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EXAMINATION OF SPAWNING STOCK SPECIFIC RECRUITMENT AND MIGRATION DYNAMICS IN LAKE ERIE WHITE BASS

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ABSTRACT

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Differential and annually varying recruitment contributions by different spawning-stocks under varying abiotic conditions may be an underlying factor in high inter-annual recruitment variability in Lake Erie fish populations. The 2011 spawning season was characterized by very high discharge conditions. To investigate recruitment contributions from different spawning-stocks during 2011 I utilized otolith micro-chemical analyses to determine the natal origins of young of the year white bass (*Morone chrysops*) that composed the Lake Erie Central Basin population during August 2011. The otoliths of fishes have unique properties that allow them to act as reliable recorders of environmental history. Under the abiotic conditions that characterized the 2011 season, >80% of the successful recruits to the population were produced by the Sandusky River spawning-stock. Other spawning-stocks made limited contributions. To examine causative factors behind these differential recruitment contributions the otolith micro-chemistry dataset was spatially linked with the physical structure of the otolith to estimate the length at which individuals emigrated from near shore nursery habitats. Results of this study showed that surviving individuals from the Sandusky spawning-stock were retained in nursery habitats to significantly larger sizes before emigration to the Central Basin than individuals from the Maumee spawning-stock. Thus, during spawning seasons characterized by high discharge, the Sandusky River spawning-stock provides the Lake Erie white bass population with substantial contributions to year classes because the Sandusky system has the propensity for retention of early life stages of fishes within productive nursery habitat.

For Jo Dee and Clara Davis

I could not have accomplished this work without both of you. Your guidance has been essential.

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INTRODUCTION

Migration of freshwater fishes for spawning, feeding, and refuge can be described all inclusively as potamodromy and it can maximize fitness for individuals who make these movements at the correct time (Northcote 1984; Lucas and Baras 2001). The spatial ecology of many philopatric riverine spawning fish can be conceptualized as a triangle (Harden Jones 1968). Larvae are spawned in an upstream location, those larvae are advected downstream to nursery habitat, ontogenetic changes prompt emigration from nursery habitat to the adult feeding grounds, survivors recruit to the population, and surviving individuals eventually return to the original spawning area to reproduce (Lucas and Baras 2001). Successful timing and execution of all three of the conceptualized triangular migration events has direct effects on survival and fitness (Lucas and Baras 2001). The substantial changes in physiology and morphology, characteristic of fish early life history, are accompanied by changing habitat and nutritional requirements that motivates behavioral decisions leading to migration between habitats (Werner and Gilliam 1984, Werner 1988). Migrations of juvenile fishes from nursery habitats to adult feeding grounds vary in intensity and timing based on growth factors at the individual level, while fine scale habitat dynamics can influence individual decisions to migrate or to stay (Secor 1999; Krause and Seccor 2004, Kerr and Secor 2009, Kerr et al. 2010). There appears to be a threshold over which it is better to incur the risks associated with migration than to remain in habitat that is not optimal (Lundberg 1988, Chapman et al. 2011). Thus, the quality of nursery habitat an individual experiences will influence migration decisions and those decisions will have lasting effects on survival and recruitment. Here I quantified the migration dynamics of a philopatric riverine-spawning fish (*Morone chrysops*) in the context of recruitment success as a response to duration of nursery habitat utilization. I tested the hypothesis that differential recruitment of some spawning-stocks resulted from differences in duration of nearshore nursery habitat utilization. Individuals that delayed emigration from turbid and productive nursery habitats until attaining a size that limited predation capture efficiency and allowed piscivorous feeding, were expected to exhibit higher recruitment rates.

In Lake Erie large inter-annual variation in recruitment of fishes is common. During annual young-of-the year (YOY) recruitment assessments, variations in year class strength of over an order of magnitude are common for all important sport fish in Lake Erie (Ohio Department of Natural Resources-Division of Wildlife [ODNR-DOW] 2012). Year class strength is dictated by the cumulative success of individuals in surviving early life stages because this is the period of highest mortality (Houde 1987). The ability of individuals to survive early life stages is affected by many abiotic and biotic variables and their interactions (Houde 1987, Madenjian et al. 1996). Abiotic factors such as water temperature, spring discharge conditions, turbidity, and wind velocity can have substantial effects on the ability of fish eggs to hatch and larvae to survive in Lake Erie (Roseman 1997, Mion et al. 1998, Roseman et al. 2005, Reichert et al. 2010). The impacts of abiotic variables can be direct, such as turbulent destruction of eggs during high discharge events (Mion et al. 1998). However, abiotic variables can also lead to mortality indirectly, such as, advection of larval fish to poor nursery areas characterized by high predator abundance or low zooplankton abundance (Jones et al. 2003, Zhao et al. 2009). Thus, the complex interactions of abiotic and biotic factors that control survival of the individual can lead to large inter-annual variation in recruitment at the lake wide scale.

