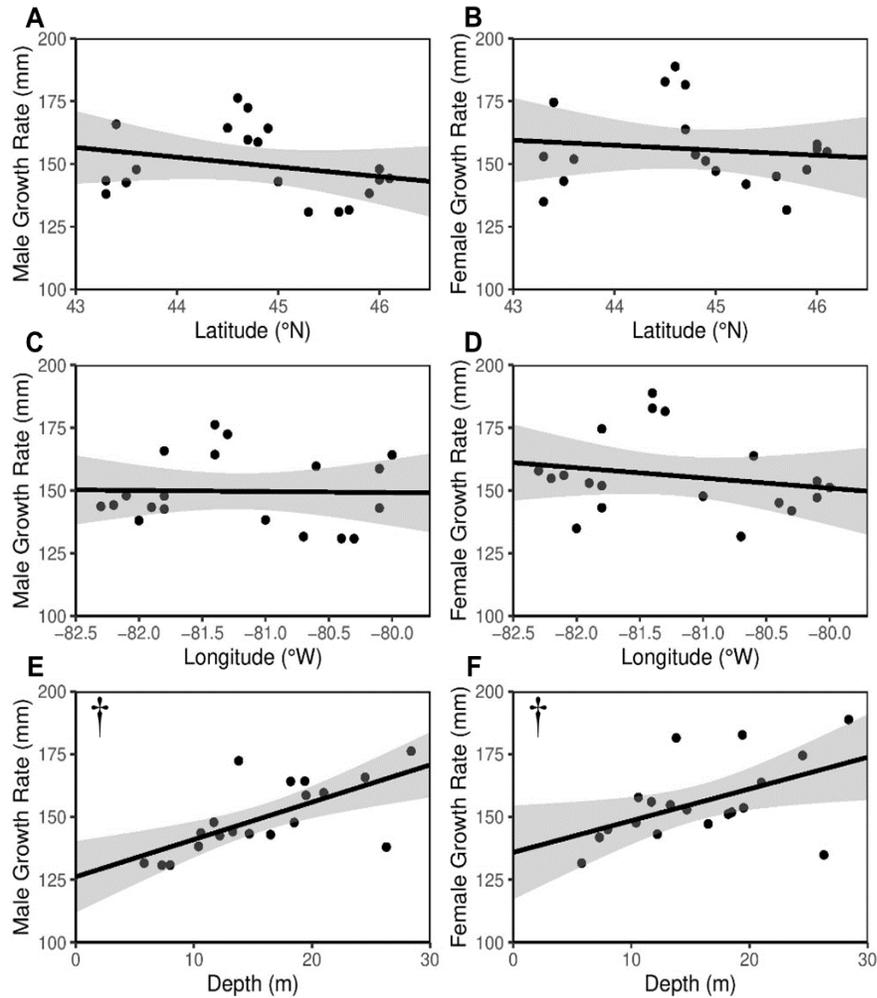


Figure 8: Relationships between growth rate at age 2 (growth rate) and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 2009–2018. (A) Male growth at age 2 versus latitude; (B) female growth at age 2 versus latitude; (C) male growth at age 2 versus longitude; (D) female growth at age 2 versus longitude; (E) male growth at age 2 versus depth; and (F) female growth at age 2 versus depth. Male and female growth at age 2 are measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}\text{N}$), longitude is measured in decimal degrees west ($^{\circ}\text{W}$), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. Daggers (†) indicate relationships where variables were significant predictors of life history trait values.

3.1.2 Clustering Based on Life History Traits 2009–2018

K-means clustering analysis based on all life history traits indicated the best model fit for Lake Huron yellow perch contained 6 separate clusters, based on 100 replicates. Cluster 1 consisted of only site 16 (**Figure 9**), which was unique to northeast Georgian Bay (**Figure 10**). Yellow perch from site 16 grew slowly, lived short lifespans, and reached maturity at a greater size and age than other sites within Georgian Bay and the rest of Lake Huron. The population was discrete from others in Georgian Bay and Lake Huron. Cluster 2 was composed of four sites including sites 1, 2, 4, and 5 (**Figure 9**), all from the South Basin (**Figure 10**). Yellow perch from sites in cluster 2 grew quickly, lived long lives, grew to large sizes, and matured at small sizes and early ages. These fish were superior in growth, maturity, and lifespan compared to others around Lake Huron. Cluster 3 contained three sites, including sites 14, 15, and 17 (**Figure 9**), all from central Georgian Bay (**Figure 10**). Fish from cluster 3 grew slowly, matured at a small size, did not get large, and lived quick, short lives. Cluster 4 contained three sites, including sites 8 and 10 from the Main Basin, and site 9 from southwest Georgian Bay (**Figure 9**); thus, cluster 4 covered two different regions of Lake Huron (**Figure 10**). Fish from cluster 4 had the fastest growth rate among clusters and matured quickly, but did not live long lives or grow large; thus, these fish grew fast, but died fast. Cluster 5 was composed of sites 3 and 7 (**Figure 9**) from the South Basin and Main Basin, respectively (**Figure 10**). Therefore, similarly to cluster 4, cluster 5 contained sites from two separate regions of Lake Huron. Yellow perch from cluster 5 had fairly fast growth rates, long lifespans, and matured early in life and at a smaller size. Cluster 5 existed as a “hybrid” cluster between cluster 2 in the South Basin and cluster 4 in the Main Basin, acting as a

combination of the two, based on life history. Cluster 6 consisted of five different sites including sites 11, 12, 18, 19, and 20 (**Figure 9**). Cluster 6 also covered multiple regions of Lake Huron; sites 11 and 12 were located in southeast Georgian Bay, while sites 18, 19, and 20 were located in the North Channel (**Figure 10**). Yellow perch from cluster 6 had average growth rates, reached maturity at an average size and age, and grew to an average maximum size; however, they lived very long lives compared to fish of other clusters. Site 6 and 13 were omitted from k-means analysis because neither site had measurements for all life history traits (**Table 3**).

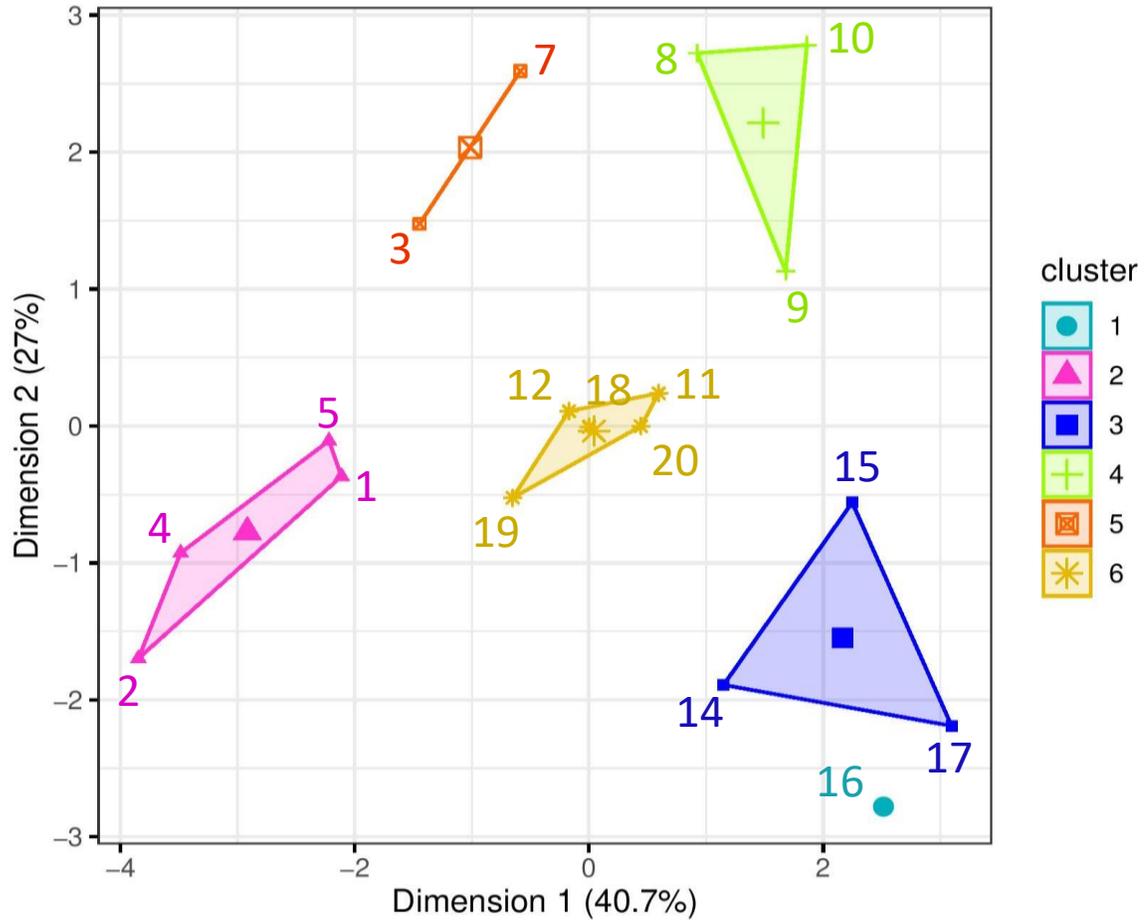


Figure 9: K-means cluster plot with site groupings based on similarities in values for the suite of life history traits determined for this study. K-means analysis identified 6 distinct clusters ranging in size from 1 to 5 sites. Numbers in each cluster correspond with site numbers, and sites belonging to the same cluster are colour coded. Sites 6 and 13 were omitted from k-means clustering. (Original in colour).

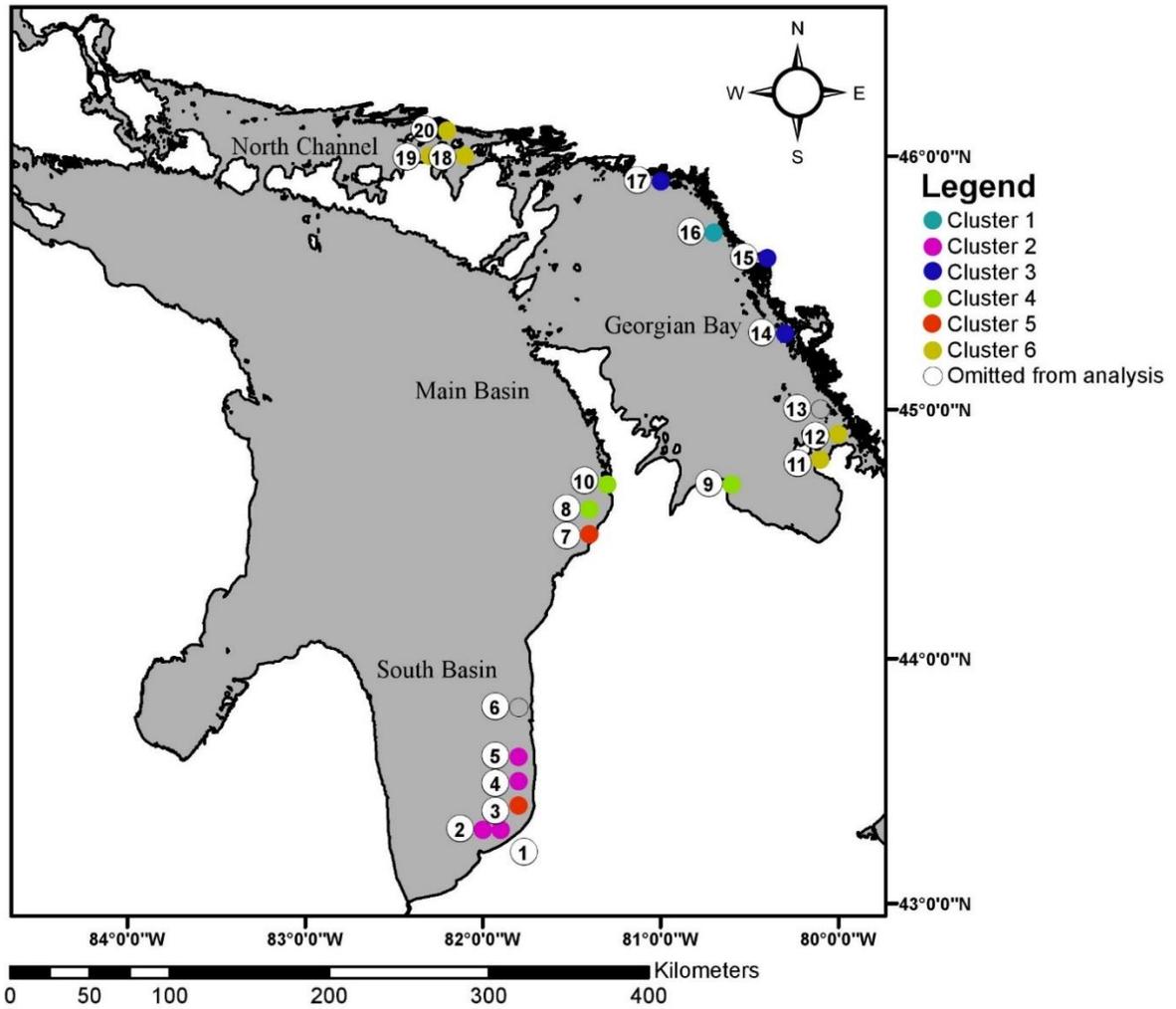


Figure 10: Map of collection sites in Lake Huron with sites coloured according to K-means clustering based on similarity in the suite of life history traits assessed. Major basins of Lake Huron are labelled, and sites are numerically labelled with an adjacent white circle (0–20). Sites 6 and 13 were omitted from k-means clustering and are indicated by a hollow circle. (Original in colour).

3.2 Historical Dataset (1990–1999)

3.2.1 Life History Trait Variation by Location and Water Depth

Size and Age at Maturity

Male size at maturity (L50) ranged 7.6-fold from 24.9 mm to 189.5 mm at sites 2 and 3 in the South Basin, with a lake-wide average of 111.4 ± 52.4 mm. Female L50 ranged 1.9-fold from 132.6 mm at site 23 in the North Channel to 248.6 mm at site 3 in the South Basin, and averaged 171.0 ± 32.0 mm lake-wide (**Table 4**). Latitude, longitude, and depth were not significant predictors of historical male yellow perch L50 in Lake Huron (Appendix **Table S2A**). Latitude was a significant predictor of female L50, which decreased from south to north (**Figure 11B**). Longitude and depth were not significant predictors of historical female L50 (Appendix **Table S2B**).

In males, historical age at maturity (A50) ranged approximately 3-fold from year 1 (calculated at -1.7 years) at site 13 in the Main Basin to 3.0 years at site 3 in the South Basin, averaging 1.1 ± 1.1 years lake-wide. Historical female A50 ranged 5.7-fold from year 1 (calculated at 0.6 years) at site 8 in the Main Basin to 3.5 years at site 3 in the South Basin, and averaged 2.2 ± 1.1 years lake-wide (**Table 4**). Latitude, longitude, and depth were not significant predictors of historical male or female yellow perch A50 on Lake Huron (**Figure 12**; Appendix **Table S2C** and **Table S2D**).

Maximum Size

Historical male maximum size ranged only 1.4-fold from 203.6 mm at site 4 in the South Basin to 289.5 mm at site 13 in the Main Basin, and averaged 232.9 ± 23.3 mm lake-wide. Historical female maximum size also ranged 1.4-fold, from 248.6 mm at site

23 in the North Channel to 344.5 mm at site 13 in the Main Basin. The lake-wide average for historical female maximum size was 308.6 ± 31.9 mm (**Table 4**). Male maximum size could not be calculated at sites 7, 9, and 18, while female maximum size could not be calculated at sites 7 and 9, both due to a shortage of old-age fish samples. Latitude, longitude, and depth were not significant predictors of male yellow perch maximum size in the historical timeframe (**Figure 13**; Appendix **Table S2E**). Relationships between historical female yellow perch maximum size and latitude, longitude, and depth were not assessed because models would not converge.

Lifespan

Male lifespan ranged 1.6-fold from 4.1 years at site 4 in the South Basin to 6.4 years at site 22 in the North Channel, with a lake-wide average of 5.1 ± 0.9 years. Females ranged 2.2-fold from 4.0 years at site 23 in the North Channel to 8.7 years at site 4 in the South Basin, and averaged 6.7 ± 1.4 years lake-wide (**Table 4**). Similar to maximum size, male lifespan could not be calculated at sites 7, 9, and 18, while female lifespan could not be calculated at sites 7 and 9, both due to a shortage of old-age fish samples. Relationships between historical male and female yellow perch lifespan and latitude, longitude, and depth were not assessed because models would not converge (**Figure 14**).

Growth Rate

Male growth at age 2 ranged only 1.1-fold from 146.2 mm at site 1 in the South Basin to 167.5 at site 21 in the North Channel, with a lake-wide average of 154.2 ± 6.1 mm. Females ranged 1.3-fold from 149.5 mm at site 4 in the South Basin to 188.1 mm at

site 21 in the North Channel, and averaged 165.6 ± 10.0 mm lake-wide (**Table 4**). Male growth rate at age 2 could not be determined at sites 7 and 9 due to a shortage of sampled age-2 fish. Latitude, longitude, and depth were not significant predictors of historical male or female growth rate (**Figure 15**; Appendix **Table S2F** and **Table S2G**).

Table 4: Sex-specific life history trait values at each site for Lake Huron yellow perch sampled in the historical timeframe (1990–1999). Length at maturity (L50) measured as fork length in mm, age at maturity (A50) measured as age in years, maximum size (max size) measured as fork length in mm, lifespan measured as age in years, and growth at age 2 (growth rate) measured as fork length in mm are assessed. The mean with standard deviation ($\bar{x} \pm SD$) for each life history trait is displayed. Male max size and lifespan could not be calculated at sites 7, 9, and 18, while male growth rate, female max size, and female lifespan could not be calculated at sites 7 and 9; sites that lack measurement for a particular life history trait are listed as N/A (not available).

Historical Dataset Life History Trait Values										
Site	Male					Female				
	L50	A50	Max Size	Lifespan	Growth Rate	L50	A50	Max Size	Lifespan	Growth Rate
1	43.4	0.3	219.8	5.4	146.2	203.1	3.3	304.1	6.4	159.7
2	24.9	0.5	226.2	5.3	151.2	178.7	2.6	318.9	7.2	166.4
3	189.5	3.0	231.0	4.2	158.7	248.6	3.5	289.5	5.3	179.2
4	133.0	1.8	203.6	4.1	147.9	178.2	3.0	340.9	8.7	149.5
5	67.8	1.2	224.9	4.6	151.2	173.5	2.6	344.5	8.2	158.2
7	135.0	0.9	N/A	N/A	N/A	142.3	-0.6	N/A	N/A	160.8
9	164.4	1.7	N/A	N/A	N/A	150.7	1.9	N/A	N/A	164.7
10	49.0	-1.7	289.5	6.3	157.4	177.2	2.1	341.6	7.8	167.7
18	138.7	1.0	N/A	N/A	167.5	136.5	1.9	319.4	7.3	188.1
19	143.7	1.5	233.1	6.4	153.4	159.6	2.0	269.5	5.8	159.7
20	136.0	1.8	235.0	4.3	154.1	132.6	1.8	248.6	4.0	167.4
$\bar{x} \pm SD$	111.4 \pm 52.4	1.1 \pm 1.1	232.9 \pm 23.3	5.1 \pm 0.9	154.2 \pm 6.1	171.0 \pm 32.0	2.2 \pm 1.1	308.6 \pm 31.9	6.7 \pm 1.4	165.6 \pm 10.0

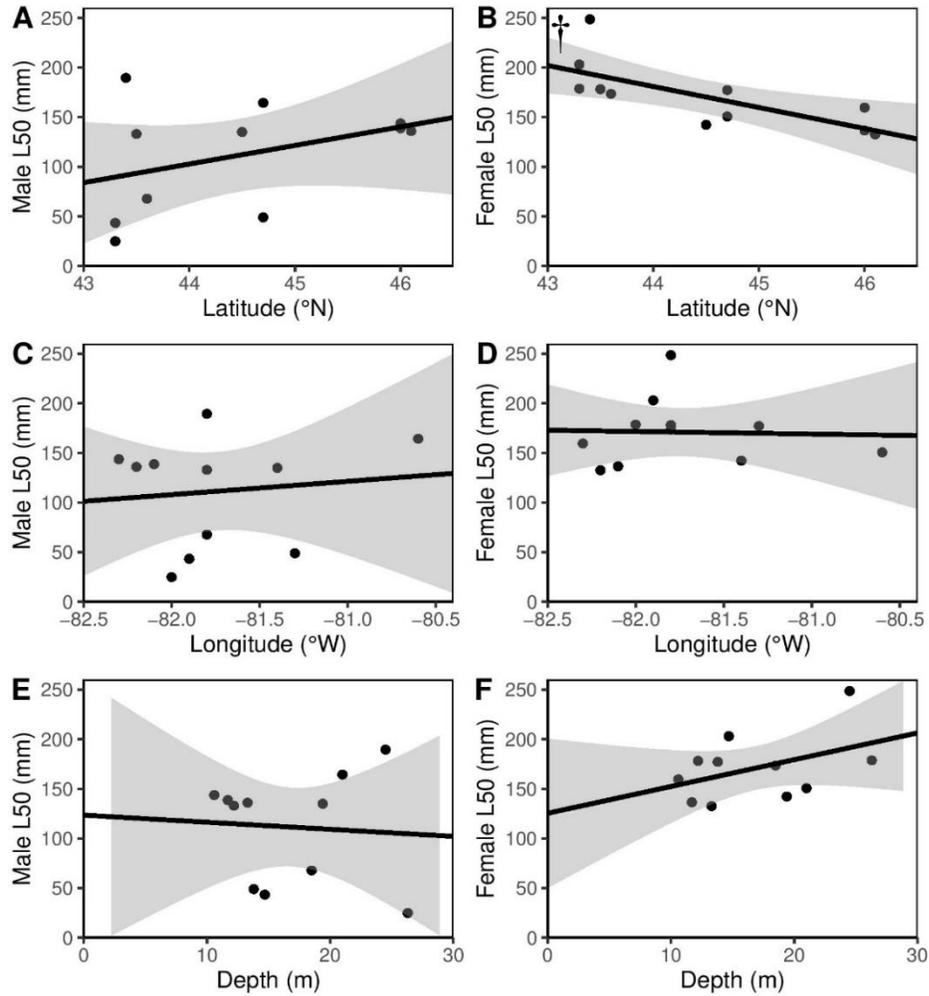


Figure 11: Relationships between size at maturity and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 1990–1999. (A) Male size at maturity versus latitude; (B) female size at maturity versus latitude; (C) male size at maturity versus longitude; (D) female size at maturity versus longitude; (E) male size at maturity versus depth; and (F) female size at maturity versus depth. Male and female size at maturity are measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}\text{N}$), longitude is measured in decimal degrees west ($^{\circ}\text{W}$), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. Daggers (\dagger) indicate relationships where variables were significant predictors of life history trait values.

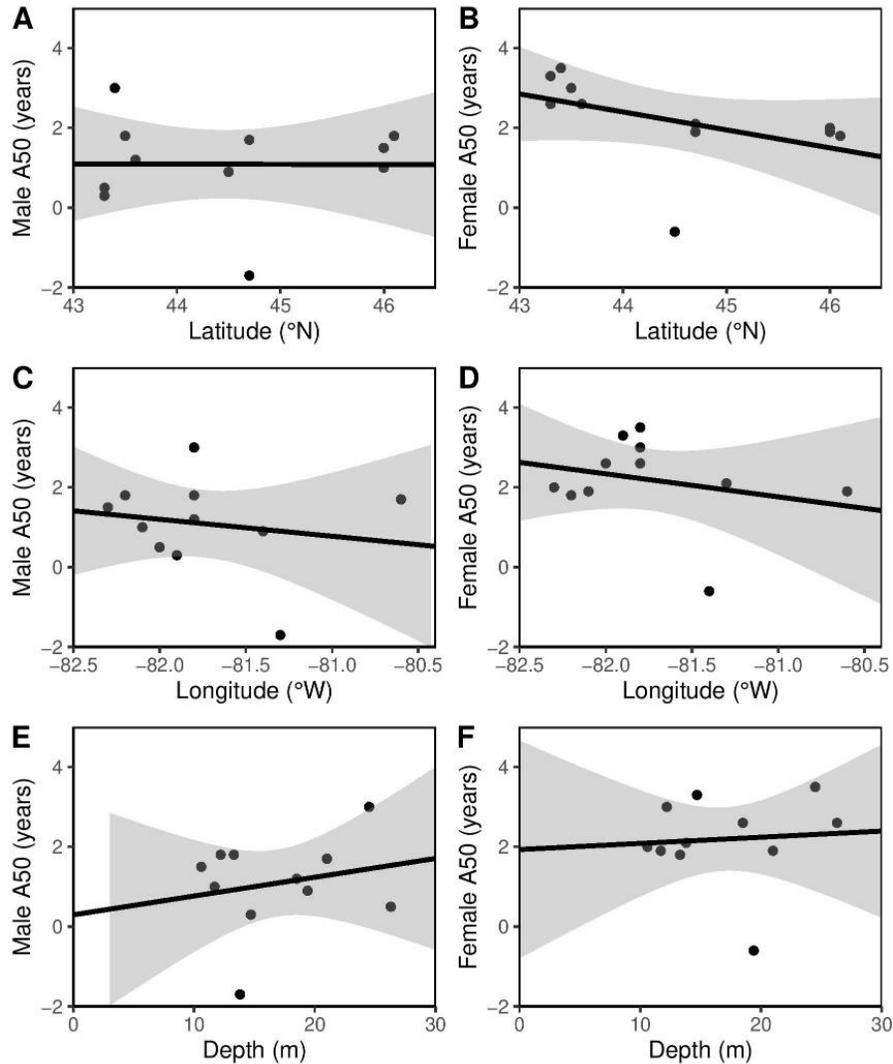


Figure 12: Relationships between historical age at maturity and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 1990–1999. (A) Male age at maturity versus latitude; (B) female age at maturity versus latitude; (C) male age at maturity versus longitude; (D) female age at maturity versus longitude; (E) male age at maturity versus depth; and (F) female age at maturity versus depth. Male and female age at maturity are measured in years, latitude is measured in decimal degrees north ($^{\circ}\text{N}$), longitude is measured in decimal degrees west ($^{\circ}\text{W}$), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. None of the relationships shown were significant.

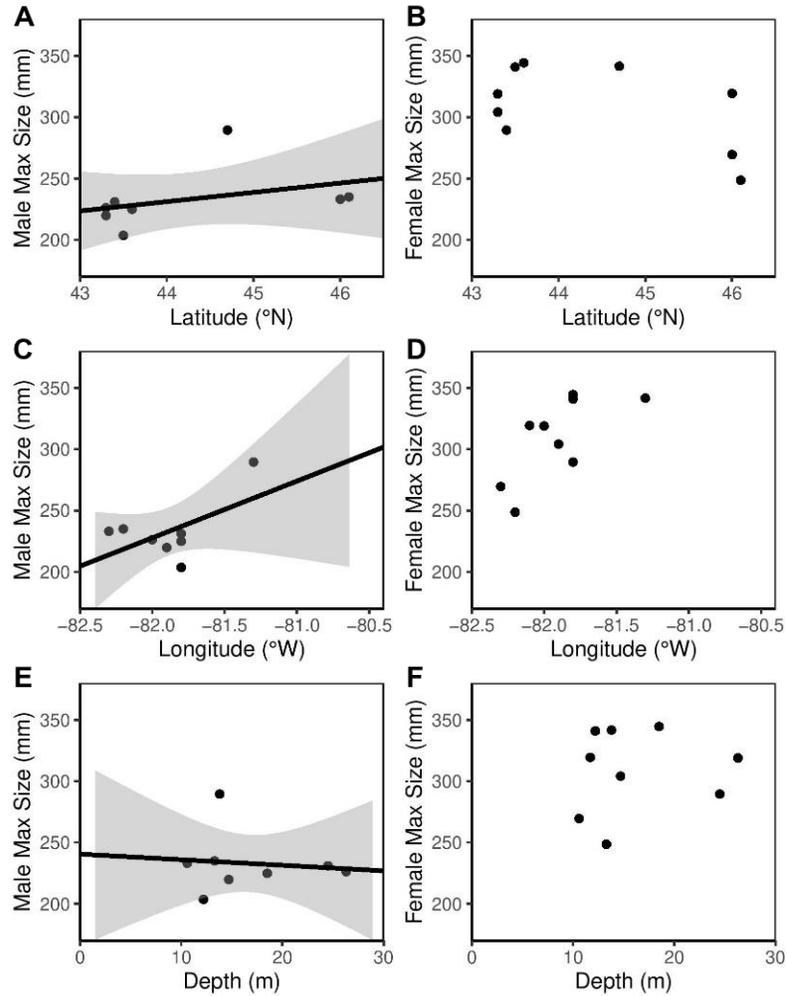


Figure 13: Relationships between historical maximum size and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 1990–1999. (A) Male maximum size versus latitude; (B) female maximum size versus latitude; (C) male maximum size versus longitude; (D) female maximum size versus longitude; (E) male maximum size versus depth; and (F) female maximum size versus depth. Male maximum size is measured in mm fork length, latitude is measured in decimal degrees north (°N), longitude is measured in decimal degrees west (°W), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown when models converged. None of the relationships shown were significant.

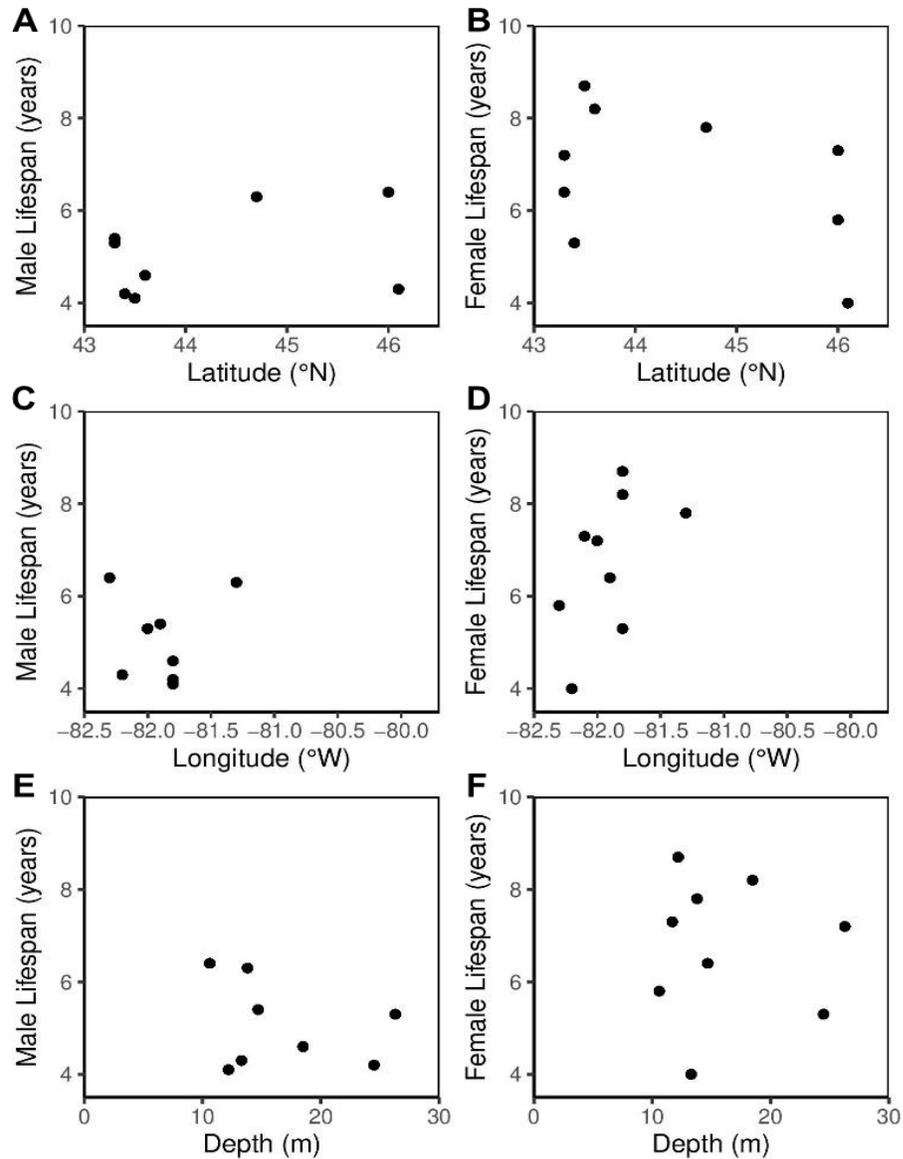


Figure 14: Relationships between historical lifespan and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 1990–1999. (A) Male lifespan versus latitude; (B) female lifespan versus latitude; (C) male lifespan versus longitude; (D) female lifespan versus longitude; (E) male lifespan versus depth; and (F) female lifespan versus depth. Male lifespan is measured in years, latitude is measured in decimal degrees north (°N), longitude is measured in decimal degrees west (°W), and depth is measured in meters (m). No trendlines with 95% confidence intervals are shown because models did not converge.

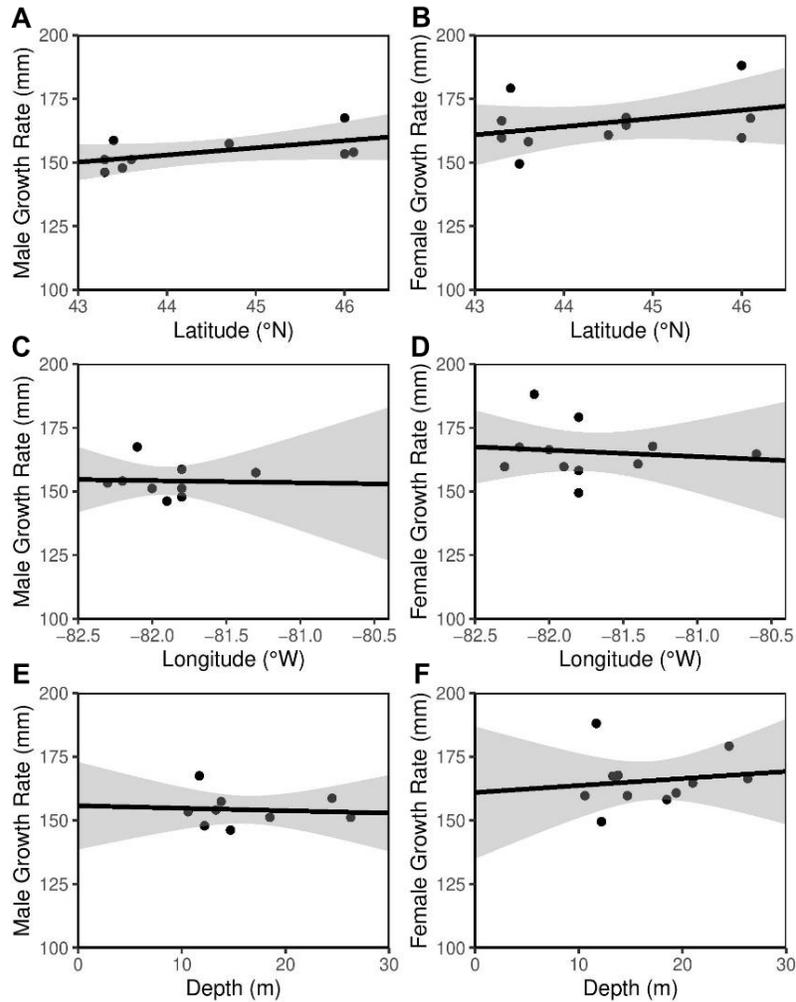


Figure 15: Relationships between historical growth rate at age 2 and predictor variables for yellow perch sampled from Lake Huron, Ontario, Canada during the years 1990–1999. (A) Male growth rate at age 2 versus latitude; (B) female growth rate at age 2 versus latitude; (C) male growth rate at age 2 versus longitude; (D) female growth rate at age 2 versus longitude; (E) male growth rate at age 2 versus depth; and (F) female growth rate at age 2 versus depth. Male and female growth rate at age 2 are measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}$ N), longitude is measured in decimal degrees west ($^{\circ}$ W), and depth is measured in meters (m). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. None of the relationships shown were significant.

3.2.2 Clustering Based on Life History Traits 1990–1999

K-means clustering analysis based on 100 replicates indicated the best model fit for the historical timeframe was 4 clusters of varying volume. Cluster 1 contained only site 3 (**Figure 16**) in the South Basin (**Figure 17**). Yellow perch from cluster 1 grew extremely fast, but matured at a greater size and older age than those from other clusters. Cluster 2 contained only site 10 (**Figure 16**) from the Main Basin (**Figure 17**). Yellow perch from cluster 2 had average growth rates and reached maturity at an average size and age, but grew to a large maximum size and lived long lives. Cluster 3 consisted of sites 19 and 20 (**Figure 16**), both from the North Channel (**Figure 17**). Yellow perch from cluster 3 had moderate growth rates, grew to an average maximum size, took longer to reach maturity, and lived longer lives compared to fish of other clusters. Cluster 4 contained sites 1, 2, 4, and 5 (**Figure 16**) all located within the South Basin (**Figure 17**). Yellow perch from cluster 4 grew relatively quickly, matured at a small size and early age, reached a large maximum size, and lived long lives. Fish belonging to cluster 4 were superior growers compared to others around Lake Huron. Sites 7, 9, and 18 were omitted from k-means analysis as each site lacked measurements for life history traits.

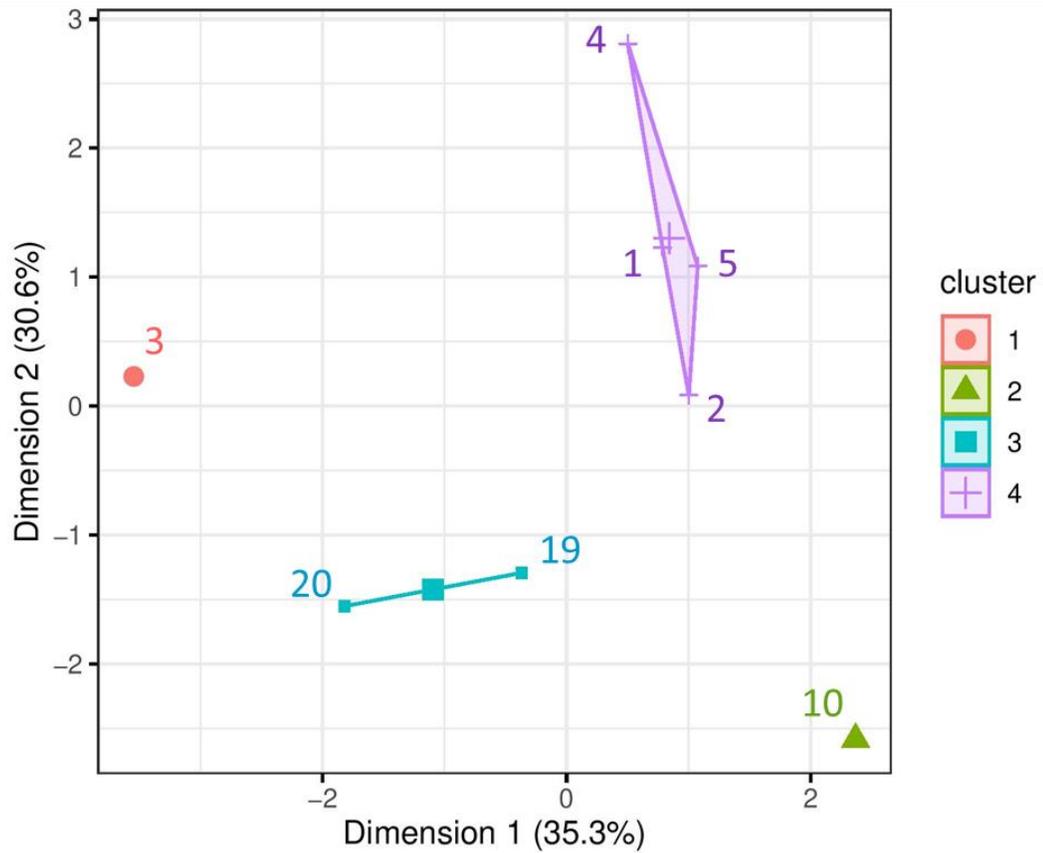


Figure 16: K-means cluster plot with site groupings based on similarities in values for all life history traits in the historical era. K-means analysis identified 4 distinct clusters ranging in size from 1 to 4 sites. Numbers in each cluster correspond with site numbers, and sites belonging to the same cluster are colour coded. Sites 7, 9, and 18 were omitted from historical k-means clustering. (Original in colour).