During years that produce excellent year classes, it is likely that favorable conditions for survival of early life stages are widespread. During years when recruitment is weak, favorable conditions are likely much rarer. Differential survivorship in some areas may lead to differential recruitment contributions for some spawning-stocks. In many freshwater systems the spatial scale at which recruitment occurs is relatively small (Meyers et al. 1997). Under a given suite of regional scale climatic conditions, spawning and nursery habitat characteristics and quality differ on a fine spatial scale due to the physical complexity characteristic of Lake Erie habitats (Zhang et al. 2008). Additionally, intra-annual spatial and temporal variability of abiotic and biotic variables in Lake Erie is large (Roseman 1997; Mion et al. 1998). Therefore, the spatial location and timing of larval production, in conjunction with the nursery habitat dynamics an individual experiences, will have a great influence on migration dynamics and ultimately, survival outcomes.

Major spawning groups of white bass (*Morone chrysops*) and walleye (*Sander vitreus*) are known to utilize Lake Erie tributaries; specifically, the Maumee River, Sandusky River, and the Western Basin Reefs are important spawning habitats (Roseman 1997, Mion et al. 1998). The white bass population in Lake Erie can be viewed as a meta-population; although the population is likely mixed during much of the year, spawning-stocks become spatially segregated into distinct spawning groups during the spring spawning season. White bass display high levels of spawning-stock segregation; for example, 70% of white bass spawning in the Sandusky River originated from that system (Hayden et al. 2011). Understanding the spawning-stock specific contributions to lake wide recruitment under a given suite of abiotic conditions is important for future management of Lake Erie fisheries because it would allow management decisions to be made at the same scale that recruitment occurs. If substantial recruitment is being made by a single spawning-stock that stock can be managed accordingly. A prerequisite for obtaining understanding of stock specific recruitment dynamics is the ability to determine spawning-stock specific recruitment contributions on an annual basis. This is difficult because, after emigration from nursery areas to feeding habitats in the open lake, the different spawning-stocks likely experience some degree of mixing. Thus, assessment of spawning-stock specific recruitment requires understanding of nursery habitat emigration dynamics and identification of the spawning-stock of origin for individuals that are recruited to the mixed juvenile population.

Recent advances in technology have allowed greater understanding of fish dispersal and migration dynamics (Lucas and Baras 2001). Sophisticated acoustic tagging techniques have provided the ability to detect migrating adult fish at great distances. Additionally, powerful hydrodynamic models have been developed that describe current velocity and patterns from observed atmospheric conditions (Ehernberg and Steig 2009). These models have subsequently been coupled with particle transport models to predict the advection pathways of planktonic larval fish (Johnson et al. 2013). These techniques have abundant applications and provide powerful new data in ongoing attempts to understand movements of fish. However, during the early-juvenile period in fishes, movement patterns can be controlled by individuals independent of the hydrodynamics of the system and manual tagging is not feasible due to the small size and high mortality rates of this life stage.

The utilization of otolith micro-chemistry as a natural tag is a technique that can quantify migration history and determine natal origins, while overcoming the tagging and tracking obstacles associated with juvenile fishes. The sagittae, asterisci, and lapilli otoliths are hearing and balance structures located in the vestibular labyrinth of teleost fishes (Campana and Neilson 1985). Otoliths are composed of a calcium carbonate ($CaCO_3$) matrix, typically precipitated as the aragonite polymorph of $CaCO_3$, and less commonly, as vaterite or calcite $CaCO_3$ polymorphs (Gauldie 1993). During accretion of the matrix material, as many as 31 trace elements may be incorporated into the crystalline lattice structure (Campana 1999). Some of these trace elements are incorporated in proportion to their abundance in the environment (Fowler et al. 1995). Once formed the structure and associated chemical composition of the otolith is not reworked by physiological processes; this property allows the otolith to act as a reliable recorder of environmental history (Campana and Neilson 1995). The utilization of otolith micro-chemical signatures as natural tags in fish populations has become widespread due to inherent advantages over other methods for answering questions regarding fish stock structure (Campana and Thorrold 2001). If differences in water chemistry are prevalent in different production areas, then fish emanating from those different areas are naturally tagged due to the incorporation of a unique chemical signature within the matrix of the otolith (Bath et al. 2000). This eliminates the need for expensive manual tagging programs, ensures that all individuals in a population receive a tag, and allows the earliest portion of an individual's life to be examined. Additionally, by determining the relationship between chemistry patterns and actual locations on the otolith, the recreation of migration events and examination of environmental history throughout the life of an individual becomes possible (Stevenson and Campana 1992, Campana and Thorrold 2001). Thus, the otoliths structure and chemistry can be utilized together, not only as a spatially explicit marking tag, but as a temporally explicit tracking device.