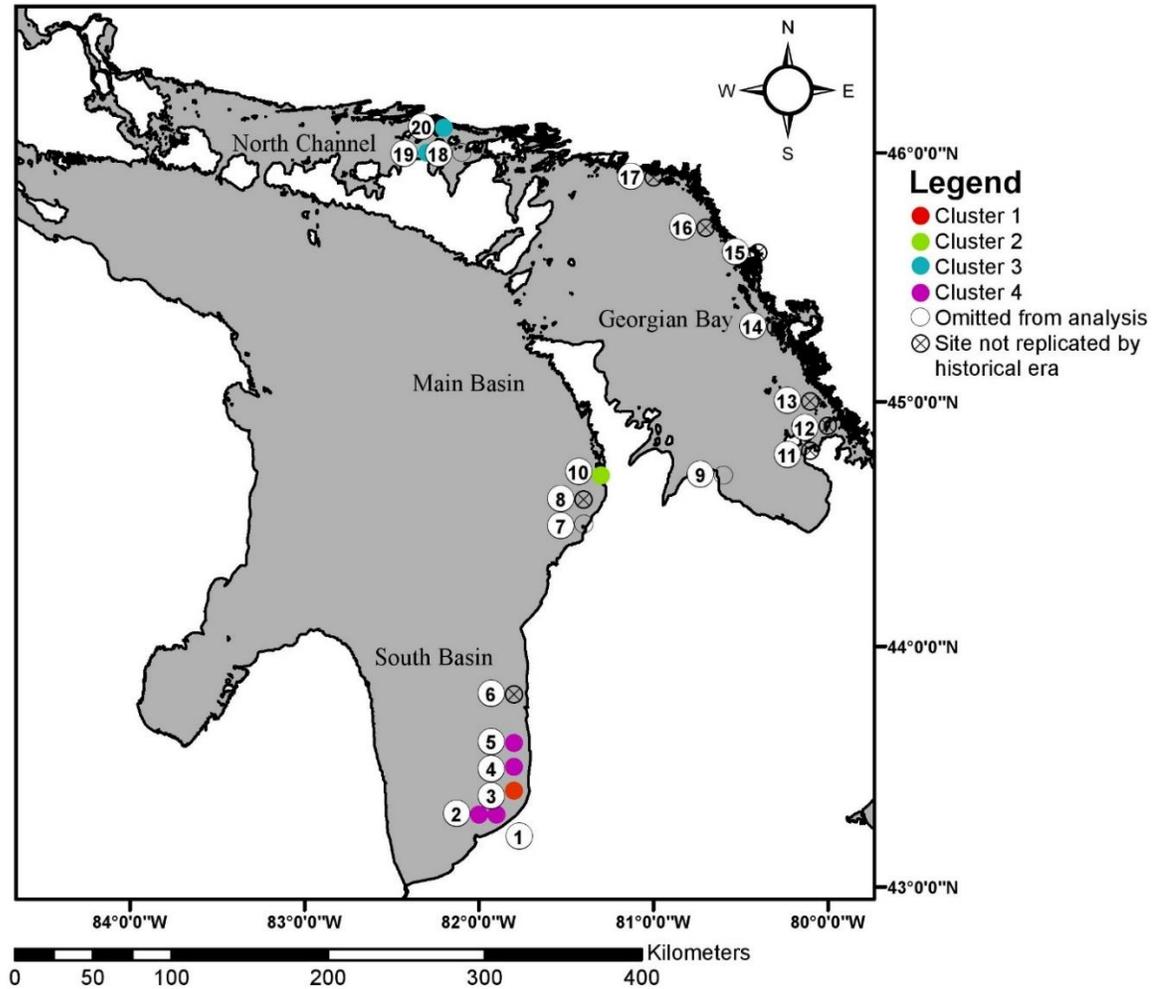


Figure 17: Map of collection sites in Lake Huron with sites coloured according to k-means clustering based on similarity in all life history traits for the historical era. Major basins of Lake Huron are labelled, and sites are numerically labelled with an adjacent white circle (0–20). Sites 7, 9, and 18 were omitted from historical k-means clustering and are indicated by a hollow circle. Sites 6, 8, and 11–17 were not replicated by the historical dataset and are indicated by a hollow circle with an x. (Original in colour).

3.3 Temporal Comparison

3.3.1 Lake-wide Life History Trait Variation across Timeframes

Size and Age at Maturity

Male size at maturity (L50) was not significantly different between timeframes (Appendix **Table S6**); variance by site appeared to be higher in the historical timeframe than in the contemporary (**Figure 18**). Similarly, female L50 was not significantly different between timeframes (Appendix **Table S5**) and variance by site appeared to be higher in the historical timeframe (**Figure 18**).

Male age at maturity (A50) was not significantly different between timeframes (Appendix **Table S5**). Variance by site appeared to be greater in the contemporary timeframe, although the historical timeframe had the highest and lowest observed male A50 values (**Figure 18**). Female A50 was not significantly different between timeframes (Appendix **Table S6**), and variance by site was similar across timeframes (**Figure 18**).

Maximum Size

Male maximum size was significantly different between the historical and contemporary timeframe (Appendix **Table S6**), indicating that male yellow perch grew to a greater maximum size in the contemporary era than they did historically (**Figure 18**). Variance by site appeared to be slightly higher in the contemporary timeframe. Female maximum size was not significantly different between timeframes (Appendix **Table S5**), and variance by site appeared to be greater in this historical timeframe (**Figure 18**).

Lifespan

Male lifespan was nearly significantly different between timeframes (Appendix **Table S5**); variance by site appeared to be higher in the historical timeframe than in the contemporary (**Figure 18**). Female lifespan was not significantly different between timeframes (Appendix **Table S5**) and variance by site appeared to be higher in the historical timeframe (**Figure 18**).

Growth Rate

Male growth rate was not significantly different between timeframes (Appendix **Table S6**). Variance by site was relatively similar between timeframes, but appeared to be greater in the contemporary timeframe (**Figure 18**). Female A50 was not significantly different between timeframes (Appendix **Table S5**), and variance by site appeared to be greater in the contemporary timeframe (**Figure 18**).

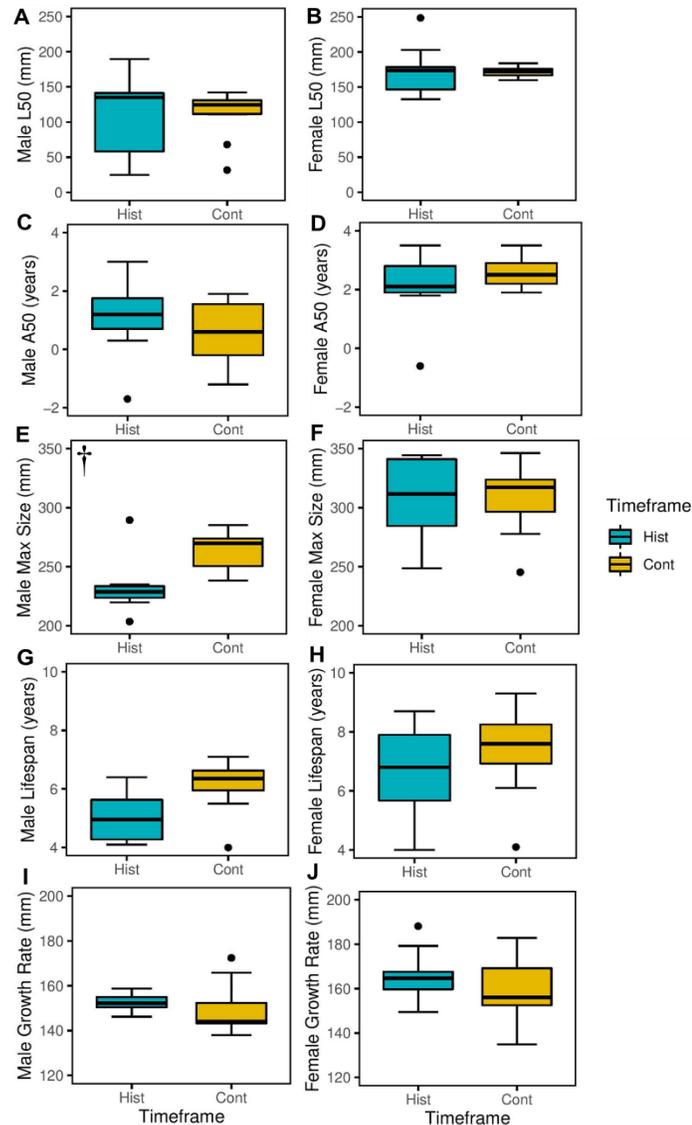


Figure 18: Box-and-whisker plots of lake-wide Lake Huron yellow perch life history trait values for the historical (Hist) and contemporary (Cont) timeframes. Blue boxes represent the historical timeframe; yellow boxes represent the contemporary timeframe. (A) male length at maturity between timeframes; (B) female length at maturity between timeframes; (C) male age at maturity between timeframes; (D) female age at maturity between timeframes; (E) male maximum size between timeframes; (F) female maximum size between timeframes; (G) male lifespan between timeframes; (H) female lifespan between timeframes; (I) male growth at age 2 between timeframes; and (J) female growth

at age 2 between timeframes. Daggers (†) indicate relationships where life history is significantly different between timeframes. (Original in colour).

3.3.2 Variation by Location and Depth across Timeframes

Size and Age at Maturity

In both the historical and contemporary timeframes, latitude, longitude, and depth were not significant predictors of male length at maturity (L50) (Appendix **Table S2A** and **Table S7A**). For female L50, longitude and depth were not significant predictors in either timeframe (Appendix **Table S2B** and **Table S7B**). Latitude was a significant predictor of female L50 in the historical timeframe but not in the contemporary (**Figure 19; Table 5**).

Male age at maturity (A50) was not significantly predicted by latitude, longitude, or depth in either timeframe (Appendix **Table S2C** and **Table S7C**). Similarly, longitude and depth did not significantly predict female A50 in either timeframe (Appendix **Table S2D** and **Table S7D**). However, latitude was a significant predictor of female A50 in the contemporary timeframe, but not in the historical (**Figure 20; Table 5**).

Maximum Size

Latitude was a significant predictor of male maximum size in the contemporary timeframe, but not in the historical (**Figure 21; Table 5**). Longitude and depth did not significantly predict male maximum size in either timeframe (Appendix **Table S2E** and **Table S7E**). Latitude and longitude were significant predictors of female maximum size in the contemporary timeframe (**Figure 22; Table 5**), while depth was not (Appendix **Table S7F**). Geographic predictors for female max size were not analyzed for the historical timeframe, as models would not converge. Thus, it is impossible to determine whether geography predicts female max size differently between timeframes.

Lifespan

Latitude and longitude were significant predictors of male lifespan in the contemporary timeframe (**Figure 23; Table 5**), while depth was not (Appendix **Table S7G**). Geographic predictors for male lifespan were not analyzed for the historical timeframe because models did not converge. Female lifespan exhibited the same relationship that male lifespan did: latitude and longitude were significant predictors of female lifespan in the contemporary timeframe (**Figure 24; Table 5**), while depth was not (Appendix **Table S7H**). Geographic predictors were not analyzed for the historical timeframe, as models would not converge. Therefore, in both male and female lifespan, it cannot be determined whether geography predicts lifespan differently between timeframes.

Growth Rate

Male growth rate was not significantly predicted by latitude or depth in either timeframe (Appendix **Table S2I** and **Table S7I**). Longitude was a significant predictor of male growth rate in the contemporary, but not historical timeframe (**Figure 25; Table 5**). Female growth rate was not significantly predicted by any of latitude, longitude, or depth in either timeframe (Appendix **Table S2J** and **Table S7J**).

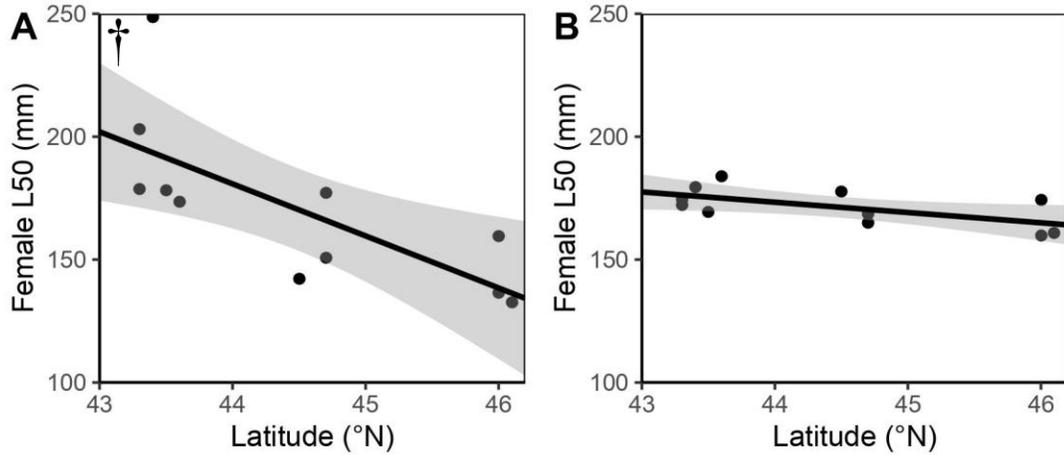


Figure 19: Relationships between historical (1990–1999) and contemporary (2009–2018) female size at maturity (L50) and latitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical female size at maturity versus latitude; (B) contemporary female size at maturity versus latitude. Female size at maturity is measured in mm fork length, latitude is measured in decimal degrees north (°N). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. A dagger (†) indicates the relationship where latitude was a significant predictor of female size at maturity.

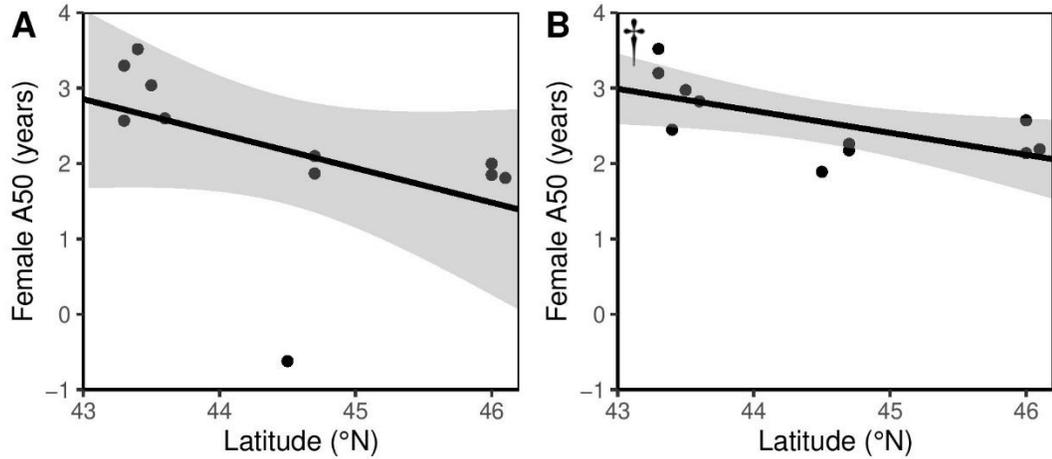


Figure 20: Relationships between historical (1990–1999) and contemporary (2009–2018) female age at maturity (A50) and latitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical female age at maturity versus latitude; (B) contemporary female age at maturity versus latitude. Female age at maturity is measured in years, latitude is measured in decimal degrees north (°N). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. A dagger (†) indicates the relationship where latitude was a significant predictor of female age at maturity.

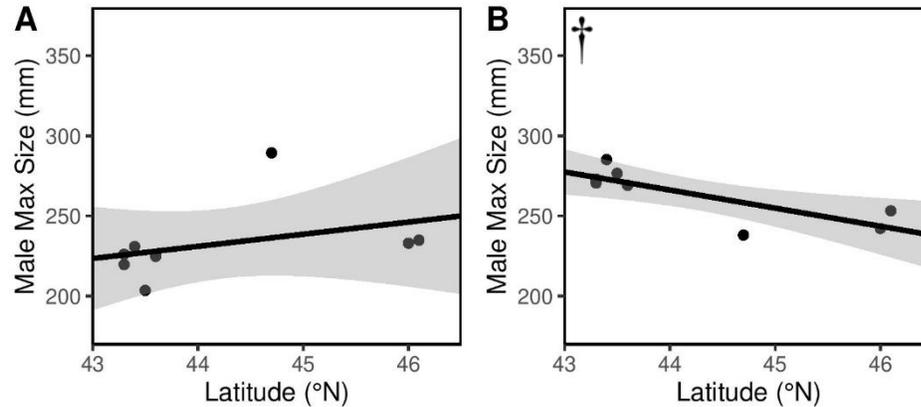


Figure 21: Relationships between historical (1990–1999) and contemporary (2009–2018) male maximum size and latitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical male maximum size versus latitude; (B) contemporary male maximum size versus latitude. Male maximum size is measured in mm fork length, latitude is measured in decimal degrees north (°N). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. A dagger (†) indicates the relationship where latitude was a significant predictors of male maximum size.

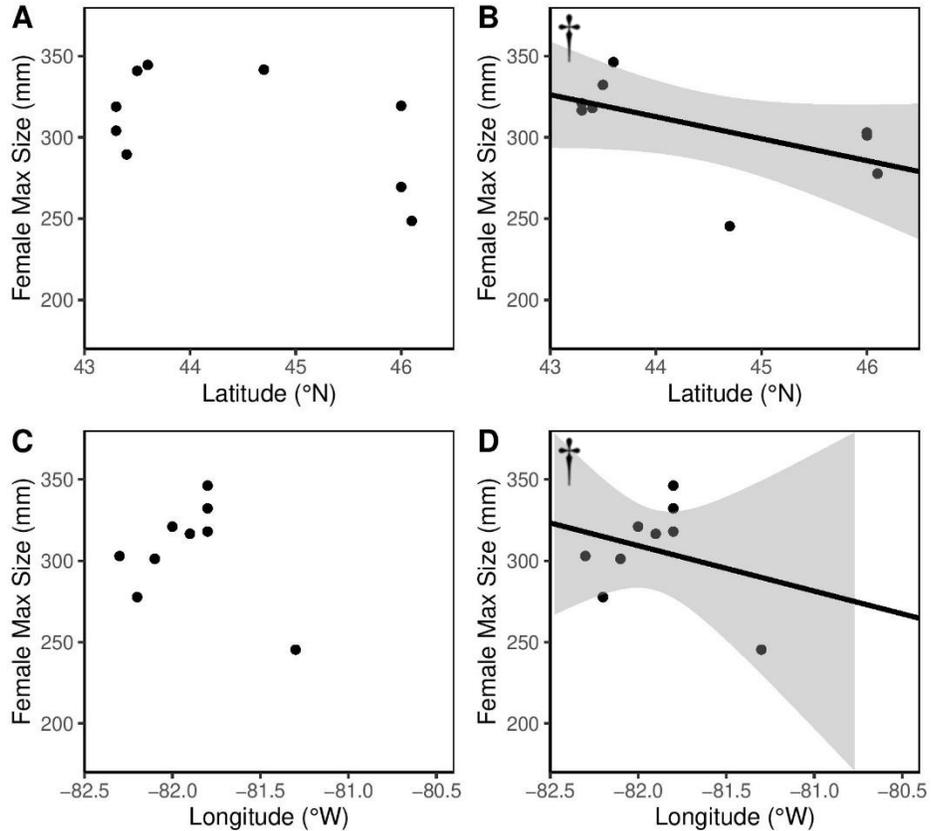


Figure 22: Relationships between historical (1990–1999) and contemporary (2009–2018) female maximum size, latitude and longitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical female maximum size versus latitude; (B) contemporary female maximum size versus latitude; (C) historical female maximum size versus longitude; and (D) contemporary female maximum size versus longitude. Female maximum size is measured in mm fork length, latitude is measured in decimal degrees north ($^{\circ}\text{N}$), and longitude is measured in decimal degrees west ($^{\circ}\text{W}$). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown when models converged. Models did not converge for historical female maximum size, and therefore trendlines with confidence intervals are not included. Daggers (\dagger) indicate relationships where variables were significant predictors of life history trait values.

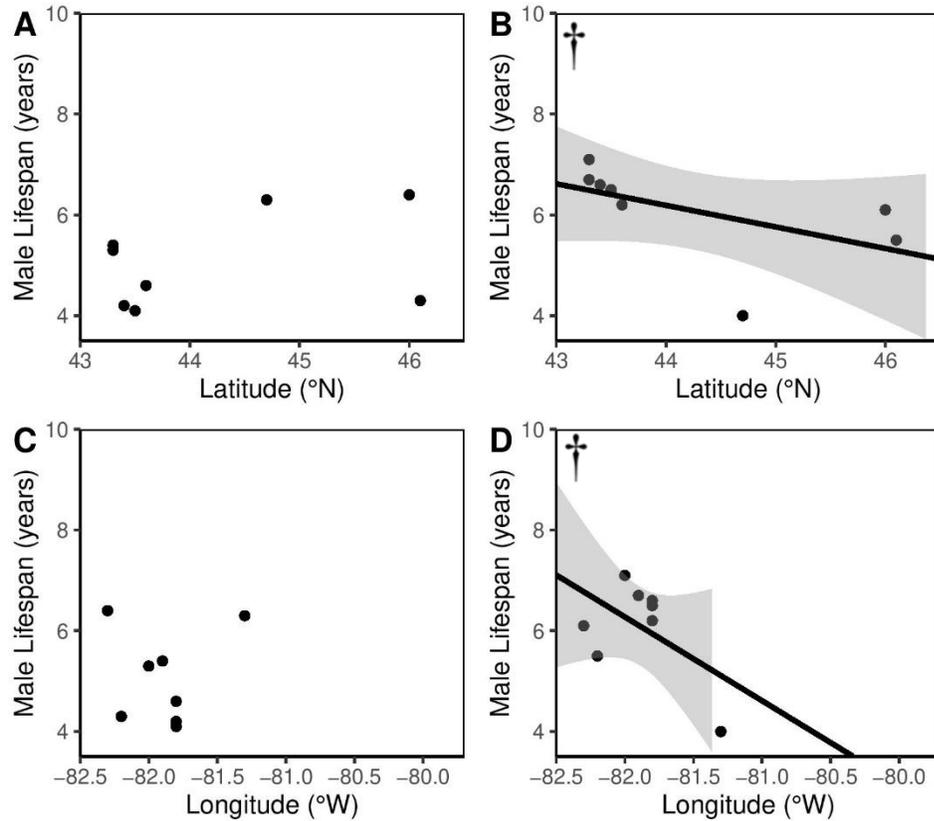


Figure 23: Relationships between historical (1990–1999) and contemporary (2009–2018) male lifespan, latitude and longitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical male lifespan versus latitude; (B) contemporary male lifespan versus latitude. (C) historical male lifespan versus longitude; and (D) contemporary male lifespan versus longitude. Lifespan is measured in mm fork length, latitude is measured in decimal degrees north (°N), and longitude is measured in decimal degrees west (°W). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown when models converged. Models did not converge for historical male lifespan, and therefore trendlines with confidence intervals are not included. Daggers (†) indicate relationships where variables were significant predictors of life history trait values.

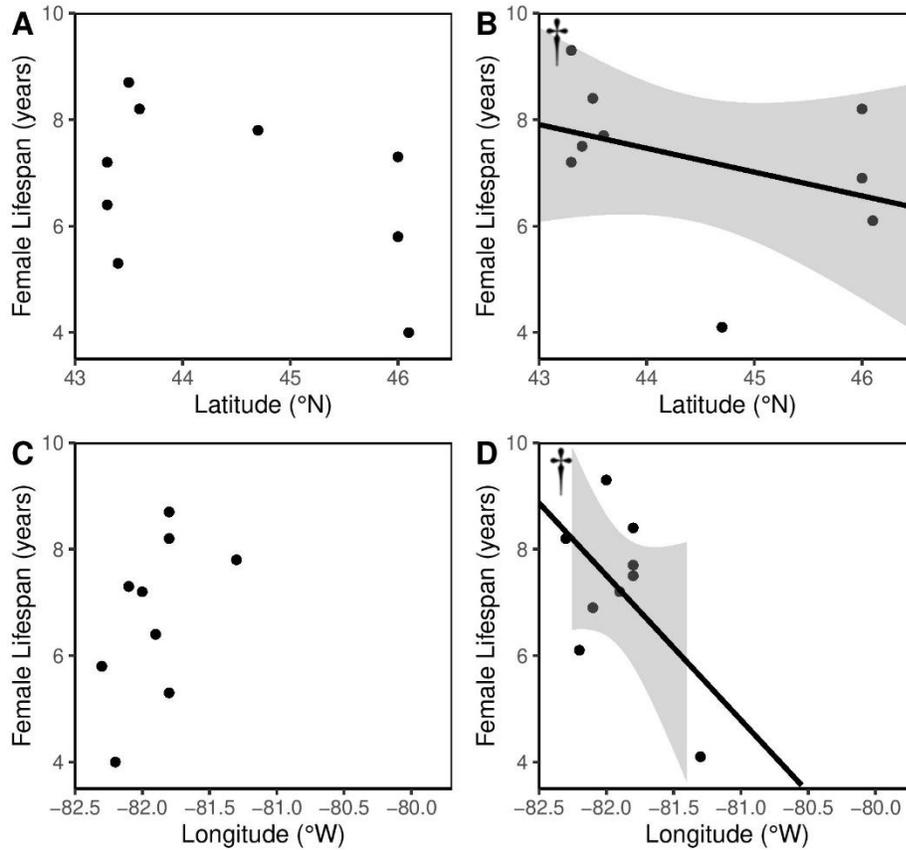


Figure 24: Relationships between historical (1990–1999) and contemporary (2009–2018) female lifespan, latitude and longitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical female lifespan versus latitude; (B) contemporary female lifespan versus latitude. (C) historical female lifespan versus longitude; and (D) contemporary female lifespan versus longitude. Lifespan is measured in mm fork length, latitude is measured in decimal degrees north (°N), and longitude is measured in decimal degrees west (°W). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown when models converged. Models did not converge for historical male lifespan, and therefore trendlines with confidence intervals are not included. Daggers (†) indicate relationships where variables were significant predictors of life history trait values.

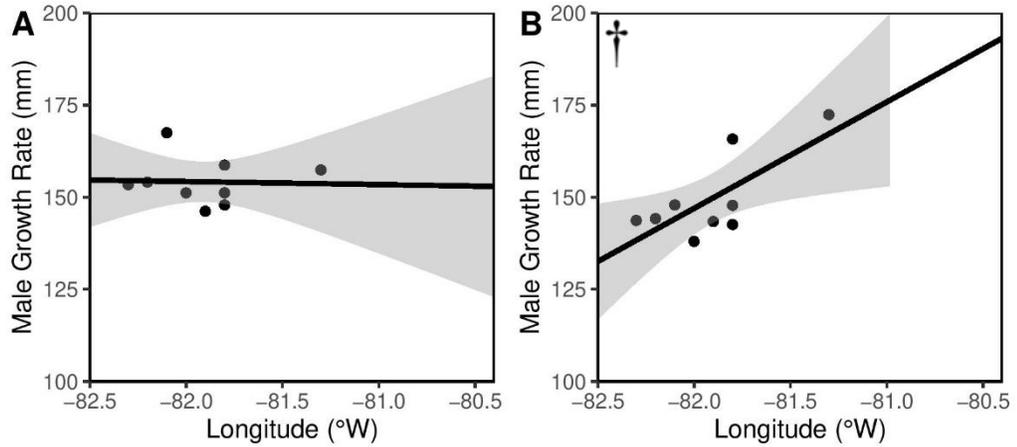


Figure 25: Relationships between historical (1990–1999) and contemporary (2009–2018) male growth at age 2 (growth rate) and latitude for yellow perch sampled from Lake Huron, Ontario, Canada. (A) Historical male growth rate versus latitude; (B) contemporary male growth rate versus latitude. Growth rate is measured in years, latitude is measured in decimal degrees north ($^{\circ}$ N). Trendlines based on Generalized Linear Mixed Models with 95% confidence intervals shaded in gray are shown. A dagger (\dagger) indicates the relationship where latitude was a significant predictor of male growth rate.

Table 5: Summary table of Generalized Linear Mixed Model results for historical (Hist) and contemporary (Cont) timeframes. Checkmarks (✓) indicate life history traits that were significantly predicted by a geographic predictor and X marks (✗) indicate life history traits that were not significantly predicted by a geographic predictor for each timeframe. Mixed models did not converge for historical female maximum size, male lifespan, and female lifespan, and are listed as N/A (not available).

Sex-specific Life History Trait	Predictor					
	Latitude		Longitude		Depth	
	<i>Hist</i>	<i>Cont</i>	<i>Hist</i>	<i>Cont</i>	<i>Hist</i>	<i>Cont</i>
<i>Male L50</i>	✗	✗	✗	✗	✗	✗
<i>Female L50</i>	✓	✗	✗	✗	✗	✗
<i>Male A50</i>	✗	✗	✗	✗	✗	✗
<i>Female A50</i>	✗	✓	✗	✗	✗	✗
<i>Male Max Size</i>	✗	✓	✗	✗	✗	✗
<i>Female Max Size</i>	N/A	✓	N/A	✓	N/A	✗
<i>Male Lifespan</i>	N/A	✓	N/A	✓	N/A	✗
<i>Female Lifespan</i>	N/A	✓	N/A	✓	N/A	✗
<i>Male Growth Rate</i>	✗	✗	✗	✓	✗	✗
<i>Female Growth Rate</i>	✗	✗	✗	✗	✗	✗

3.3.3 Variation in Clusters Based on Life History Traits across Timeframes

Clustering based on life history trait variation was similar across timeframes. Major clusters of yellow perch were detected in the South Basin, Main Basin, and North Channel in both time periods. In both timeframes, the South Basin contained two unique clusters that were distinct from others in Lake Huron, with site 3 belonging to a different cluster than sites 1, 2, 4, and 5 in the South Basin. Fish from site 3 were good growers across timeframes. Comparatively, fish from sites 1, 2, 4, and 5, were superior growers compared to all others around Lake Huron across timeframes. Site 10 in the Main Basin made up a cluster unique from others in Lake Huron in both time periods, although yellow perch differed in life history between timeframes. In the historical time period, yellow perch from site 10 grew slowly and lived long. In the contemporary time period, yellow perch from site 10 grew quickly and were short lived. In the North Channel, sites 19 and 20 made up their own discrete cluster in both timeframes. Fish from the North Channel cluster were average in growth and maturity, but lived long in both timeframes. Based on replicated sites, there was almost no variation in clusters across timeframes. However, temporal variation in clusters could exist in regions of Lake Huron where sites were not replicated, for example in the Main Basin, where sites 7 and 8 were not replicated, and in the North Channel, where site 18 was not replicated. Temporal variation could not be determined for any Georgian Bay clusters because no historical sites in Georgian Bay could be used in k-means clustering.

4.0 Discussion

4.1 Contemporary Dataset (2009–2018)

4.1.1 Life History Trait Variation by Location and Water Depth

Environmental conditions, such as productivity, directly influence fish life history traits. In this case, life history trait values change spatially along a gradient of increasing or decreasing productivity (Beverton, 1987; Vollestad, 1992; Jonsson & L'Abée-Lund, 1993; Lobón-Cerviá et al., 1993; Belk & Houston, 2002; Heibo et al., 2005). This is because productivity encompasses a range of aquatic characteristics including average water temperature, average depth, as well as phytoplankton, zooplankton, benthic invertebrate, and macrophyte abundance, which directly affect fish life history (Begg et al., 1999; Begg & Waldman, 1999; Begg et al., 2005). For example, areas that are deep and cold on average, with low phytoplankton, zooplankton, benthic invertebrate, and macrophyte abundance, are considered low in productivity (Dai et al., 2019). Life history traits reflect low productivity in the form of slow fish growth (Lobón-Cerviá et al., 1993; Belk & Houston, 2002) with long lives (Gunderson & Dygert, 1988) and maturity at an older age and larger size (Colby & Nepszy, 1981; Beverton, 1987; Vollestad, 1992; Jonsson & L'Abée-Lund, 1993; Heibo et al., 2005). Accordingly, fish life history parameters change along productivity gradients; fish grow faster, live shorter lives, and mature at younger ages and smaller sizes when productivity is high, and vice versa when it is low (Begg et al., 2005).

In Lake Huron, productivity is highest in the South Basin, and decreases along a latitudinal gradient. Thus, spatial variation in yellow perch life history traits by latitude likely reflects a corresponding productivity gradient. For example, yellow perch with life

history values associated with high productivity such as early age at maturity, small size at maturity, and fast growth rates, were typically located in the South Basin where productivity on Lake Huron is known to be high (Dai et al., 2019). Subsequently, fish with moderate life history values were usually located in the Main Basin or southern Georgian Bay, where productivity is lower than in the south (Brothers et al., 2016; Stefanoff et al., 2018; Dai et al., 2019). Fish with life history values associated with low productivity such as slow growth rates, long lifespans, and a large age and size at maturity, were concentrated in areas of lower productivity, such as northern Georgian Bay and the North Channel (Brothers et al., 2016; Stefanoff et al., 2018; Dai et al., 2019). My results support my initial hypothesis that yellow perch life history is reflective of a productivity gradient in Lake Huron, where productivity is the greatest in the South Basin and decreases with latitude.

Similar to what I observed in Lake Huron, life history trait variation along environmental gradients such as productivity have been documented in a variety of freshwater fish. For example, Wilson et al. (2019) examined among-lake variation in life history traits including growth rate, age at maturity, size at maturity, and reproduction in lake trout (*Salvelinus namaycush*) from western Canada along environmental clines such as climate and productivity. Clinal life history trait variation was consistent with growth plasticity and local adaptations, and was explained primarily by climate and by productivity to a lesser extent. Similarly, Jonsson & L'Abée-Lund (1993) reviewed clinal variation in life history traits such as growth rate, age at maturity, and lifespan of anadromous brown trout (*Salmo trutta*) from 102 European rivers varying in latitude. Variation in life history traits was explained primarily by latitude, with water temperature

and productivity estimated as the most important factors responsible for variation.

Ultimately, life history trait variation with productivity exists among freshwater systems, especially those that differ greatly in latitude; however, my study may be one of the first to document fish life history trait variation with productivity within a single large lake.

Spatial variation in life history trait values was most often on a regional basis encompassing fish from several sampling locations. Fish with similar life history trait values were from sites immediately adjacent to one another, part of the same region, or close enough together that conditions produced similar life history trait values.

Correspondingly, fish with highly different life history trait values were almost always from separate regions of Lake Huron. For example, fish with the lowest life history trait values were almost always from a different region than fish with the highest life history trait values. Regional variation in life history trait values is similar to what I originally hypothesized, where fish from similar areas of Lake Huron would have similar life history trait values, but life history values would still vary over the huge area of Lake Huron. My findings are similar to those of Happel et al. (2018), who examined spatial variation in Lake Huron and Lake Michigan lake trout using stomach contents and fatty acid profiles. Lake trout varied within Lakes Michigan and Huron, and between Lakes Michigan and Huron, as trout from different regions utilized different prey sources. Based on results of Happel et al. (2018) and my findings, regional stratification of fish populations is a frequent occurrence within Lake Huron and other Laurentian Great Lakes.

Although spatial variation existed primarily on a regional scale, there was some intra-regional variation. Specifically, fish with the lowest female size at maturity were

from a site adjacent to fish with the highest female size at maturity, in the same region of Lake Huron. The same phenomenon occurred for female age at maturity. In both cases, fish with the lowest life history trait values were located at site 16, while fish with the highest life history trait values were located at site 17, both in northeast Georgian Bay. Although surprising, spatial variation on an intra-regional scale is not a new concept in Lake Huron or the Laurentian Great Lakes. For example, Sullivan & Stepien (2014) examined genetic variation of seven spawning populations of yellow perch in the Huron-Erie corridor. Different spawning populations of yellow perch were genetically distinct, suggesting high levels of spatial variation within the Huron-Erie corridor. Likewise, Eberts et al. (2017) investigated lake whitefish (*Coregonus clupeaformis*) population structure using stable isotopes analyses. Although most spatial variation was between major regions, lake whitefish populations varied on an intra-regional scale within Georgian Bay. Thus, when considering my study and others, intra-regional spatial variation in fish occurs in Lake Huron (particularly in Georgian Bay), which presents a unique challenge for fisheries management in Lake Huron.

Latitude and depth were the most important predictors of yellow perch life history trait values, confirming that geography was a primary driver of environmental variation in Lake Huron. Latitude was a significant predictor for male and female age at maturity and maximum size, while depth was a significant predictor of male and female growth rate. Thus, latitude and depth accounted for the majority of geographic influence on yellow perch life history, like I initially hypothesized. Similar to my observations, latitude was found to be a significant predictor of life history traits in Eurasian perch (*Perca fluviatilis*) (Heibo et al., 2005; Estlander et al., 2017), roach (*Rutilus rutilus*)

(Lappalainen et al., 2008), Australian salmon (*Arripis trutta*) (Hughes et al., 2017), and over 25 other European freshwater fish species (Blanck & Lamouroux, 2007). Depth has also been recorded as a significant predictor of fish life history traits, but typically in marine scenarios as opposed to freshwater (Drazen & Haedrich, 2012; Pecuchet et al., 2017; Winston et al., 2017), possibly because depth range over space is much smaller in freshwater lakes and rivers than it is in the ocean (Boehrer & Schultze, 2008). Nonetheless, in Lake Huron, latitude and depth are primary drivers of environmental condition and therefore fish life history trait values, causing variation in yellow perch population characteristics.

Although latitude and depth were the most important predictors, longitude was an occasional predictor of yellow perch life history. Longitude was a significant predictor of male age at maturity, female maximum size, and female lifespan. Thus, contrary to my original predictions, longitude played a role in predicting life history. This is interesting, as longitude only ranged from -82.0 to -80.0 °W, and is typically not associated with a gradient of productivity or as a predictor of fish life history. Instead, longitude is used as an indicator of local habitat variation, as observed by Garnett & Batzer (2014) in fish community structure from floodplains of the greater Altamaha River and Savannah River basins. Thus, Lake Huron yellow perch life history variation with longitude could be the result of local habitat differences around the lake, as opposed to a gradient of productivity, as was the case with latitude and depth. Regardless, longitude plays an unexpected role in predicting yellow perch life history in Lake Huron.

4.1.2 Clustering Based on Life History Traits 2009–2018

At least six discrete clusters of yellow perch exist within Lake Huron, based on spatial variation in the suite of life history traits assessed. The discovery of multiple clusters of yellow perch corresponds with my initial hypothesis that yellow perch life history traits vary in Lake Huron and that yellow perch would be subdivided based on spatial variation in life history. However, more importantly, cluster locations provide insight into potential locations of yellow perch subpopulations. Clusters of fish based on spatial variation in life history have served as indicators of fish population structure in a variety of scenarios (Begg et al., 1999; Begg & Waldman, 1999; Abaunza et al., 2008b; Cadrin et al., 2013). For example, Abaunza et al. (2008a) used spatial variation in life history traits as the basis for recognition of stock management units in horse mackerel (*Trachurus trachurus*), and found several different subpopulations existed in the northeast Atlantic Ocean. Similarly, Ballagh et al. (2012) examined population structure of blue threadfin (*Eleutheronema tetradactylum*) across Northern Australia using spatial variation in life history traits, and found evidence for highly localised spatial population subdivision, to the order of tens of kilometers. In this study, spatial variation in life history around Lake Huron is indicative of at least 6 different clusters of yellow perch, which may be locations of individual yellow perch subpopulations.