I utilized otolith micro-chemical analyses to determine natal origins of individual juvenile white bass that survived to become members of the August Lake Erie Central Basin population. I also combined an otolith micro-structural analysis with the spatially explicit micro-chemistry dataset to estimate the duration of nursery habitat utilization exhibited by survivors and to determine patterns in nursery habitat emigration trajectories. Further, I combined the findings from these studies and data from the 2011 ODNR-DOW trawl survey to develop a

Geographic Information System (GIS)-based spatial model of lake-wide white bass population abundance and a spawning-stock specific analysis of lake-wide recruitment contributions. The results of this study provide insights into spawning-stock specific recruitment contributions, potential causes of differential contributions, and the importance of individual spawning stocks under the abiotic conditions that characterized the 2011 spawning season.

METHODS

Water Chemistry

Water samples were taken in spring 2011 in upper and lower Sandusky Bay (n=22), in Maumee Bay (n=2), and in the open waters of the Central Basin of Lake Erie (n=3) to determine the extent of spatial variability in water chemistry among known white bass spawning locations in Lake Erie. These samples were processed in the field by filtering 50ml of water through a Target 0.45um nylon filter and acidifying with trace metals grade HNO_3 to produce a 2.0% acid solution (Eaton and Franson 2005). Trace-elemental chemical analyses were performed on a Thermo Elemental iCap 6500 Inductively Coupled Plasma–Optical Emissions Spectrometer interfaced with a CETAC autosampler (ICP-OES; ASX 520) following standard methods (Eaton and Franson 2005). Elements analyzed included Ba, Ca, Mg, Mn, and Sr because these elements are incorporated into otoliths in proportion to their concentration in water (Campana 1999). To control instrument drift, standards of known concentrations were analyzed before and after each set of ten samples to ensure quality control. Analysis of water chemistry data was performed by standardizing the ratio of each elements concentration to total Ca (mmole element:mole Ca^{-1}). Ratios of elements were then compared among sites using a one-way analysis of variance (ANOVA α=0.05) and Tukey's post hoc HSD test.

Spawning Stock Elemental Signatures - Maumee and Sandusky Watersheds 2011

During late June 2011early-juvenile white bass were collected from Sandusky and Maumee bays, Lake Erie, OH (n=10 from each) using a flat bottom semi-balloon micro mesh otter trawl (4m head rope, 8-mm bar mesh body, and 4-mm bar mesh cod end). Tows were conducted in the Lower Sandusky Bay near Johnsons Island (41^0 29.278; 82^0 43.888) and near the mouth of the Maumee River in Maumee Bay (41^0 41.795; 83^0 24.984) (Figure 1). Samples were immediately preserved in 90% ethanol and stored in acid washed polyethylene bottles. These two groups of early-juvenile white bass (15.2-22.0 mm SL) were assumed to have been spawned near the location of capture in the two bays. The purpose of these collections was to determine the micro-chemical composition in the sagittal otolith of fish that were spawned in each area. Previous research has demonstrated that observed differences in water chemistry between the Sandusky and Maumee watersheds is reflected in the micro-chemical composition of the otolith (Pangel et al. 2010, Hayden et al. 2011).

The early-juvenile white bass sampled in June 2011 were measured to the nearest 0.1 mm standard length (SL) under a dissecting microscope (Nikon SMZ 645) at 8x magnification, using an ocular micrometer. Otoliths were then removed with acid-washed glass probes by careful dissection under 8-16x magnification and were immediately placed in a solution of 2% H_2O_2 to remove any remaining tissue. They were then rinsed in Milli-Q™ (Milli-Pore) ultrapure water and allowed to dry under a fume hood. The otoliths were placed individually into rubber mounting wells that had been previously half filled with West System epoxy resin (#105 resin and #206 slow hardener). The wells were then filled to capacity and the otoliths were oriented in the embedding media with the longest axis (anterior to posterior) parallel to the longest side of the well to aid in subsequent cutting along the transverse axis. Sectioning on the transverse plane was accomplished using a low speed diamond blade saw (South Bay Technologies Model 650) such that a ≈ 300 um section that included the otolith core was retained. After sectioning the transverse sections of otolith were subsequently polished with progressively finer polishing media (3M Imperial 1000 grit, 2000 grit, and Precision Surfaces International 12 um lapping sheets) to a thickness of ≈ 30 um with the primordial core exposed. Otoliths were then mounted to glass slides using a thin layer of West System epoxy (15 samples per slide). The otolith-mounted slides were triple rinsed in Milli-Q™ ultrapure water and sonicated for 5 minutes in Milli-Q™ water. Slides were allowed to dry and sealed in acid-washed Petri dishes.