Using clusters as indicators of potential yellow perch subpopulation locations, subpopulations of yellow perch exist primarily between major regions of Lake Huron, with some subpopulations existing within Georgian Bay. For example, sites in the South Basin, Main Basin, and North Channel belong to one large cluster of yellow perch in each region, with regional clusters differing from one another and following a productivity

gradient as described above. However, I also discovered 4 distinct clusters of perch within Georgian Bay, divided between the southwest, southeast, central, and northern areas of Georgian Bay. Correspondingly, other fish populations have been found to be structured this way in Lake Huron. For example, Eberts et al. (2017) discovered six putative clusters of lake whitefish in Lake Huron using clustering based on stable isotopes values of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$). Lake whitefish clusters varied primarily by region, and were generally divided between the South Basin, Main Basin, North Channel, and Georgian Bay. However, multiple distinct clusters of lake whitefish existed in Georgian Bay as well. Thus, based on my findings and those of others, fish population structure in Lake Huron is divided primarily between regions, but diversity exists within Georgian Bay.

Certain clusters covered more than one major region of Lake Huron. Cluster 5 consisted of site 3 from the South Basin and site 7 from the Main Basin; cluster 4 consisted of sites 8 and 10 from the Main Basin and site 9 from southwest Georgian Bay; cluster 6 contained sites 18, 19 and 20 from the North Channel and sites 11 and 12 from southeast Georgian Bay. Fish from sites in different regions that belonged to the same cluster appear to be geographically isolated, and therefore subpopulation mixing via migration is unlikely. For example, although both a part of cluster 6, fish from southeast Georgian Bay are presumably not interacting with those in the North Channel. Thus, these findings do not indicate that one single “subpopulation” exists across two geographically isolated regions; rather, sites from different regions occasionally belong to the same cluster because the environment and habitat that influences life history is similar, resulting in similar life history trait values (Begg et al., 1999; Begg & Waldman,

1999; Begg et al., 2005; Cadrin et al., 2013). Therefore, clusters based on life history should not be viewed as exact locations of discrete subpopulations, but as indicators of where yellow perch population subdivision may be occurring. In this case, population subdivision exists between the South Basin, Main Basin, North Channel, southwest Georgian Bay, southeast Georgian Bay, central Georgian Bay, and northern Georgian Bay.

4.1.3 Management Implications

Clusters based on spatial variation in life history trait values can be compared to management units in Lake Huron. Comparing clusters to management units provides insight as to whether or not yellow perch population structure is accurately represented by management units. In my study, I found that clusters existed primarily between major regions of Lake Huron and covered expansive areas of the lake. Correspondingly, management units in Lake Huron already cover large areas and exist between major regions (Speers, 2018). This is the case in the South Basin, Main Basin, and North Channel, where one or two management units completely cover each region. My study detected intra-regional variation as well, as I found multiple clusters of fish within Georgian Bay. However, in attempt to appropriately represent intra-regional variation in Georgian Bay, fisheries management areas are already finely divided and managed there (Speers, 2018). For example, Georgian Bay contains over 10 different management units. Based on these comparisons, broad-scale division of management units in the South Basin, Main Basin, and North Channel, along with fine-scale division of management units in Georgian Bay, should be successful in encompassing yellow perch population structure.

Other studies have compared clusters of fish to management regimes in order to test whether management units appropriately represent population structure. Eberts et al. (2017) derived clusters of lake whitefish using stable isotopes analyses and compared them to management units in Lake Huron. Researchers discovered 6 discrete clusters of lake whitefish and found that management units were too small and numerous to reflect the true population structure of lake whitefish in Lake Huron, suggesting that management unit sizes and locations be reconsidered. In a broader scenario, Jackson et al. (2010) examined spatial variation in life history traits of snapper (*Pagrus auratus*) in Shark Bay, Australia, and detected three distinct clusters of snapper within Shark Bay. When compared to management units, results supported previous findings that management units should be much more fine-scale within Shark Bay to accurately represent subdivided snapper populations. When comparing my findings to management unit structure in Lake Huron, it appears that current management regimes adequately represent yellow perch population structure.

4.2 Temporal Comparison

4.2.1 Lake-wide Life History Trait Variation across Timeframes

Most yellow perch life history trait values showed no variation across timeframes. For example, the only life history trait that showed any significant difference across timeframes was male maximum size, which increased temporally. Negligible temporal variation in yellow perch life history traits did not align with my initial hypothesis, which was that yellow perch life history values would vary over time due to the early-2000s ecosystem shift in Lake Huron. Consequently, my predictions that growth rate and size would decrease temporally due to Lake Huron becoming more oligotrophic were not

supported. However, temporal variation in fish life history values has been observed in the Laurentian Great Lakes and beyond. For example, lake whitefish (*Coregonus clupeaformis*) maturation schedules (specifically age at maturity and size at maturity) increased temporally in Lake Huron, possibly reflecting plastic responses to decreased growth rates associated with the early-2000s ecosystem shift (Wang et al., 2008). Likewise, Mangeni-Sande et al. (2019) examined temporal variation in life history traits of dagaa (*Rastrineobola argentea*) in Lake Victoria, and found that mean standard length and length at maturity decreased temporally from the 1970s to 2015. Although temporal variation in fish life history traits has been observed in other studies, I found little temporal variation in the life history traits that I assessed for Lake Huron yellow perch.

4.2.2 Variation by Location and Depth across Timeframes

Yellow perch life history variation with predictors of longitude and depth was consistent across timeframes; however, the influence of latitude varied across timeframes. For example, depth was not a significant predictor of any life history traits in either timeframe, and was therefore consistent temporally. The influence of longitude varied only slightly across timeframes; longitude was a significant predictor of male growth rate in the contemporary but not historical timeframe, however it was not a significant predictor of any other life history traits across timeframes. The greatest variation across timeframes was in latitude as a significant predictor of life history traits. Latitude was a significant predictor of female size at maturity in the historical but not contemporary timeframe, but was also a significant predictor of female age at maturity and male maximum size in the contemporary but not historical timeframe. Unfortunately, not all life history traits could be compared across timeframes; female maximum size and male

and female lifespan could not be determined for the historical timeframe, which made temporal comparisons regarding variation with location and depth impossible for those life history traits. However, based on what I could compare, the influence of longitude and depth remained relatively consistent temporally, while the influence of latitude varied widely across timeframes. These results did not fully match my original hypothesis, which was that the influence of latitude, longitude, and depth would remain consistent over time.

Similar to results of this study, temporal comparisons of fish life history variation with location and depth have not shown consistent variation over time. For example, Frías-Alvarez et al. (2014) studied spatial and temporal variation in reproductive-based life history traits including superfetation, brood size, embryo mass, and reproductive allotment for 11 distinct populations of porthole livebearer (*Poeciliopsis gracilis*) and lerma livebearer (*Poeciliopsis infans*). Brood size varied temporally and spatially among populations of porthole livebearer. Furthermore, in both species, brood size varied temporally on a monthly scale within populations, while superfetation varied spatially and temporally between populations. Other life history traits showed no spatial or temporal variation for either species. Palacios-Hernández et al. (2020) examined spatial and temporal variation in life history traits including size at maturity and litter size of bonnethead shark (*Sphyrna tiburo*) across latitudinal extremes of the Gulf of Mexico between a historical (1993-1994) and contemporary (2007-2014) timeframe. Temporal variation was found only in litter size, while latitudinal variation was found only in size at maturity and size at maternity. In both of the aforementioned studies, spatial and temporal comparisons of fish life history showed inconsistent variation among life history traits

and location; in this case, only some life history traits and populations actually showed temporal variation. Thus, based on my findings and those of others, temporal variation is inconsistent and highly variable among life history traits and locations.

4.2.3 Variation in Clusters Based on Life History Traits across Timeframes

Clusters of yellow perch based on life history trait variation were similar across time periods. For example, among replicated sites across both timeframes, clusters of perch were found in the South Basin, Main Basin, and North Channel. Additionally, fish from site 3 in the South Basin did not belong to the same cluster as fish from the remaining South Basin sites, and instead existed as their own cluster of fish in both timeframes. These findings correspond with my initial hypothesis, which was that yellow perch population structure based on life history trait values would be the same over time. My conclusions were different than those in other studies of Great Lakes yellow perch population structure. For example, Sullivan & Stepien (2015) investigated temporal variation in yellow perch population structure in Lakes St. Clair, Erie, and Ontario using genetic analysis of 15 nuclear DNA microsatellite loci from 2001-2009. Genetic diversity was similar across sites temporally; however, population structure varied among individual years, suggesting that population structure shifts annually based on where spawning groups reproduce. Despite yellow perch population structure shifting temporally in other waterbodies of the Laurentian Great Lakes, I did not find any temporal variation in Lake Huron yellow perch population structure based on life history traits.

4.2.4 Management Implications

Lack of temporal variation in both life history trait values and clusters of fish based on life history traits has important implications for management of yellow perch in Lake Huron. Although yellow perch faced a variety of stressors that resulted in population declines (Diana et al., 1987; Lucchesi, 1988; Diana et al., 1997; Belyea et al., 1997; Fielder, 2008; Fielder, 2010), ecosystem shifts (Ridgway, 2010; Riley & Adams, 2010; Gobin et al., 2015; Ridgway & Middel, 2015; Barbiero et al., 2018), altered environmental conditions (Hecky et al., 2004; Nalepa et al., 2009; Higgins & Vander Zanden, 2010; Barbiero et al., 2011a; Cha et al., 2011; Warner & Lesht, 2015; Pothoven et al., 2016; Barbiero et al., 2018; Dai et al., 2019; Stadig et al., 2020), and commercial harvest pressure (Diana et al., 1987; Craig, 2000; Fielder & Thomas, 2006; Speers, 2018), these changes did not manifest as changes to the measured life history trait parameters. Thus, changes to yellow perch populations over the past 40 years have not come about as a result of alteration of the life history parameters I measured. Understanding why fish populations change, including the direct links to factors affecting demography, is a key aspect of fisheries management and predictive planning for the future. For example, if oligotrophication of Lake Huron had slowed down growth of yellow perch, but harvest pressure remained constant, population decline would be expected without some sort of intervention. However, given that I did not find any major life history shifts affecting growth, size, or lifespan, going forward managers should most likely focus on factors affecting successful reproduction and recruitment, as well as mortality.

4.3 Study Limitations

4.3.1 Contemporary and Historical Dataset Limitations

I faced a variety of limitations regarding sampling locations in my study. A major limitation was the absence of data for the American side of Lake Huron. Yellow perch population structure on the American side of the lake remains unexplored, and the picture for the whole lake thereby remains incomplete. Future research should attempt to include data from the American side of the lake. Additionally, there was a lack of sample sites from the northern Main Basin and western Georgian Bay. My study was limited to data included in OMNRF databases, and neither database contained yellow perch sampled in those locations. This is not the result of lack of sampling effort; the OMNRF Offshore Index Program routinely samples these areas (Speers, 2018). Rather, yellow perch are just not captured in these areas, so there were no data to use for life history trait calculation. As a result, northern Main Basin and western Georgian Bay were not well represented, and therefore it is unknown how perch populations are structured in these locales. Given the scarcity of yellow perch in these parts of Lake Huron, their absence is not as big a factor as the missing American perspective.

Other study constraints existed with respect to life history trait calculation. Not all life history traits were calculated the same way, and use of different methodologies when determining life history traits can skew interpretation of life history trait values. In this study, 3 different methods were used in life history trait calculation: size and age at maturity were inferred from logistic regression, maximum size and lifespan were estimated based on the mean of the top 5% of fish sampled, and growth rate was estimated based on the mean of all sampled fish at age 2. Each method of life history trait

calculation measured a different aspect of the population with a different degree of accuracy. For example, life history trait values based on logistic regression are simulated measurements that take all sampled fish into account. As a result, these values are highly influenced by the number of fish and range of fish size sampled; if the majority of fish sampled are small/young and larger year classes are missing, then life history trait values based on logistic regression will be extremely small. This explains why some life history trait values calculated using logistic regression had low or even negative values across timeframes (observed in male size and age at maturity). On the contrary, life history traits calculated using only a small subset of the population, for example the top 5% of fish or only fish at age 2, are not as influenced by the number of fish sampled or range of fish size sampled, as they do not take the entire population into account. Thus, variation in methodologies used in life history trait calculation must be taken into consideration when analyzing life history trait values and corresponding results.

4.3.2 Temporal Comparison Limitations

Limitations in the temporal comparison almost always originated from the historical dataset. For example, in some cases, the historical dataset contained inconsistent, low quality data that was not present in the contemporary dataset. I had to omit many samples from the historical database in my study because they did not contain all necessary measurements to qualify for including in life history trait calculations. Additionally, many sites that were to be replicated across timeframes simply did not have enough fish sampled in the historical dataset to qualify for the study. Thus, only 11 sites could be replicated across timeframes, which cut the number of sites I could use for temporal comparison nearly in half. This limited the scope of my temporal comparison by

1) making a complete site-replicated comparison of life history trait values and clusters of fish across all of the Canadian side of Lake Huron impossible, and 2) reducing important data points for investigating whether or not location and depth influenced life history traits consistently over time. For example, in the historical dataset, some linear mixed models used for examining the influence of location or depth on life history did not converge, making any temporal comparison impossible involving those models impossible. As a result of these limitations, the temporal comparison was not as robust as initially expected, and comparisons of life history variation with location and depth over time should be taken with caution.

4.4 Linking Life History Theory, Yellow Perch Population Ecology, and the Environment

Life history theory is one way of explaining variation in anatomy and behaviour of organisms due to processes such as evolution and natural selection. The use of life history theory in understanding complex relationships within ecosystems has been extensively referenced in ecology, but is also continually evolving. For example, life history theory was initially used to understand growth and maturity in one species. Charnov & Berrigan (1991) first examined how life history theory could be used to derive life history trait parameters in fish. Researchers showed that dimensionless numbers could be used to describe relationships between growth and maturity, and therefore understand fish based on life history. As the use of life history theory became more recognized, studies began to examine interspecific variation based on life history. Winkle et al. (1993) compared responses of striped bass (*Morone saxatilis*) and smallmouth bass (*Micropterus dolomieu*) life history to environmental changes, and

found that each species responded independently based on life history. Life history trait theory has since progressed, and is now used in an array of complex studies. For example, life history theory is now used to predict changes in fish assemblage over drought periods (Malone et al., 2021) or different hydrologic regimes (Mims & Olden, 2012). My study serves as further expansion of the field of life history theory by showcasing innovative use of life history theory; in this case, to understand fish population structure. Subsequently, my work can serve as reference for future research using life history theory.

My research also provides a modern perspective on yellow perch life history theory and biology. Since the 1980s, studies have used life history theory methods similar to those in this study to investigate yellow perch biology. For example, Whiteside et al. (1985) followed growth rate of yellow perch in their first 70 days after hatch in Lake Itasca and found no correlation between growth rate and zooplankton abundance, suggesting food availability was not a limiting factor for yellow perch growth rate. Likewise, Fisher & Willis (1997) examined early yellow perch life history traits in two South Dakota lakes, and found that perch from one lake grew quickly and to desirable size, while perch from the other lake grew slowly and did not grow large. Purchase et al. (2005b) investigated yellow perch biology by examining covariation in perch life history traits in 70 different lakes. Results showed that life history varied between sexes in most life history traits examined, and that slow-growing populations matured young and small in warm lakes but old and large in cold lakes. Based on this research, examinations of yellow perch biology using life history theory have been conducted, although not

recently. However, my study accounts for this by serving as modern support for the use of life history theory when examining yellow perch biology.

My study further augments understanding of yellow perch population ecology as well. Other studies have used life history traits to examine yellow perch population ecology, for example, Dembkowski et al. (2016) studied synchrony of larval perch life history across fish populations. Results showed synchrony in larval yellow perch abundance and life history across populations. Feiner et al. (2017) examined life history traits driving variation in maturation among yellow perch stocks in the Great Lakes, and found positive correlations between growth and mortality, with faster-growing stocks becoming mature at younger ages but larger sizes. Additionally, stocks that matured at large sizes for a given age in females matured at smaller age-specific sizes in males. Studies such as these provide valuable information for analyzing yellow perch population ecology across multiple waterbodies. However, none of these studies examine yellow perch population ecology within a single waterbody. My work builds from these studies and expands knowledge of yellow perch life history traits by analyzing fine-scale yellow perch population structure within one lake, as opposed to across many different lakes.

One of the most important aspects of life history theory is the interaction between life history and the environment. This relationship is well referenced and understood (Begg et al., 1999; Begg & Waldman, 1999; Begg et al., 2005); however, advancements in the understanding of life history-environment relationships in freshwater fish are limited (Mims & Olden, 2012). As such, studies of freshwater fish using the life history-environment relationship exist, but are rare for yellow perch. Ward et al. (2017) analyzed stocked populations of rainbow trout (*Oncorhynchus mykiss*) to test predictions from life

history theory regarding growth and maturity across climatic and environmental gradients. Results supported predictions that life history traits reflect environmental variables, but particularly that life history is best explained by climatic effects. Using yellow perch as the study organism, Purchase et al. (2005a) attempted to predict life history trait values from environmental characteristics of 72 populations across Ontario, Canada. Results indicated that lakes with specific environmental characteristics produced large, fast growing fish based on life history trait values, confirming the life history-environment relationship. Similarly, Weber et al. (2011) examined yellow perch life history trait values across habitats in southern Lake Michigan, and found that various environmental gradients, such as water temperature and wind events, directly influenced larval perch growth and survival, again highlighting the life history-environment relationship. In my study, changes in environment (specifically productivity) around Lake Huron were apparent in perch life history trait values; consequently, I provided further support for the life history-environment relationship aspect of life history theory.

References

- Abaunza, P., Gordo, L.S., Santamaría, M.T.G., Iversen, S.A., Murta, A.G., Gallo, E. (2008a). Life history parameters as basis for the initial recognition of stock management units in horse mackerel (*Trachurus trachurus*). *Fisheries Research, Horse Mackerel: Identification of Stocks*, 89, 167–180.
<https://doi.org/10.1016/j.fishres.2007.09.021>
- Abaunza, P., Murta, A.G., Campbell, N., Cimmaruta, R., Comesaña, A.S., Dahle, G., García Santamaría, M.T., Gordo, L.S., Iversen, S.A., MacKenzie, K., Magoulas, A., Mattiucci, S., Molloy, J., Nascetti, G., Pinto, A.L., Quinta, R., Ramos, P., Sanjuan, A., Santos, A.T., Stransky, C., Zimmermann, C. (2008b). Stock identity of horse mackerel (*Trachurus trachurus*) in the Northeast Atlantic and Mediterranean Sea: Integrating the results from different stock identification approaches. *Fisheries Research, Horse Mackerel: Identification of Stocks*, 89, 196–209. <https://doi.org/10.1016/j.fishres.2007.09.022>
- Bacheler, N.M., Paoli, T.J., Schacht, G.M. (2011). Controls on Abundance and Distribution of Yellow Perch: Predator, Water Quality, and Density-Dependent Effects. *Transactions of the American Fisheries Society*, 140, 989–1000.
<https://doi.org/10.1080/00028487.2011.603979>
- Ballagh, A.C., Welch, D.J., Newman, S.J., Allsop, Q., Stapley, J.M. (2012). Stock structure of the blue threadfin (*Eleutheronema tetradactylum*) across northern Australia derived from life-history characteristics. *Fisheries Research*, 121–122, 63–72. <https://doi.org/10.1016/j.fishres.2012.01.011>
- Barbiero, R.P., Balcer, M., Rockwell, D.C., Tuchman, M.L. (2009). Recent shifts in the

- crustacean zooplankton community of Lake Huron. *Canadian Journal of Fisheries and Aquatic Sciences*, 66, 816.
- Barbiero, R.P., Lesht, B.M., Warren, G.J. (2011a). Evidence for bottom–up control of recent shifts in the pelagic food web of Lake Huron. *Journal of Great Lakes Research*, 37, 78–85. <https://doi.org/10.1016/j.jglr.2010.11.013>
- Barbiero, R.P., Schmude, K., Lesht, B.M., Riseng, C.M., Warren, G.J., Tuchman, M.L. (2011b). Trends in *Diporeia* populations across the Laurentian Great Lakes, 1997–2009. *Journal of Great Lakes Research*, 37, 9–17. <https://doi.org/10.1016/j.jglr.2010.11.009>
- Barbiero, R.P., Lesht, B.M., Warren, G.J., Rudstam, L.G., Watkins, J.M., Reavie, E.D., Kovalenko, K.E., Karatayev, A.Y. (2018). A comparative examination of recent changes in nutrients and lower food web structure in Lake Michigan and Lake Huron. *Journal of Great Lakes Research*, 44, 573–589. <https://doi.org/10.1016/j.jglr.2018.05.012>
- Barton, D.R., Howell, E.T., Fietsch, C.-L. (2013). Ecosystem changes and nuisance benthic algae on the southeast shores of Lake Huron. *Journal of Great Lakes Research*, 39, 602–611. <https://doi.org/10.1016/j.jglr.2013.09.010>
- Barton, K. (2020). RStudio Package “MuMIn.”
- Bates, D., Mächler, M., Bolker, B., Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 67, 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Begg, G.A., Hare, J.A., Sheehan, D.D. (1999). The role of life history parameters as

- indicators of stock structure. *Fisheries Research*, 43, 141–163.
[https://doi.org/10.1016/S0165-7836\(99\)00071-5](https://doi.org/10.1016/S0165-7836(99)00071-5)
- Begg, G.A. & Waldman, J.R. (1999). An holistic approach to fish stock identification. *Fisheries Research*, 43, 35–44. [https://doi.org/10.1016/S0165-7836\(99\)00065-X](https://doi.org/10.1016/S0165-7836(99)00065-X)
- Begg, G.A. (2005). Chapter 6 - Life History Parameters, in: Cadrin, S.X., Friedland, K.D., Waldman, J.R. *Stock Identification Methods*. Academic Press, Burlington, 119–150. <https://doi.org/10.1016/B978-012154351-8/50007-1>
- Belk, M.C. & Houston, D.D. (2002). Bergmann’s Rule in Ectotherms: A Test Using Freshwater Fishes. *The American Naturalist*, 160, 803–808.
<https://doi.org/10.1086/343880>
- Belyea, G. Y., Maruca, S.L., Diana, J.S., Schneeberger, P.J., Scott, S.J., Jr, R.D.C., Ludwig, J.P., Summer, C.L. (1997). Impact of Double-Crested Cormorant Predation on the Yellow Perch Population in the Les Cheneaux Islands of Michigan. *Symposium on Double-Crested Cormorants: Population Status and Management Issues in the Midwest*.
- Beverton, R.J.H. (1987). Longevity in Fish: Some Ecological and Evolutionary Considerations, in: Woodhead, A.D., Thompson, K.H. *Evolution of Longevity in Animals: A Comparative Approach*. Springer US, Boston, MA, 161–185.
https://doi.org/10.1007/978-1-4613-1939-9_12
- Blanck, A. & Lamouroux, N. (2006). Large-scale intraspecific variation in life-history traits of European freshwater fish: Traits variation in freshwater fish. *Journal of Biogeography*, 34, 862–875. <https://doi.org/10.1111/j.1365-2699.2006.01654.x>

- Boehrer, B. & Schultze, M. (2008). Stratification of lakes. *Rev. Geophys.* 46, RG2005.
<https://doi.org/10.1029/2006RG000210>
- Borsetti, S., Munroe, D., Rudders, D.B., Dobson, C., Bochenek, E.A. (2018). Spatial variation in life history characteristics of waved whelk (*Buccinum undatum L.*) on the U.S. Mid-Atlantic continental shelf. *Fisheries Research*, 198, 129–137.
<https://doi.org/10.1016/j.fishres.2017.10.006>
- Brenden, T.O., Bence, J.R., Szalai, E.B. (2012). An Age-Structured Integrated Assessment of Chinook Salmon Population Dynamics in Lake Huron’s Main Basin since 1968. *Transactions of the American Fisheries Society*, 141, 919–933.
<https://doi.org/10.1080/00028487.2012.675910>
- Brothers, S., Vadeboncoeur, Y., Sibley, P. (2016). Benthic algae compensate for phytoplankton losses in large aquatic ecosystems. *Global Change Biology*, 22, 3865–3873. <https://doi.org/10.1111/gcb.13306>
- Buchholz-Sørensen, M. & Vella, A. (2016). Population Structure, Genetic Diversity, Effective Population Size, Demographic History and Regional Connectivity Patterns of the Endangered Dusky Grouper, *Epinephelus marginatus* (Teleostei: Serranidae), within Malta’s Fisheries Management Zone. *PLOS ONE*, 11, e0159864. <https://doi.org/10.1371/journal.pone.0159864>
- Cadrin, S.X., Kerr, L.A., Mariani, S. (2013). Stock Identification Methods: Applications in Fishery Science. *Elsevier Science & Technology*, San Diego, United States.
- Cha, Y., Stow, C.A., Nalepa, T.F., Reckhow, K.H. (2011). Do Invasive Mussels Restrict Offshore Phosphorus Transport in Lake Huron? *Environmental Science and Technology*, 45, 7226–7231. <https://doi.org/10.1021/es2014715>

- Chaparro-Pedraza, P.C. & Roos, A.M.D. (2021). Individual energy dynamics reveal nonlinear interaction of stressors threatening migratory fish populations. *Functional Ecology*, 35, 727–738. <https://doi.org/10.1111/1365-2435.13751>
- Charnov, E.L. & Berrigan, D. (1991). Evolution of life history parameters in animals with indeterminate growth, particularly fish. *Evolutionary Ecology*, 5, 63–68. <https://doi.org/10.1007/BF02285246>
- Charrad, M., Ghazzali, N., Boiteau, V., Niknafs, A. (2014). NbClust: An R Package for Determining the Relevant Number of Clusters in a Data Set. *Journal of Statistical Software*, 61, 1–36. <https://doi.org/10.18637/jss.v061.i06>
- Clark, R.D., Bence, J.R., Claramunt, R.M., Clevenger, J.A., Kornis, M.S., Bronte, C.R., Madenjjan, C.P., Roseman, E.F. (2017). Changes in Movements of Chinook Salmon between Lakes Huron and Michigan after Alewife Population Collapse. *North American Journal of Fisheries Management*, 37, 1311–1331. <https://doi.org/10.1080/02755947.2017.1378778>
- Colby, P.J. & Nepszy, S.J. (1981). Variation among Stocks of Walleye (*Stizostedion vitreum*): Management Implications. *Canadian Journal Fisheries and Aquatic Sciences*, 38, 1814–1831. <https://doi.org/10.1139/f81-228>
- Coleman, F.C. & Koenig, C.C. (2010). The Effects of Fishing, Climate Change, and Other Anthropogenic Disturbances on Red Grouper and Other Reef Fishes in the Gulf of Mexico. *Integrative and Comparative Biology*, 50, 201–212. <https://doi.org/10.1093/icb/icq072>
- Cooke, S.J., Martins, E.G., Struthers, D.P., Gutowsky, L.F.G., Power, M., Doka, S.E.,

- Dettmers, J.M., Crook, D.A., Lucas, M.C., Holbrook, C.M., Krueger, C.C. (2016). A moving target—incorporating knowledge of the spatial ecology of fish into the assessment and management of freshwater fish populations. *Environmental Monitoring and Assessment*, 188, 239. <https://doi.org/10.1007/s10661-016-5228-0>
- Craig, J.F. (2008). Percid Fishes: Systematics, Ecology and Exploitation. *John Wiley & Sons*.
- Dai, Q., Bunnell, D.B., Diana, J.S., Pothoven, S.A., Eaton, L., O'Brien, T.P., Kraus, R.T. (2019). Spatial patterns of rainbow smelt energetic condition in Lakes Huron and Erie in 2017: Evidence for Lake Huron resource limitation. *Journal of Great Lakes Research*, 45, 830–839. <https://doi.org/10.1016/j.jglr.2019.06.001>
- Dembkowski, D.J., Willis, D.W., Wuellner, M.R. (2016). Synchrony in larval yellow perch abundance: the influence of the Moran Effect during early life history. *Canadian Journal of Fisheries and Aquatic Sciences*, 73, 10. <https://doi.org/10.1139/cjfas-2015-0310>
- Diana, J.S., Jones, C.A., Lucchesi, D.O, Schneider, J.C. (1987) Evaluation of the yellow perch fishery and its importance to the local economy of the Les Cheneaux area: final report. <https://repository.library.noaa.gov/view/noaa/2094>
- Diana, J.S., Belyea, G.Y., Clark, R.D., Sutton, A.D. (1997) History, Status, and Trends In Populations of Yellow Perch and Double-Crested Cormorants in Les Cheneaux Islands, Michigan. Special Report No. 17 97.
- Drazen, J.C. & Haedrich, R.L. (2012). A continuum of life histories in deep-sea demersal fishes. *Deep Sea Research Part I: Oceanographic Research Papers*, 61, 34–42. <https://doi.org/10.1016/j.dsr.2011.11.002>

- Dunlop, E.S., Milne, S.W., Ridgway, M.S. (2010). Temporal trends in the numbers and characteristics of Lake Huron fish schools between 2000 and 2004. *Journal of Great Lakes Research*, 36, 74–85. <https://doi.org/10.1016/j.jglr.2009.12.006>
- Dunlop, E.S. & Riley, S.C. (2013). The contribution of cold winter temperatures to the 2003 alewife population collapse in Lake Huron. *Journal of Great Lakes Research*, 39, 682–689. <https://doi.org/10.1016/j.jglr.2013.08.001>
- Eberts, R.L., Wissel, B., Simpson, G.L., Crawford, S.S., Stott, W., Hanner, R.H., Manzon, R.G., Wilson, J.Y., Boreham, D.R., Somers, C.M. (2017). Isotopic Structure of Lake Whitefish in Lake Huron: Evidence for Regional and Local Populations Based on Resource Use. *North American Journal of Fisheries Management*, 37, 133–148. <https://doi.org/10.1080/02755947.2016.1245225>
- Estlander, S., Kahilainen, K.K., Horppila, J., Olin, M., Rask, M., Kubečka, J., Peterka, J., Říha, M., Huuskonen, H., Nurminen, L. (2017). Latitudinal variation in sexual dimorphism in life-history traits of a freshwater fish. *Evolutionary Ecology*, 7, 665–673. <https://doi.org/10.1002/ece3.2658>
- Feiner, Z., Chong, S., Fielder, D., Hoyle, J., Knight, C., Lauer, T., Thomas, M., Tyson, J., Höök, T. (2017). Sex-based tradeoffs between growth, mortality, and maturation in Great Lakes yellow perch stocks. *Canadian Journal of Fisheries and Aquatic Sciences*, 74. <https://doi.org/10.1139/cjfas-2016-0173>
- Fielder, D.G. & Thomas, M.V. (2006) Fish Population Dynamics of Saginaw Bay, Lake Huron 1998–2004 1.
- Fielder, D.G. (2008). Examination of Factors Contributing to the Decline of the Yellow

- Perch Population and Fishery in Les Cheneaux Islands, Lake Huron, with Emphasis on the Role of Double-crested Cormorants. *Journal of Great Lakes Research*, 34, 506–523. [https://doi.org/10.3394/0380-1330\(2008\)34\[506:EOFCTT\]2.0.CO;2](https://doi.org/10.3394/0380-1330(2008)34[506:EOFCTT]2.0.CO;2)
- Fielder, D.G. (2010). Response of yellow perch in Les Cheneaux Islands, Lake Huron to declining numbers of double-crested cormorants stemming from control activities. *Journal of Great Lakes Research*, 36, 207–214. <https://doi.org/10.1016/j.jglr.2009.12.015>
- Fisher, S.J. & Willis, D.W. (1997). Early Life History of Yellow Perch in Two South Dakota Glacial Lakes. *Journal of Freshwater Ecology*, 12, 421–429. <https://doi.org/10.1080/02705060.1997.9663552>
- Frías-Alvarez, P., Garcia, C.M., Vázquez-Vega, L.F., Zúñiga-Vega, J.J. (2014). Spatial and temporal variation in superfoetation and related life history traits of two viviparous fishes: *Poeciliopsis gracilis* and *P. infans* 14. *Naturwissenschaften*, 101, 1085–1098. DOI 10.1007/s00114-014-1247-2
- Garnett, J.A. & Batzer, D.P. (2014). Longitudinal variation in community structure of floodplain fishes along two rivers of the Southeastern USA. *Canadian Journal of Fisheries and Aquatic Sciences*, 71, 1291+.
- Genner, M.J., Sims, D.W., Southward, A.J., Budd, G.C., Masterson, P., Mchugh, M., Rendle, P., Southall, E.J., Wearmouth, V.J., Hawkins, S.J. (2010). Body size-dependent responses of a marine fish assemblage to climate change and fishing over a century-long scale. *Global Change Biology*, 16, 517–527. <https://doi.org/10.1111/j.1365-2486.2009.02027.x>

- Gislason, D., McLaughlin, R.L., Robinson, B.W., Cook, A., Dunlop, E.S. (2018). Rapid changes in age and size at maturity in Lake Erie yellow perch (*Perca flavescens*) are not explained by harvest. *Canadian Journal of Fisheries and Aquatic Sciences*, 75, 211.
- Gobin, J., Lester, N.P., Cottrill, A., Fox, M.G., Dunlop, E.S. (2015). Trends in growth and recruitment of Lake Huron lake whitefish during a period of ecosystem change, 1985 to 2012. *Journal of Great Lakes Research*, 41, 405–414.
<https://doi.org/10.1016/j.jglr.2015.03.003>
- Graham, C.F., Eberts, R.L., Morgan, T.D., Boreham, D.R., Lance, S.L., Manzon, R.G., Martino, J.A., Rogers, S.M., Wilson, J.Y., Somers, C.M. (2016). Fine-Scale Ecological and Genetic Population Structure of Two Whitefish (Coregoninae) Species in the Vicinity of Industrial Thermal Emissions. *PLoS ONE*, 11, e0146656. <https://doi.org/10.1371/journal.pone.0146656>
- Gunderson, D.R. & Dygert, P.H. (1988). Reproductive effort as a predictor of natural mortality rate. *ICES Journal of Marine Science*, 44, 200–209.
<https://doi.org/10.1093/icesjms/44.2.200>
- Hammer, M., Jansson, A., Jansson, B.-O. (2021). Diversity Change and Sustainability: Implications for Fisheries 10. *Biodiversity: Ecology, Economics, Policy*, 22, 97–105
- Happel, A., Jonas, J.L., McKenna, P.R., Rinchar, J., He, J.X., Czesny, S.J. (2018). Spatial variability of lake trout diets in Lakes Huron and Michigan revealed by stomach content and fatty acid profiles. *Canadian Journal of Fisheries and Aquatic Sciences*, 75, 95–105. <https://doi.org/10.1139/cjfas-2016-0202>

- Haque, R., Singha, K.P., Karmakar, S. (2019). Environmental stressors on fish and it's adaptation physiology. *Aqua International*, 2019, 46–52.
- Hartman, K.J. & Margraf, F.J. (1993). Evidence of predatory control of yellow perch (*Perca flavescens*) recruitment in Lake Erie, U.S.A. *Journal of Fish Biology*, 43, 109–119. <https://doi.org/10.1111/j.1095-8649.1993.tb00414.x>
- He, J.X., Bence, J.R., Madenjian, C.P., Pothoven, S.A., Dobiesz, N.E., Fielder, D.G., Johnson, J.E., Ebener, M.P., Cottrill, R.A., Mohr, L.C., Koproski, S.R. (2015). Coupling age-structured stock assessment and fish bioenergetics models: a system of time-varying models for quantifying piscivory patterns during the rapid trophic shift in the main basin of Lake Huron. *Canadian Journal of Fisheries and Aquatic Sciences*, 72, 7.
- He, J.X., Bence, J.R., Roseman, E.F., Fielder, D.G., Ebener, M.P. (2016). Using time-varying asymptotic length and body condition of top piscivores to indicate ecosystem regime shift in the main basin of Lake Huron: a Bayesian hierarchical modeling approach. *Canadian Journal of Fisheries and Aquatic Sciences*, 73, 1092.
- Hecky, R.E., Smith, R.E.H., Barton, D.R., Guildford, S.J. (2004). The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, 61, 1285–1293.
- Heibo, E., Magnhagen, C., Vøllestad, L.A. (2005). Latitudinal Variation in Life-History Traits in Eurasian Perch. *Ecology*, 86, 3377–3386. <https://doi.org/10.1890/04-1620>

- Higgins, S.N. & Vander Zanden, M.J. (2010). What a difference a species makes: a meta-analysis of dreissenid mussel impacts on freshwater ecosystems. *Ecological Monographs*, 80, 179–196. <https://doi.org/10.1890/09-1249.1>
- Hughes, J.M., Stewart, J., Lyle, J.M., McAllister, J., Stocks, J.R., Suthers, I.M. (2017). Influence of latitudinal variation in environmental gradients and population structure on the demography of a widespread pelagic fish, *Arripis trutta* (Forster, 1801). *Environmental Biology and Fish*, 100, 121–135. <https://doi.org/10.1007/s10641-016-0565-y>
- Husson, F., Josse, J., Lê, S. (2008). FactoMineR: An R Package for Multivariate Analysis. *Journal of Statistical Software*, 25. <https://doi.org/10.18637/jss.v025.i01>
- Ivan, L.N., Höök, T.O., Thomas, M.V., Fielder, D.G. (2011). Long-Term and Interannual Dynamics of Walleye and Yellow Perch in Saginaw Bay, Lake Huron. *Transactions of the American Fisheries Society*, 140, 1078–1092. <https://doi.org/10.1080/00028487.2011.603976>
- Jackson, G., Norriss, J.V., Mackie, M.C., Hall, N.G. (2010). Spatial variation in life history characteristics of snapper (*Pagrus auratus*) within Shark Bay, Western Australia. *New Zealand Journal of Marine and Freshwater Research*, 44, 1–15. <https://doi.org/10.1080/00288331003641646>
- Jardine, T.D., McGeachy, S.A., Paton, C.M., Savoie, M., Cunjak, R.A. (2003) Stable Isotopes in Aquatic Systems: Sample Preparation, Analysis, and Interpretation. 45.
- Johnson, J.E., DeWitt, S.P., Gonder, D.J.A. (2010). Mass-Marking Reveals Emerging

- Self Regulation of the Chinook Salmon Population in Lake Huron. *North American Journal of Fisheries Management*, 30, 518–529.
<https://doi.org/10.1577/M09-094.1>
- Jonsson, B. & L'Abée-Lund, J. (1993). Latitudinal clines in life-history variables of anadromous brown trout in Europe. *Journal of Fish Biology*, 43, 1–16.
<https://doi.org/10.1111/j.1095-8649.1993.tb01175.x>
- Kassambara, A. (2020). RStudio Package “factoextra.”
- Kolding, J. & Zwieten, P.V. (2014). Sustainable fishing of inland waters. *Journal of Limnology*, 73. <https://doi.org/10.4081/jlimnol.2014.818>
- Kornis, M.S., Weidel, B.C., Zanden, M.J.V. (2017). Divergent life histories of invasive round gobies (*Neogobius melanostomus*) in Lake Michigan and its tributaries. *Ecology of Freshwater Fish*, 26, 563–574. <https://doi.org/10.1111/eff.12300>
- Kurek, J. & Cwynar, L.C. (2009). Effects of within-lake gradients on the distribution of fossil chironomids from maar lakes in western Alaska: implications for environmental reconstructions. *Hydrobiologia*, 623, 37–52.
<https://doi.org/10.1007/s10750-008-9646-z>
- Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software*, 82, 1–26.
<https://doi.org/10.18637/jss.v082.i13>
- Lappalainen, J., Tarkan, A.S., Harrod, C. (2008). A meta-analysis of latitudinal variations in life-history traits of roach, *Rutilus rutilus*, over its geographical range: linear or non-linear relationships? *Freshwater Biology*, 53, 1491–1501.
<https://doi.org/10.1111/j.1365-2427.2008.01977.x>

- Larsson, P., Tibblin, P., Koch-Schmidt, P., Engstedt, O., Nilsson, J., Nordahl, O., Forsman, A. (2015). Ecology, evolution, and management strategies of northern pike populations in the Baltic Sea. *AMBIO*, 44, 451–461.
<https://doi.org/10.1007/s13280-015-0664-6>
- Layman, C.A., Araujo, M.S., Boucek, R., Hammerschlag-Peyer, C.M., Harrison, E., Jud, Z.R., Matich, P., Rosenblatt, A.E., Vaudo, J.J., Yeager, L.A., Post, D.M., Bearhop, S. (2012). Applying stable isotopes to examine food-web structure: an overview of analytical tools. *Biological Reviews*, 87, 545–562.
<https://doi.org/10.1111/j.1469-185X.2011.00208.x>
- Lobón-Cerviá, J., Dgebuadze, Y., Utrilla, C.G., Rincón, P.A., Granado-Lorencio, C. (1996). The reproductive tactics of dace in central Siberia: evidence for temperature regulation of the spatio-temporal variability of its life history. *Journal of Fish Biology*, 48, 1074–1087. <https://doi.org/10.1111/j.1095-8649.1996.tb01805.x>
- Lucchesi, D.O. (2004). A biological analysis of the yellow perch population in the Les Cheneaux Islands, Lake Huron. (Fisheries research report: 1958).
- Lucchesi, D.O. & Bruce, S. (2006). *Evaluation of Scales and Otoliths for Walleye and Yellow Perch Age Estimation*. Special Report. South Dakota Department of Game, Fish, and Parks.
- Macdonald, P., Angus, C.H., Marshall, C.T. (2013). Spatial variation in life history characteristics of common megrim (*Lepidorhombus whiffiagonis*) on the Northern Shelf. *Journal of Sea Research, Proceedings of the 8th International*

Symposium on Flatfish Ecology, Part I 75, 62–68.