Otoliths were assayed for trace metals by utilizing laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) at the Great Lakes Institute for Environmental Research, University of Windsor, ON, Canada. The LA-ICP-MS system consisted of a Quantronix Integra C femtosecond laser that operated at a 100 Hz pulse rate producing a 24.8-25.9 mJ/pulse at the 2.5mm pinhole. The laser was linked to a Thermo-Elemental X7 quadrupole ICPMS operating in low resolution peak-jumping mode (isotope dwell time: 10 ms, carrier gas: Ar). Instrument drift was controlled by analyzing a National Institute of Standards and Technology 610 (NIST 610) glass standard before and after each slide of otoliths. A gas blank was analyzed before and after each sample to obtain a background reading. To account for variability in sample mass, internal standards were set to the stoichiometric concentration of calcium in aragonite (400432 $\mu g\ Ca \cdot g^{-1}\ CaCO_3$). This system produced a laser crater ≈23 um in diameter, that traversed the otolith from the edge (corresponding to time of capture) to the core (corresponding to time of hatch), at speeds of 4.6 to 5.8 um/s. The isotopes assayed included ^{25}Mg, ^{43}Ca, ^{44}Ca, ^{86}Sr, ^{88}Sr, ^{120}Sn, ^{137}Ba, and ^{138}Ba. These isotopes were above limits of detection

(LOD) in 100% of samples and coefficients of variation (CV) calculated for NIST 610 standards were within 3.0% for all experiments. This small suite of elements was chosen because the water chemistry results suggested that only Sr and Ba would be useful discriminators in these systems and measuring a smaller number of elements allowed the instrument to cycle through the elements more quickly, delivering more measurements at closer intervals along the transect.

Raw chemistry data (elemental counts per second) from the LA-ICP-MS were analyzed using Thermo Plasma Lab software (Thermo Scientific™). The data-processing protocol provides background subtracted and drift-corrected elemental concentrations. Each otolith transect was integrated from edge to core (≈ 200 um). The edge of the otolith was determined by observing a Sn spike, which was produced when the laser ablated the epoxy mounting material. The core was identified with the chemistry data by observing a pronounced spike in Mn which was associated with the primordial region (Ludsin et al. 2006). The data were then processed and subjected to calculations in an Excel macro that was developed at the University of Windsor for otolith data reduction (Yang 2003). The transect data were also run through a Bore function to standardize all measurement locations to internal time stamp standards (Yang 2003). The laser speed of each traverse was then calculated from X, Y coordinate data and time stamp information, which allowed the association of each measurement with an actual location on the otolith.

Concentrations of trace elements present in the otoliths of the known origin early-juvenile white bass sampled in June 2011 in the Sandusky and Maumee bays were compared with a single factor ANOVA (α=0.05). This analysis allowed the determination of elements that could be used to reliably distinguish individuals produced at the two different spawning locations. It also suggested the concentrations of each element to expect in the primordial core region of otoliths in older fish that had been produced at these spawning sites in 2011. Further, it yielded a relative measure of the variability (CV) associated with otolith trace elemental concentrations of white bass produced at each spawning location.

Stock Composition Analysis of the August Central Basin White Bass Population

During August 2011, the Ohio Department of Natural Resources, Division of Wildlife, Lake Erie Research units at Sandusky and Fairport Harbor conducted an extensive trawling survey of the Western and Central Basins of Lake Erie (DNR-DOW 2012) (Figure 1). Sample collections of late juvenile white bass were immediately frozen and provided to Bowling Green State University. The fish were thawed, measured to the nearest 0.1 mm (SL), and weighed to the nearest 0.1 g. Of the 94 late-juvenile white bass that were collected in August, the majority were sampled at the Cleveland trawl sites (circled on Figure 1). The otoliths of 51 of these fish were analyzed with the LA-ICP-MS system. To determine which individuals to sub-sample for otolith trace elemental analyses the length frequency distribution was examined for the 94 fish collected and it was determined that the distribution was normal with a mean size of 110.8 mm (SE=1.26). The length distribution was divided into 20 mm SL length increments (5 bins, 40-140 mm) and individuals from the Cleveland trawl site were randomly sub-sampled for analysis in direct proportion to the total abundance in each length bin. This method was utilized to ensure that fish in rare size classes on the tails of the distribution would be sampled.

Otolith preparation of unknown-origin, August-sampled white bass was conducted with the same methods employed on June-sampled early-juvenile white bass, with the exception that during sectioning the embedded otoliths were sectioned to an initial thickness of 500 um before polishing due to their large size (1500-2000 um core to edge on longest axis). LA-ICP-MS analysis was conducted on the same date as the analyses for June samples and the methods remained the same. Briefly, a laser traverse was made from the dorsal edge of the otolith to the core along the longest axis of the transverse section of the otolith (core to edge). Data processing remained the same as for June samples with the exception that only the region from the otoliths primordial core to a point 200 um from that core was integrated and used for further analyses. This was done to determine what the chemical composition of the otolith was during the time period corresponding to the larval and early-juvenile life stage.

To establish normality of all data, which is required to meet assumptions of parametric analyses, *a priori* normality testing was conducted on all elemental concentration data. Elemental concentration data were transformed through Box-Cox best transformation analysis using JMP™ Statistical software. The best transformation for Sr:Ca ratios in August sampled white bass, (mmol Sr:mol Ca)$^{1.2}$ - 1) / 1.43678008493477); resulted in a normal distribution of the data (Shapiro Wilk W test $P > 0.05$). This transformation was applied to Sr:Ca ratios for all further parametric analyses.

To determine the natal origin of August juvenile white bass collected in the Central Basin of Lake Erie, the concentrations of the elements assayed from known-origin juvenile white bass (Sandusky and Maumee) sampled in June were used to train a linear discriminant function analysis model. The best model used only the Sr:Ca ratio to classify unknown origin individuals. The model assigned group membership to each unknown origin individual based on the Sr:Ca ratio present in the inner area of the otolith that was integrated (core to 200 um) and the relationship of that ratio to that of known-origin individuals. To assess the predictive power of the analysis, for these June-collected fish, I examined posterior probabilities by a jackknifed assessment of cross validated reclassification accuracy (Walther and Thorrold 2008). The model exhibited 100% re-classification accuracy. Additions of other elements to the model did not improve classification accuracy or change any individual classifications. This classification modeling approach allowed me to determine watershed of origin for all unknown-origin juvenile white bass.

Emigration Dynamics

When an early-juvenile white bass migrates out of these nursery habitats into the open waters of Lake Erie, there is generally a shift in elemental concentrations in the otolith concordant with changes in water chemistry (Reichert et al. 2010; Hayden et al. 2011). Thus, identifying the location on the otolith where this distinct shift occurs and knowing the standard length-otolith length relationship, I determined the size at which individual juvenile white bass emigrated from nursery habitats.

To determine where along the laser ablation traverse the shift in otolith chemistry associated with movement between water masses occurred, a recursive partitioning model was utilized; this is a form of regression and classification tree analysis (Guadard et al. 2006). The analysis uses continuous response and predictor variables (i.e. concentration of Sr and distance traversed along the laser ablation transect) to quantify the difference in sums of squares between means of two groups. The predictor variable (um traversed) was then split at the point of a regime shift (maximum difference in means of response variable). This was achieved by maximizing the log worth, which is related to the p-value associated with the sums of squares (Gaudard et al. 2006). The recursive partitioning model provided a systematic and structured tool for detecting trace elemental chemistry shifts and allowed detection of the location of a chemistry regime shift along the laser ablation transect.

The standard length of individual fish when they left their respective nursery habitats was estimated by creating a model that predicted fish length from otolith size. Micrographs of each otolith used in the micro-chemical analyses were taken using a Leica transmitted light microscope at magnifications between 100-1200x. These micrographs were stitched together using Sigma Scan Pro 5™ image analysis software and measurements of otolith radii were taken from the core of the otolith along the longest transverse axis to the edge (core to rostrum point) using ImageJ (NIH) image analysis software. These measurements were then used in conjunction with fish standard length data to produce a regression model that predicted fish length as a function of otolith radius.

While linear regression models of fish size to scale size are commonly accepted, there appears to be a decoupling of the relationship between otolith size and somatic size, and this is especially evident in larval and juvenile life stages (Hare and Cowen 1995). These relationships between the somatic size of a fish and its hard structures have been examined in depth (Francis 1990). The rationale behind the decoupling of the otolith size/somatic size relationship in early life stages is suggested to be because of the substantial shifts in physiology and morphology that takes place during early life history periods of fish development (Campana 1990). These physiological, ontogenetic-shift induced changes in the relationship between somatic size and otolith size can be accounted for and the variability minimized, by developing a model that changes the slope of the regression in concert with the ontogenetic changes experienced during development (Ladig et al. 1991; Hare and Cowen 1995). To account for the change in the relationship between fish length and otolith radius I developed a third order polynomial regression model that fit the actual biological data and predicted fish length from otolith radius for the entire period from hatch to the late juvenile stage for this population. The regression model parameters were:

$$(\text{Fish Length mm}) = -26.52558 + (0.1005349 * \text{otolith radius}) - (4.6047e^{-6} * (\text{otolith radius} - 1027.27)^{2}) - (3.2715e^{-8} * (\text{otolith radius} - 1027.27)^{3}).$$

Where otolith radius is in microns from core to posterior rostrum edge on a transverse otolith section ($r^2 = 0.983$).

With this relationship established I was able to use the size of the otolith at the time of chemistry shift, identified by the recursive partitioning model, to predict fish length at the time of emigration from the Sandusky and Maumee water masses. The size of white bass at emigration was subsequently compared between individuals classified as Sandusky origin and Maumee origin using a one-way ANOVA ($\alpha = 0.05$).

Spatial Model of Migration Dynamics and Stock Mixing: Lake Erie White Bass

To determine the total contributions from each spawning stock to the entire Ohio Lake Erie YOY white bass population, I constructed a Geographic Information System (GIS)-based spatial model. The goals of the modeling were to: 1) quantify the total size of the Ohio Lake Erie YOY white bass population in 2011; and 2) assess the proportional contributions of the Sandusky spawning-stock to the Ohio Lake Erie population.

As a prerequisite to this modeling approach, several assumptions were made. First, no individuals from the Sandusky spawning stock migrated from the mouth of the Sandusky Bay to the Western Basin. Secondly, individuals comprising the Western Basin population were produced in the Maumee River, the Detroit River, or the open waters of the Western Basin.

These assumptions are supported by evidence in tagging studies that show riverine spawning fish produced in the Western Basin of Lake Erie generally migrate eastward to the Central Basin (Wang et al. 2007). Further, water currents in this area, although strongly influenced by seiche activity and wind, are generally to the eastward; during the spring of 2011 currents generally followed this pattern (Bartish 1987, NOAA GLERL 2012).

Annually, the Ohio Division of Wildlife Fairport and Sandusky Fisheries research units conduct an extensive trawl survey to assess YOY fish abundance in August and September. Data from these agencies was obtained which described number of fish captured at each trawl location, date of survey, spatial location of trawl survey sites, net size, length of tows, and speed of tows. From these data, YOY white bass catch per hectare trawled (CPHT) was calculated at each survey location.

The Ohio trawl survey was conducted by two survey vessels. The Western Basin survey was conducted by the (R/V) Explorer and the Central Basin survey was conducted by the (R/V) Grandon. Comparison of trawl data between different vessels is problematic because of differences in fishing efficiency (van Salazay and Holt 2001). An inter-calibration study was conducted with the ODNR, Ontario Ministry of Natural Resources (OMNR), and United States Geological Survey (USGS) vessels in 2006 to determine relative fishing efficiency (Tyson et al. 2006). The purpose of the application of fishing power correction (FPC) factors was to standardize catches from other Lake Erie research vessels to the OMNR survey vessel the (R/V) Keenosay. Tyson et al. (2006) showed that the (R/V) Grandon generally fished at higher efficiency for most YOY fish species. Specifically, YOY white bass were captured with significantly greater efficiency by the (R/V) Grandon, so a FPC factor of 0.679 was determined to be necessary (i.e., applied to the RV Grandon data to estimate downwards the abundance of YOY white bass). I reviewed fishing efficiency for several similar species of which larger numbers of individuals were sampled to better interpret results from the study. FPC factors determined by Tyson et al. (2006) for the (R/V) Grandon (Central Basin) for YOY white perch and yellow perch were 0.699 and 0.829 respectively. Since the FPC for the YOY white bass sampled by the (R/V) Grandon was significant and corresponded closely to values for similar species I applied the FPC factor of 0.679 to the Central Basin density estimates. Results of the study also determined that the (R/V) Explorer (Western Basin) had a lower sampling efficiency for YOY white bass than the R/V Keenosay and thus a FPC factor of 3.203 was called for to adjust the catch data for comparison directly with the R/V Keenosay; however, this FPC was not significantly different from 1.0 (FPC=1.0 implies no correction is needed) (Tyson et. al 2006). During the inter-calibration study low numbers of white bass were sampled, which resulted in large 95% confidence intervals for this species ((R/V) Explorer 95% C.I. FPC = (-0.81) to (+5.60)) (Tyson et al. 2006). The (R/V) Explorer FPCs for YOY white perch and yellow perch were 1.121 and 0.933 respectively. Since the FPC for YOY white bass sampled by the (R/V) Explorer was not significantly different from 1.0, and sharply contrasted with values obtained for similar yet more abundant species; I did not apply a correction factor to CPHT estimates from the (R/V) Explorer.