<https://doi.org/10.1016/j.seares.2012.05.017>

Malone, E.W., Perkin, J.S., Gibbs, W.K., Padgett, M., Kulp, M., Moore, S.E. (2021).

High and dry in days gone by: Life-history theory predicts Appalachian mountain stream fish assemblage transformation during historical drought. *Ecology of Freshwater Fish*, 2021, 1, 1–16. <https://doi.org/10.1111/eff.12606>

Mangeni-Sande, R., Taabu-Munyaho, A., Ogutu-Ohwayo, R., Nkalubo, W., Natugonza,

V., Nakiyende, H., Nyamweya, C.S., Muwanika, V.B. (2019). Spatial and temporal differences in life history parameters of *Rastrineobola argentea* (Pellegrin, 1904) in the Lake Victoria basin in relation to fishing intensity. *Fisheries Management and Ecology*, 26, 406–412.

<https://doi.org/10.1111/fme.12281>

Mims, M.C. & Olden, J.D. (2012). Life history theory predicts fish assemblage response to hydrologic regimes. *Ecology*, 93, 35–45.

Morgan, T.D., Graham, C.F., McArthur, A.G., Raphenya, A.R., Boreham, D.R., Manzon,

R.G., Wilson, J.Y., Lance, S.L., Howland, K.L., Patrick, P.H., Somers, C.M. (2017). Genetic population structure of the round whitefish (*Prosopium cylindraceum*) in North America: multiple markers reveal glacial refugia and regional subdivision. *Canadian Journal of Fisheries and Aquatic Sciences*,

<https://doi.org/10.1139/cjfas-2016-0528>

Nalepa, T.F., Fanslow, D.L., Pothoven, S.A., Foley, A.J., Lang, G.A. (2007). Long-term

Trends in Benthic Macroinvertebrate Populations in Lake Huron over the Past Four Decades. *Journal of Great Lakes Research*, 33, 421–436.

[https://doi.org/10.3394/0380-1330\(2007\)33\[421:LTIBMP\]2.0.CO;2](https://doi.org/10.3394/0380-1330(2007)33[421:LTIBMP]2.0.CO;2)

Nalepa, T.F., Pothoven, S.A., Fanslow, D.L. (2009). Recent changes in benthic macroinvertebrate populations in Lake Huron and impact on the diet of lake whitefish (*coregonus clupeaformis*). *Aquatic Ecosystem Health & Management*, 12, 2–10. <https://doi.org/10.1080/14634980802715175>

New, M., Hulme, M., Jones, P. (2021). Representing Twentieth-Century Space–Time Climate Variability. Part I. *Journal of Climate*, 12, 29.

Ontario Ministry of Natural Resources and Forestry. (2019). Lake Huron Commercial Fishing Summary for 2018. Ontario ministry of Natural Resources and Forestry, Upper Great Lakes Management Unit, Lake Huron. Report TR-LHA-2019-02. ISSN 1709-7347 ISBN 978-1-4868-3390-0

Palacios-Hernández, D., Castillo-Géniz, J.L., Méndez-Loeza, I., Pérez-Jiménez, J.C. (2020). Temporal and latitudinal comparisons of reproductive parameters in a heavily exploited shark, the bonnethead, *Sphyrna tiburo* (L. 1758), in the southern Gulf of Mexico. *Journal of Fish Biology*, 97, 100–112.

<https://doi.org/10.1111/jfb.14330>

Pecuchet, L., Lindegren, M., Hidalgo, M., Delgado, M., Esteban, A., Fock, H.O., Gil de Sola, L., Punzón, A., Sólmundsson, J., Payne, M.R. (2017). From traits to life-history strategies: Deconstructing fish community composition across European seas. *Global Ecology and Biogeography*, 26, 812–822.

<https://doi.org/10.1111/geb.12587>

- Piou, C., Taylor, M.H., Papaix, J., Prévost, E. (2015). Modelling the interactive effects of selective fishing and environmental change on Atlantic salmon demogenetics. *Journal of Applied Ecology*, 52, 1629–1637. <https://doi.org/10.1111/1365-2664.12512>
- Pothoven, S.A., Madenjian, C.P., Höök, T.O. (2017). Feeding ecology of the walleye (Percidae, *Sander vitreus*), a resurgent piscivore in Lake Huron (Laurentian Great Lakes) after shifts in the prey community. *Ecology Freshwater Fish*, 26, 676–685. <https://doi.org/10.1111/eff.12315>
- Prats, J., Val, R., Dolz, J., Armengol, J. (2012). Water temperature modeling in the Lower Ebro River (Spain): Heat fluxes, equilibrium temperature, and magnitude of alteration caused by reservoirs and thermal effluent: water temperature modeling in the lower Ebro River. *Water Resources*, 48. <https://doi.org/10.1029/2011WR010379>
- Purchase, C.F., Collins, N.C., Morgan, G.E., Shuter, B.J. (2005a) Predicting Life History Traits of Yellow Perch from Environmental Characteristics of Lakes. *Transactions of the American Fisheries Society*, 134, 1369–1381. <https://doi.org/10.1577/T04-182.1>
- Purchase, C.F., Collins, N.C., Morgan, G.E., Shuter, B.J. (2005b) Sex-specific covariation among life-history traits of yellow perch (*Perca flavescens*). *Evolutionary Ecology Research*, 2005, 7: 549–566.
- Ridgway, M.S. (2010). Seasonal and annual patterns in density of double-crested cormorants in two coastal regions of Lake Huron. *Journal of Great Lakes Research*, 36, 411–418. <https://doi.org/10.1016/j.jglr.2010.05.010>

- Ridgway, M.S. & Middel, T.A. (2015). Coastal zone occupancy by double-crested cormorants on a Laurentian great lake before, during, and after a food web regime shift. *Canadian Journal of Fisheries and Aquatic Sciences*, 72, 1004.
- Riley, S.C., Roseman, E.F., Nichols, S.J., O'Brien, T.P., Kiley, C.S., Schaeffer, J.S. (2008). Deepwater Demersal Fish Community Collapse in Lake Huron. *Transactions of the American Fisheries Society*, 137, 1879–1890.
<https://doi.org/10.1577/T07-141.1>
- Riley, S.C. & Adams, J.V. (2010). Long-Term Trends in Habitat Use of Offshore Demersal Fishes in Western Lake Huron Suggest Large-Scale Ecosystem Change. *Transactions of the American Fisheries Society*, 139, 1322–1334.
<https://doi.org/10.1577/T09-090.1>
- Riley, S.C. & Dunlop, E.S. (2016). Misapplied survey data and model uncertainty result in incorrect conclusions about the role of predation on alewife population dynamics in Lake Huron: a comment on He et al. *Canadian Journal of Fisheries and Aquatic Sciences*, 73, 860.
- Roswell, C.R., Pothoven, S.A., Höök, T.O. (2014). Patterns of age-0 yellow perch growth, diets, and mortality in Saginaw Bay, Lake Huron. *Journal of Great Lakes Research*, 40, 123–132. <https://doi.org/10.1016/j.jglr.2014.01.008>
- R Core Team. (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
<https://www.R-project.org/>
- Schaeffer, J.S., Diana, J.S., Haas, R.C. (2000). Effects of Long-Term Changes in the

- Benthic Community on Yellow Perch in Saginaw Bay, Lake Huron. *Journal of Great Lakes Research*, 26, 340–351. [https://doi.org/10.1016/S0380-1330\(00\)70697-6](https://doi.org/10.1016/S0380-1330(00)70697-6)
- Schaeffer, J.S., Bowen, A., Thomas, M., French, J.R.P., Curtis, G.L. (2005). Invasion History, Proliferation, and Offshore Diet of the Round Goby *Neogobius melanostomus* in Western Lake Huron, USA. *Journal of Great Lakes Research*, 31, 414–425. [https://doi.org/10.1016/S0380-1330\(05\)70273-2](https://doi.org/10.1016/S0380-1330(05)70273-2)
- Scheuerell, M.D., Hilborn, R., Ruckelshaus, M.H., Bartz, K.K. (2006). The Shiraz model: a tool for incorporating anthropogenic effects and fish-habitat relationships in conservation planning. *Canadian Journal of Fisheries and Aquatic Sciences*, 63, 1596–1607.
- Sharpe, D.M.T., Wandera, S.B., Chapman, L.J. (2012). Life history change in response to fishing and an introduced predator in the East African cyprinid *Rastrineobola argentea*. *Evolutionary Applications*, 5, 677–693. <https://doi.org/10.1111/j.1752-4571.2012.00245.x>
- Speers, J.D. (2019) Offshore Index Assessment Program 2018 Summary Report. Ontario Ministry of Natural Resources and Forestry, Upper Great Lakes Management Unit, Lake Huron. Report PS-LHA-IA18-SUM. ISSN 1929-3402 (Online). ISBN 978-1-4868-3252-1 (2019 ed.)
- Stadig, M.H., Collingsworth, P.D., Lesht, B.M., Höök, T.O. (2020). Spatially heterogeneous trends in nearshore and offshore chlorophyll a concentrations in Michigan and Huron (1998–2013). *Freshwater Biology*, 65, 366–378. <https://doi.org/10.1111/fwb.13430>

- Stefanoff, S., Vogt, R.J., Howell, T., Sharma, S. (2018). Phytoplankton and benthic algal response to ecosystem engineers and multiple stressors in the nearshore of Lake Huron. *Journal of Great Lakes Research*, 44, 447–457.
<https://doi.org/10.1016/j.jglr.2018.02.009>
- Sterner, T. (2007). Unobserved diversity, depletion and irreversibility: The importance of subpopulations for management of cod stocks. *Ecological Economics*, 61, 566–574. <https://doi.org/10.1016/j.ecolecon.2006.05.015>
- Sullivan, T.J. & Stepien, C.A. (2014). Genetic diversity and divergence of yellow perch spawning populations across the Huron–Erie Corridor, from Lake Huron through western Lake Erie. *Journal of Great Lakes Research, Conservation and Management of Fisheries and Aquatic Communities in Great Lakes Connecting Channels*, 40, 101–109. <https://doi.org/10.1016/j.jglr.2012.12.004>
- Sullivan, T.J. & Stepien, C.A. (2015). Temporal Population Genetic Structure of Yellow Perch Spawning Groups in the Lower Great Lakes. *Transactions of the American Fisheries Society*, 144, 211–226. <https://doi.org/10.1080/00028487.2014.982260>
- Vázquez, D.P. & Stevens, R.D. (2004). The Latitudinal Gradient in Niche Breadth: Concepts and Evidence. *The American Naturalist*, 164, E1–E19.
<https://doi.org/10.1086/421445>
- Vollestad, L. (1992). Geographic Variation in Age and Length at Metamorphosis of Maturing European Eel: Environmental Effects and Phenotypic Plasticity. *Journal of Animal Ecology*, 61, 41–48.
- Wang, H.-Y., Hook, T.O., Ebener, M.P., Mohr, L.C., Schneeberger, P.J. (2008). Spatial

- and temporal variation of maturation schedules of lake whitefish (*Coregonus clupeaformis*) in the Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, 65, 2157.
- Wang, H.-Y., Shen, S.-F., Chen, Y.-S., Kiang, Y.-K., Heino, M. (2020). Life histories determine divergent population trends for fishes under climate warming. *Nature Communications*, 11, 4088. <https://doi.org/10.1038/s41467-020-17937-4>
- Ward, H.G.M., Post, J.R., Lester, N.P., Askey, P.J., Godin, T. (2017). Empirical evidence of plasticity in life-history characteristics across climatic and fish density gradients. *Canadian Journal of Fisheries and Aquatic Sciences*, 74, 464–474. <https://doi.org/10.1139/cjfas-2016-0023>
- Warner, D.M. & Lesht, B.M. (2015). Relative importance of phosphorus, invasive mussels and climate for patterns in chlorophyll a and primary production in Lakes Michigan and Huron. *Freshwater Biology*, 60, 1029–1043. <https://doi.org/10.1111/fwb.12569>
- Weber, M.J., Dettmers, J.M., Wahl, D.H. (2011). Growth and Survival of Age-0 Yellow Perch across Habitats in Southwestern Lake Michigan: Early Life History in a Large Freshwater Environment. *Transactions of the American Fisheries Society*, 140, 1172–1185. <https://doi.org/10.1080/00028487.2011.608605>
- Whiteside, M.C., Swindoll, C.M., Doolittle, W.L. (1985). Factors affecting the early life history of yellow perch, *Perca flavescens*. *Environmental Biology and Fish*, 12, 47–56. <https://doi.org/10.1007/BF00007709>
- Wilson, K.L., Gisi, J.D., Cahill, C.L., Barker, O.E., Post, J.R. (2019). Life-history

variation along environmental and harvest clines of a northern freshwater fish:
Plasticity and adaptation. *Journal of Animal Ecology*, 88, 717–733.

<https://doi.org/10.1111/1365-2656.12965>

Winkle, W.V., Rose, K.A., Winemiller, K.O., Deangelis, D.L., Christensen, S.W., Otto, R.G., Shuter, B.J. (1993). Linking Life History Theory, Environmental Setting, and Individual-Based Modeling to Compare Responses of Different Fish Species to Environmental Change. *Transactions of the American Fisheries Society*, 122, 459–466. [https://doi.org/10.1577/1548-8659\(1993\)122<0459:LLHTES>2.3.CO;2](https://doi.org/10.1577/1548-8659(1993)122<0459:LLHTES>2.3.CO;2)

Winston, M.S., Taylor, B.M., Franklin, E.C. (2017). Intraspecific variability in the life histories of endemic coral-reef fishes between photic and mesophotic depths across the Central Pacific Ocean. *Coral Reefs*, 36, 663–674.

<https://doi.org/10.1007/s00338-017-1559-8>

Zhong, Y., Notaro, M., Vavrus, S.J. (2019). Spatially variable warming of the Laurentian Great Lakes: an interaction of bathymetry and climate. *Climate Dynamics*, 52, 5833–5848. <https://doi.org/10.1007/s00382-018-4481-z>

Appendix

Supplementary list of tables and figures

Table S1: Output from generalized linear mixed models examining the influence of latitude, longitude, and depth, on Lake Huron yellow perch sex-specific life history traits using data from the contemporary era (2009–2018). A) male size at maturity; B) female size at maturity; (C) male age at maturity; (D) female age at maturity; (E) male maximum size; (F) female maximum size; (G) male lifespan; (H) female lifespan; (I) male growth rate; (J) female growth rate. Beta estimates, 95% confidence intervals, and p-values are listed for each predictor. P-values in bold are those that are <0.05 and indicate a significant relationship between an effect and sex-specific life history trait. The marginal r-squared (R^2M) and conditional r-squared (R^2C) for each mixed model are included.....116

Table S2: Lake Huron yellow perch sex-specific life history traits and effects of latitude, longitude, and depth, with p-values derived from linear mixed models using data from the historical timeframe (1990–1999). A) male size at maturity; B) female size at maturity; (C) male age at maturity; (D) female age at maturity; (E) male maximum size; (F) male growth rate; (G) female growth rate. Beta estimates, 95% confidence intervals, and p-values are listed for each predictor. P-values in bold are those that are <0.05 and indicate that an effect influences a sex-specific life history trait. The marginal r-squared (R^2M) and conditional r-squared (R^2C) for each linear mixed model are included. Values are not available for female maximum size, male lifespan, and female lifespan, as mixed models did not converge.....119

Table S3: Contemporary (2009–2018) sex-specific life history trait values for Lake Huron yellow perch at sites replicated across both timeframes. Length at maturity (L50)

is measured as fork length in mm, age at maturity (A50) is measured as age in years, maximum size (max size) is measured as fork length in mm, lifespan is measured as age in years, and growth at age 2 (growth rate) is measured as fork length in mm are assessed. The mean with standard deviation ($\bar{x} \pm SD$) for each life history trait is displayed. Male max size and lifespan were omitted at sites 7, 9, and 18, while male growth rate, female max size, and female lifespan were omitted at sites 7 and 9, in order to accurately replicate data from the historical era. Sites that lack measurement for a particular life history trait are listed as N/A (not available).....121

Table S4: Lake Huron yellow perch sex-specific life history traits with timeframe, number of sample sites (n), normality test results (Normality test p), and statistical test used for comparison between timeframes. Life history traits include male and female length at maturity (L50), male and female age at maturity (A50), male and female maximum size (max size), male and female lifespan, and male and female growth at age 2 (growth rate). Timeframe is separated into modern contemporary (Cont) and historical (Hist) eras. Only sites replicated across both timeframes were used in temporal comparisons; therefore, n is equal for both timeframes for each life history trait. Normality tests with significance ($p < 0.05$) are bolded and indicate that life history data are not normally distributed for that timeframe; therefore the Wilcoxon Rank-sum test is used as opposed to an unpaired two-samples t-test.....122

Table S5: Lake Huron yellow perch life history traits analysed using unpaired two-sample t-tests for the historical (Hist) and contemporary (Cont) timeframes. Life history traits with data of a normal distribution based on the normality test (normality test $p > 0.05$) for both timeframes (in Table 7) are shown; this includes female length at maturity

(L50), male age at maturity (A50), female maximum size (max size), male and female lifespan, and female growth at age 2 (growth rate). The mean with standard deviation ($\bar{x} \pm SD$) and median (Mdn) with interquartile range (IQR) are included. F-tests checked equality of variance between timeframes in each life history trait, with the F-statistic (F) and p-value (p) included. When $p = < 0.05$ for the F-test (bolded), variance is not equal across timeframes, so a Welch's two-sample t-test was used instead of the classic Student's t-test. T-test results include the t-statistic (t), degrees of freedom (d.f.), and p-value.....123

Table S6: Lake Huron yellow perch sex-specific life history traits analysed using Wilcoxon Rank-sum tests for the historical (Hist) and contemporary (Cont) timeframes. Life history traits that did not follow normal distribution based on the normality test (normality test $p > 0.05$) for at least one timeframe (shown in table 7) are analysed, including male length at maturity (L50), female age at maturity (A50), male maximum size (max size), and male growth at age 2 (growth rate). The mean with standard deviation ($\bar{x} \pm SD$) and median (Mdn) with interquartile range (IQR) are included, with male L50, max size, and growth rate measured in mm fork length, and female A50 measured in years. Wilcoxon rank-sum test results, including the W-statistic (W) and p-value, are included. P-values < 0.05 are bolded and indicate that the median values are significantly different between timeframes for a particular life history trait.....124

Table S7: Output from generalized linear mixed models examining the influence of latitude, longitude, and depth, on Lake Huron yellow perch sex-specific life history traits from the contemporary timeframe (2009–2018) using data only from sites replicated

across timeframes. A) male size at maturity; B) female size at maturity; (C) male age at maturity; (D) female age at maturity; (E) male maximum size; (F) female maximum size; (G) male lifespan; (H) female lifespan; (I) male growth rate; (J) female growth rate. Beta estimates, 95% confidence intervals, and p-values are listed for each predictor. P-values in bold are those that are <0.05 and indicate a significant relationship between an effect and sex-specific life history trait. The marginal r-squared (R^2M) and conditional r-squared (R^2C) for each mixed model are included.....125

Table S1: Output from generalized linear mixed models examining the influence of latitude, longitude, and depth, on Lake Huron yellow perch sex-specific life history traits using data from the contemporary era (2009–2018). A) male size at maturity; B) female size at maturity; (C) male age at maturity; (D) female age at maturity; (E) male maximum size; (F) female maximum size; (G) male lifespan; (H) female lifespan; (I) male growth rate; (J) female growth rate. Beta estimates, 95% confidence intervals, and p-values are listed for each predictor. P-values in bold are those that are <0.05 and indicate a significant relationship between an effect and sex-specific life history trait. The marginal r-squared (R^2M) and conditional r-squared (R^2C) for each mixed model are included.