To calculate CPHT, length and speed of tows was converted from nautical miles to metric units, multiplied by net area, and converted to hectares towed. Number of individuals captured was then divided by area towed to obtain a value for CPHT at each trawl survey location. This estimate of CPHT only accounts for individuals that were associated with the benthic portion of the lake, which the net sampled, and individuals that did not avoid the gear.

Data from mid-water trawls suggest that YOY white bass also utilize the pelagic portion of the water column; therefore, total abundance estimates obtained by this modeling approach should be viewed as minimum estimates (ODNR DOW unpublished data).

Longitudinal and latitudinal point density data were input into ARC GIS 10.1™ (ESRI) for spatial analyses. GPS data were converted to decimal degree data and projection was achieved using the 1984 World Geodetic System. A base map for Lake Erie, Ohio was constructed by utilizing shape files (.shp) on Lake Erie bathymetric contours, Great Lakes shorelines, Lake Erie near shore and offshore areas, and Ohio state and county boundaries (see Appendix A for metadata). All X, Y point density data were overlaid on this base map for further analyses.

The geo-processing associated with construction of this model was performed using the ARC GIS 10.1 Spatial Analyst™ and Geostatistical Analyst™ extensions. Briefly, a polygon was created using overlay tools that included only the Ohio waters of Lake Erie (LEOHIO). The West and Central Basins were split at a point extending from Point Pelee, ON to the mouth of the Huron River, OH. This is the boundary used to separate the Western (District 1) and Central Basin (District 2) Ohio management units (ODNR 2012).

Interpolation of August and September point density data was accomplished using the Inverse Distance Weighted (IDW) tool in the Geostatistical Analyst™ extension (Johnston et al. 2001). This tool is a local polynomial exact interpolator that uses a weighted average for deterministic multivariate interpolation of density values at un-sampled locations by utilizing known values at sampled points (Johnston et al. 2001). This method assumes that values that are closer together are more similar to each other than those that are farther apart. As distance increases the influence of neighboring values decreases. The influence of neighboring points as distance increases can be controlled by the power term (p); as p becomes larger, distant points have less influence on predicted values. To determine the optimal value of p, the Geostatistical Analyst™ extension was used to calculate Root Mean Square Prediction Error (RMSPE) for each value of p through a resampling procedure and I utilized the value that produced the prediction surface with the lowest RMSPE (Johnston et al. 2001). A surface was created that utilized these methods to predict the density of juvenile white bass over the sampling extent covered by the August trawling survey. I clipped this extent to cover areas only within the bounds of the Ohio waters of Lake Erie. This provided an interpolated surface that estimated the density of juvenile white bass within the Ohio waters of Lake Erie.

Each cell in the raster grid for both August and September was assigned a floating point value for white bass density through the application of the above methods. Floating point values do not produce an attribute table that can be viewed and exported in the ARCMAP table of contents. To obtain statistics on cell values and develop a population estimate, "Extract Raster Zonal Statistics" and "Export to Excel" tools in the Xtools Pro™ extension were utilized (Data East). This provided data describing each grid cell's estimated value and summary statistics for the Western and Central Basin white bass populations in August.

RESULTS

Water Chemistry

Water samples collected from the Central Basin of Lake Erie, Sandusky Bay, and Maumee Bay in the spring of 2011 indicated that significant differences in Sr:Ca ratios were present. Ratios of Sr:Ca were significantly different between Lake Erie, Sandusky, and Maumee systems (ANOVA F=54.75, df = 2, 24, $P<0.0001$, and Tukeys HSD). The ratio of Sr:Ca in Sandusky Bay (9.540 mmole Sr:mole Ca^{-1}, S.E= 0.689 , n=22) was 1.6 times greater than observed in Maumee Bay (5.979 mmole Sr:mole Ca^{-1}), S.E.= 0.844 , n=2) and the Sandusky Bay had Sr:Ca ratios 4.4 times greater than Lake Erie water samples (2.180 mmole Sr: mole Ca^{-1}; S.E.= 0.255, n=3) (Figure 2).

Spawning Stock Elemental Signatures - Maumee and Sandusky Watersheds 2011

Significant differences in Sr:Ca ratios were detected in early-juvenile white bass otoliths collected within the Maumee and Sandusky nursery habitats (F=123.17 df=2,18 $P<0.0001$) (Figure 3). Known-origin YOY early-juvenile white bass from Sandusky and Maumee bays had a mean concentration of Sr equal to 1776.27 ug $Sr \cdot g^{-1}$ $CaCO_3$ (SE= 73.768, n=10) and 921.09 ug $Sr \cdot g^{-1}$ $CaCO_3$ (SE= 22.267 n=10), respectively. The observed difference in otolith Sr concentration allowed me to differentiate the trace elemental signatures of fish produced in the Sandusky and Maumee systems using only this element. I developed a LDFA model to classify individual white bass into river of origin spawning-stock groups based on the Sr:Ca ratio assayed in the sagittal otolith. The model produced 100% jackknifed reclassification accuracy of individuals.

Stock Composition Analysis of the August Central Basin White Bass Population

The primary objective of the otolith elemental analyses was to conduct a Stock Composition Analysis (SCA) to determine the river system of origin of white bass that comprised the Central Basin population in August 2011. Analyses of elemental signatures of juvenile white bass collected at the Cleveland trawl sites in the Central Basin of Lake Erie during August 2011 indicated that 80.4% (41 of 51) of sampled individuals had been produced in the Sandusky River/Bay system (Figure 4). This SCA was accomplished by utilizing the LDFA model developed from known origin white bass sampled in the Sandusky and Maumee Bays in June 2011 using a forward stepwise procedure. Predicted probabilities of group membership of unknown origin white bass ranged from 79.9% to 100% with a mean predicted probability of 99.5%.

In June 2011 white bass with known origins in the open waters of Lake Erie or the Detroit River (Detroit water mass) could not be obtained, and thus, the differentiation of Maumee origin individuals and Detroit water mass origin individuals was not possible. However, water chemistry data from the open waters of Lake Erie suggest that otolith Sr:Ca ratios of individuals with natal origins in the Detroit waster mass should be lower than the Sr signature produced in Maumee origin individuals. By examining the otolith transect data I was able to anecdotally make the determination of natal origin for the 10 individuals classified as Maumee origin by the LDFA. Careful observation of the shift from moderate Sr concentration (characteristic of the Maumee water mass) to low Sr concentration (characteristic of the Detroit water mass) as the laser ablation traverse moved from the core region towards the edge was characteristic of those fish that likely emanated from the Maumee water mass (n=7). A consistent and low Sr concentration was present across the laser ablation traverse in otoliths from two individuals. In one individual a low Sr concentration was observed in the inner region of the otolith, followed by a shift to high Sr concentrations. I assumed that these individuals had been produced in the Detroit water mass (n=3).

Emigration Dynamics

Results of recursive partitioning model analysis indicated that the radius of the otolith at the time of emigration from the Sandusky nursery habitat ranged from 524.4 um-1326.0 um with a mean value of 830.5 um (SE=39.06 n=41). When these data were input on the fish length: otolith size polynomial regression, mean length (SL; mm) at emigration for the Sandusky stock was estimated at 56.5 mm (SE=3.44 n=41); with a range of emigration sizes between 28.2 mm and 105.5 mm (n=41) (Figure 5). These results suggest that the Sandusky origin stock of juvenile white bass was present in the Sandusky water mass for substantial amounts of time before emigration to the open waters of the Central Basin.

The fish classified as non-Sandusky origin (n=10) revealed three contrasting trends in otolith elemental signature shifts. One group (n=7) emigrated from an area of moderate Sr concentration (Maumee River) to an area of low Sr concentration at a small size (mean size = 10.2 mm; SE=7.01; range 5.0-15.95 mm). This group emigrated from nursery habitat to the open waters of Lake Erie at a significantly smaller mean size than individuals with origins in the Sandusky system (ANOVA df =2,50 F=35.279, P<0.0001). The second group (n=2) exhibited no shift in Sr concentration, which remained stable at low levels consistent with signatures produced in the open lake or Detroit River. A third individual (n=1) exhibited a low Sr concentration during the larval and early-juvenile period and then displayed a chemistry shift to a high Sr concentration, followed by a shift back to low Sr concentration. This same pattern was observed in juvenile yellow perch (*Perca flavesences*) in Lake Erie and it was hypothesized that this represented a movement from the open lake into the Sandusky water mass (Pangle et al. 2010).

Spatial Model of