Linear mixed model = Life History Trait ~ Latitude + Longitude + Depth + (1 Time)			
A. Male Size at Maturity			
Predictors	Estimate	95% CI	p
(Intercept)	-74.73	-1679.42 – 1720.49	0.933
Latitude	10.74	-5.50 – 26.49	0.212
Longitude	3.45	-12.46 – 21.43	0.698
Depth	-0.15	-2.49 – 2.14	0.899
R^2M / R^2C		0.153 / 0.282	
B. Female Size at Maturity			
Predictors	Estimate	95% CI	p
(Intercept)	144.88	-534.14 – 838.99	0.687
Latitude	-6.99	-13.57 – -0.53	0.053
Longitude	-4.20	-10.99 – 2.71	0.249
Depth	-0.39	-1.31 – 0.54	0.428
R^2M / R^2C		0.278 / 0.507	
C. Male Age at Maturity			
Predictors	Estimate	95% CI	p
(Intercept)	23.17	-33.07 – 81.50	0.444
Latitude	0.70	0.15 – 1.24	0.024
Longitude	0.64	0.08 – 1.22	0.044
Depth	-0.06	-0.14 – 0.01	0.131
R^2M / R^2C		0.570 / 0.728	

D. Female Age at Maturity

Predictors	Estimate	95% CI	p
(Intercept)	31.88	-6.50 – 68.62	0.118
Latitude	-0.42	-0.76 – -0.06	0.033
Longitude	0.12	-0.26 – 0.489	0.534
Depth	-0.05	-0.10 – 0.01	0.109
R^2M / R^2C	0.233 / 0.233		

E. Male Maximum Size

Predictors	Estimate	95% CI	p
(Intercept)	904.18	-251.44 – 1873.70	0.123
Latitude	-26.60	-35.98 – -15.78	<0.001
Longitude	-6.42	-17.84 – 3.52	0.259
Depth	0.36	-0.97 – 1.82	0.614
R^2M / R^2C	0.579 / 0.885		

F. Female Maximum Size

Predictors	Estimate	95% CI	p
(Intercept)	-998.38	-2170.51 – 43.90	0.106
Latitude	-26.44	-36.70 – -15.58	<0.001
Longitude	-30.30	-41.97 – -19.83	<0.001
Depth	-0.20	-1.57 – 1.39	0.798
R^2M / R^2C	0.779 / 0.884		

G. Male Lifespan

Predictors	Estimate	95% CI	p
(Intercept)	0.65	-52.68 – 50.87	0.981
Latitude	-0.40	-0.85 – 0.08	0.117
Longitude	-0.28	-0.82 – 0.23	0.314
Depth	0.00	-0.07 – 0.07	0.972
R^2M / R^2C	0.258 / 0.284		

H. Female Lifespan

Predictors	Estimate	95% CI	p
(Intercept)	-42.96	-113.19 – -21.11	0.238
Latitude	-0.52	-1.12 – 0.12	0.132
Longitude	-0.90	-1.60 – -0.26	0.021
Depth	-0.03	-0.12 – 0.07	0.569
R^2M / R^2C	0.404 / 0.404		

I. Male Growth Rate

Predictors	Estimate	95% CI	p
(Intercept)	41.72	-615.97 – 707.83	0.904
Latitude	3.05	-3.61 – 9.68	0.386
Longitude	0.70	-5.88 – 7.37	0.841
Depth	1.78	0.78 – 2.78	0.003
<i>R</i>²M / <i>R</i>²C		0.443 / 0.443	

J. Female Growth Rate

Predictors	Estimate	95% CI	p
(Intercept)	-412.36	-1250.41 – 442.72	0.359
Latitude	5.37	-3.17 – 13.82	0.238
Longitude	-3.71	-12.10 – 4.85	0.408
Depth	1.68	0.42 – 2.97	0.021
<i>R</i>²M / <i>R</i>²C		0.303 / 0.303	

Table S2: Lake Huron yellow perch sex-specific life history traits and effects of latitude, longitude, and depth, with p-values derived from linear mixed models using data from the historical timeframe (1990–1999). A) male size at maturity; B) female size at maturity; (C) male age at maturity; (D) female age at maturity; (E) male maximum size; (F) male growth rate; (G) female growth rate. Beta estimates, 95% confidence intervals, and p-values are listed for each predictor. P-values in bold are those that are <0.05 and indicate that an effect influences a sex-specific life history trait. The marginal r-squared (R^2M) and conditional r-squared (R^2C) for each linear mixed model are included. Values are not available for female maximum size, male lifespan, and female lifespan, as mixed models did not converge.

Linear mixed model = Life History Trait ~ Latitude + Longitude + Depth + (1 Time)			
A. Male Size at Maturity			
Predictors	Estimate	95% CI	p
(Intercept)	326.16	-6346.79 – 6999.11	0.926
Latitude	24.13	-15.38 – 63.64	0.271
Longitude	16.17	-62.28 – 94.62	0.698
Depth	2.03	-6.76 – 10.81	0.665
R^2M / R^2C		0.139 / 0.262	
B. Female Size at Maturity			
Predictors	Estimate	95% CI	p
(Intercept)	-34.61	3006.89 – 2937.68	0.983
Latitude	-23.67	-41.63 – -5.71	0.037
Longitude	-15.25	-50.50 – 20.01	0.425
Depth	0.68	-3.30 – 4.67	0.747
R^2M / R^2C		0.531 / 0.647	
C. Male Age at Maturity			
Predictors	Estimate	95% CI	p
(Intercept)	-64.15	-214.74 – 86.44	0.432
Latitude	0.22	-0.67 – 1.10	0.650
Longitude	-0.66	-2.43 – 1.10	0.486

	Depth	0.09	-0.11 – 0.28	0.393
<i>R</i>²<i>M</i> / <i>R</i>²<i>C</i>		0.098 / 0.168		

D. Female Age at Maturity

Predictors	Estimate	95% CI	p
(Intercept)	-27.76	-148.83 – 93.31	0.667
Latitude	-0.64	-1.35 – 0.07	0.119
Longitude	-0.73	-2.14 – 0.69	0.349
Depth	-0.05	-0.20 – 0.11	0.586
<i>R</i>²<i>M</i> / <i>R</i>²<i>C</i>		0.297 / 0.323	

E. Male Maximum Size

Predictors	Estimate	95% CI	p
(Intercept)	5.56e+03	4929.22 – 6185.02	0.660
Latitude	25.17	19.00 – 31.34	0.563
Longitude	79.20	69.32 – 89.08	0.619
Depth	2.94	1.90 – 3.98	0.610
<i>R</i>²<i>M</i> / <i>R</i>²<i>C</i>		0.825 / 0.992	

F. Male Growth Rate

Predictors	Estimate	95% CI	p
(Intercept)	633.63	-491.12 – 1758.38	0.320
Latitude	5.76	1.32 – 10.19	0.052
Longitude	9.11	-5.70 – 23.91	0.282
Depth	0.66	-0.22 – 1.54	0.200
<i>R</i>²<i>M</i> / <i>R</i>²<i>C</i>		0.451 / 0.451	

G. Female Growth Rate

Predictors	Estimate	95% CI	p
(Intercept)	-461.94	-1644.42 – 720.54	0.469
Latitude	6.21	-0.70 – 13.12	0.121
Longitude	-4.05	-17.87 – 9.77	0.584
Depth	1.12	-0.34 – 2.72	0.171
<i>R</i>²<i>M</i> / <i>R</i>²<i>C</i>		0.267 / 0.267	

Table S3: Contemporary (2009–2018) sex-specific life history trait values for Lake Huron yellow perch at sites replicated across both timeframes. Length at maturity (L50) is measured as fork length in mm, age at maturity (A50) is measured as age in years, maximum size (max size) is measured as fork length in mm, lifespan is measured as age in years, and growth at age 2 (growth rate) is measured as fork length in mm are assessed. The mean with standard deviation ($\bar{x} \pm SD$) for each life history trait is displayed. Male max size and lifespan were omitted at sites 7, 9, and 18, while male growth rate, female max size, and female lifespan were omitted at sites 7 and 9, in order to accurately replicate data from the historical era.

Sites that lack measurement for a particular life history trait are listed as N/A (not available).

Reduced Contemporary Life History Trait Values										
Site	Male					Female				
	L50	A50	Max Size	Lifespan	Growth Rate	L50	A50	Max Size	Lifespan	Growth Rate
1	111.0	-0.2	270.6	6.7	143.4	174.6	3.2	316.6	7.2	153.0
2	68.1	-1.2	273.0	7.1	138.0	172.2	3.5	321	9.3	134.9
3	141.9	1.6	285.3	6.6	165.8	179.4	2.5	318	7.5	174.6
4	31.8	-0.4	276.7	6.5	142.6	169.3	3.0	332.2	8.4	143.2
5	112.1	0.6	269.2	6.2	147.8	183.8	2.8	346.2	7.7	151.9
7	120.7	-0.2	N/A	N/A	N/A	177.7	1.9	N/A	N/A	182.8
9	124.7	0.8	N/A	N/A	N/A	165.0	2.3	N/A	N/A	163.8
10	125.0	-0.1	238.2	4.0	172.4	168.5	2.2	245.4	4.1	181.6
18	136.0	1.8	N/A	N/A	147.9	159.7	2.1	301.2	6.9	156.1
19	139.0	1.9	242.3	6.1	143.7	174.4	2.6	302.9	8.2	157.9
20	126.0	1.5	253.3	5.5	144.2	160.8	2.2	277.7	6.1	154.8
$\bar{x} \pm SD$	112.4 ± 31.9	0.6 ± 1.0	263.6 ± 15.9	6.1 ± 0.9	149.5 ± 10.9	171.4 ± 7.3	2.6 ± 0.5	306.8 ± 28.4	7.3 ± 1.4	159.5 ± 14.4

Table S4: Lake Huron yellow perch sex-specific life history traits with timeframe, number of sample sites (n), normality test results (Normality test p), and statistical test used for comparison between timeframes. Life history traits include male and female length at maturity (L50), male and female age at maturity (A50), male and female maximum size (max size), male and female lifespan, and male and female growth at age 2 (growth rate). Timeframe is separated into modern contemporary (Cont) and historical (Hist) eras. Only sites replicated across both timeframes were used in temporal comparisons; therefore, n is equal for both timeframes for each life history trait. Normality tests with significance ($p < 0.05$) are bolded and indicate that life history data are not normally distributed for that timeframe; therefore the Wilcoxon Rank-sum test is used as opposed to an unpaired two-samples t-test.

Sex-specific Life History Trait	Timeframe	n	Normality test p	Statistical test used
Male L50	Hist	11	0.141	Wilcoxon Rank-sum Test
	Cont	11	0.004	
Female L50	Hist	11	0.173	Unpaired two-samples T-test
	Cont	11	0.915	
Male A50	Hist	11	0.252	Unpaired two-samples T-test
	Cont	11	0.329	
Female A50	Hist	11	0.030	Wilcoxon Rank-sum Test
	Cont	11	0.653	
Male Max Size	Hist	8	0.020	Wilcoxon Rank-sum Test
	Cont	8	0.377	
Female Max Size	Hist	9	0.343	Unpaired two-samples T-test
	Cont	9	0.496	
Male Lifespan	Hist	8	0.185	Wilcoxon Rank-sum Test
	Cont	8	0.096	
Female Lifespan	Hist	9	0.840	Unpaired two-samples T-test
	Cont	9	0.543	
Male Growth Rate	Hist	9	0.517	Wilcoxon Rank-sum Test
	Cont	9	0.014	
Female Growth Rate	Hist	11	0.304	Unpaired two-samples T-test
	Cont	11	0.572	

Table S5: Lake Huron yellow perch life history traits analysed using unpaired two-sample t-tests for the historical (Hist) and contemporary (Cont) timeframes. Life history traits with data of a normal distribution based on the normality test (normality test $p > 0.05$) for both timeframes (in Table 7) are shown; this includes female length at maturity (L50), male age at maturity (A50), female maximum size (max size), male and female lifespan, and female growth at age 2 (growth rate). The mean with standard deviation ($\bar{x} \pm SD$) and median (Mdn) with interquartile range (IQR) are included. F-tests checked equality of variance between timeframes in each life history trait, with the F-statistic (F) and p-value (p) included. When $p = < 0.05$ for the F-test (bolded), variance is not equal across timeframes, so a Welch's two-sample t-test was used instead of the classic Student's t-test. T-test results include the t-statistic (t), degrees of freedom (d.f.), and p-value.

Sex-Specific Life History Trait	Timeframe	$\bar{x} \pm SD$	Mdn (IQR)	F-test for equality of variances		T-test for equality of means		
				F	p	t	d.f.	p
Female L50	Hist	171.0 \pm 32.0	173.5 (36.4)	0.052	<0.001	0.039	11	0.970
	Cont	171.4 \pm 7.3	172.2 (12.7)					
Male A50	Hist	1.1 \pm 1.1	1.2 (1.3)	0.783	0.706	-1.126	20	0.273
	Cont	0.6 \pm 1.0	0.6 (1.8)					
Female Max Size	Hist	308.6 \pm 31.9	318.9 (61.8)	0.795	0.754	-0.116	16	0.909
	Cont	306.8 \pm 28.4	316.6 (37.2)					
Male Lifespan	Hist	5.1 \pm 0.9	5.0 (1.9)	1.010	0.903	2.143	14	0.050
	Cont	6.1 \pm 0.9	6.4 (1.0)					
Female Lifespan	Hist	6.7 \pm 1.4	7.2 (2.5)	0.992	0.991	0.736	16	0.473
	Cont	7.3 \pm 1.4	7.5 (1.8)					
Female Growth Rate	Hist	165.6 \pm 10.0	164.7 (8.0)	2.064	0.269	-1.094	20	0.287
	Cont	159.5 \pm 14.4	156.1 (22.7)					

Table S6: Lake Huron yellow perch sex-specific life history traits analysed using Wilcoxon Rank-sum tests for the historical (Hist) and contemporary (Cont) timeframes. Life history traits that did not follow normal distribution based on the normality test (normality test $p > 0.05$) for at least one timeframe (shown in table 7) are analysed, including male length at maturity (L50), female age at maturity (A50), male maximum size (max size), and male growth at age 2 (growth rate). The mean with standard deviation ($\bar{x} \pm SD$) and median (Mdn) with interquartile range (IQR) are included, with male L50, max size, and growth rate measured in mm fork length, and female A50 measured in years. Wilcoxon rank-sum test results, including the W-statistic (W) and p-value, are included. P-values < 0.05 are bolded and indicate that the median values are significantly different between timeframes for a particular life history trait.

Sex Specific Life History Trait	Timeframe	Wilcoxon Rank-sum test			
		$\bar{x} \pm SD$	Mdn (IQR)	W	p
Male L50	Hist	111.4 \pm 52.4	124.7 (25.0)	51.5	0.577
	Cont	112.4 \pm 31.9	135.0 (94.7)		
Female A50	Hist	2.2 \pm 1.0	2.1 (1.1)	75.5	0.339
	Cont	2.6 \pm 0.5	2.5 (0.8)		
Male Max Size	Hist	232.9 \pm 23.3	228.6 (13.5)	56.0	0.010
	Cont	263.6 \pm 15.9	269.9 (30.7)		
Male Growth Rate	Hist	154.2 \pm 6.1	153.4 (8.5)	19.5	0.070
	Cont	149.5 \pm 10.9	144.2 (13.9)		

Table S7: Output from generalized linear mixed models examining the influence of latitude, longitude, and depth, on Lake Huron yellow perch sex-specific life history traits from the contemporary timeframe (2009–2018) using data only from sites replicated across timeframes. A) male size at maturity; B) female size at maturity; (C) male age at maturity; (D) female age at maturity; (E) male maximum size; (F) female maximum size; (G) male lifespan; (H) female lifespan; (I) male growth rate; (J) female growth rate. Beta estimates, 95% confidence intervals, and p-values are listed for each predictor. P-values in bold are those that are <0.05 and indicate a significant relationship between an effect and sex-specific life history trait. The marginal r-squared (R^2M) and conditional r-squared (R^2C) for each mixed model are included.

Linear mixed model = Life History Trait ~ Latitude + Longitude + Depth + (1 Time)			
A. Male Size at Maturity			
Predictors	Estimate	95% CI	p
(Intercept)	69.28	-3158.20 – 3296.76	0.968
Latitude	25.16	3.02 – 47.30	0.063
Longitude	13.56	-24.21 – 51.32	0.507
Depth	2.03	-1.81 – 5.87	0.359
R^2M / R^2C		0.361 / 0.673	
B. Female Size at Maturity			
Predictors	Estimate	95% CI	p
(Intercept)	130.03	-664.07 – 924.14	0.758
Latitude	-4.04	-8.80 – 0.73	0.151
Longitude	-2.67	-11.94 – 6.61	0.591
Depth	0.18	-0.84 – 1.20	0.745
R^2M / R^2C		0.349 / 0.391	
C. Male Age at Maturity			
Predictors	Estimate	95% CI	p
(Intercept)	-70.80	-142.95 – 1.34	0.142
Latitude	0.70	0.15 – 1.25	0.064
Longitude	-0.50	-1.36 – 0.36	0.324

	Depth	-0.03	-0.10 – 0.05	0.544
R^2M / R^2C		0.461 / 0.915		

D. Female Age at Maturity

Predictors	Estimate	95% CI	p
(Intercept)	-19.82	-61.09 – 21.44	0.378
Latitude	-0.35	-0.59 – -0.11	0.026
Longitude	-0.46	-0.95 – 0.02	0.102
Depth	-0.01	-0.06 – 0.05	0.861
R^2M / R^2C		0.563 / 0.563	

E. Male Maximum Size

Predictors	Estimate	95% CI	p
(Intercept)	-1104.84	-3140.15 – 930.48	0.347
Latitude	-12.90	-21.34 – -4.47	0.040
Longitude	-23.61	-50.32 – 3.09	0.158
Depth	0.33	-1.25 – 1.92	0.701
R^2M / R^2C		0.717 / 0.717	

F. Female Maximum Size

Predictors	Estimate	95% CI	p
(Intercept)	-4926.12	-8992.38 – -859.86	0.064
Latitude	-25.67	-41.70 – -9.64	0.026
Longitude	-78.05	-131.56 – -24.53	0.036
Depth	-1.18	-4.36 – 1.99	0.498
R^2M / R^2C		0.645 / 0.645	

G. Male Lifespan

Predictors	Estimate	95% CI	p
(Intercept)	-204.1	-225.33 – -182.86	<0.001
Latitude	-0.79	-0.88 – -0.70	<0.001
Longitude	-3.00	-3.24 – -2.76	<0.001
Depth	-0.01	-0.02 – 0.00	0.388
R^2M / R^2C		0.974 / 0.997	

H. Female Lifespan

Predictors	Estimate	95% CI	p
(Intercept)	-358.3	-517.03 – -199.56	0.009
Latitude	-1.03	-1.68 – -0.39	0.027
Longitude	-5.02	-7.05 – -2.99	0.010
Depth	0.00	-0.12 – 0.12	0.997
R^2M / R^2C		0.742 / 0.834	

I. Male Growth Rate

Predictors	Estimate	95% CI	p
(Intercept)	3427.07	2336.57 – 4517.58	0.002
Latitude	5.13	0.32 – 9.92	0.094
Longitude	42.84	30.68 – 55.00	0.001
Depth	0.34	-0.24 – 0.91	0.376
R^2M / R^2C		0.623 / 0.954	

J. Female Growth Rate

Predictors	Estimate	95% CI	p
(Intercept)	1306.00	-426.16 – 3038.16	0.183
Latitude	4.28	-5.84 – 14.40	0.434
Longitude	16.37	-3.87 – 36.62	0.157
Depth	0.09	-2.15 – 2.33	0.938
R^2M / R^2C		0.243 / 0.243	
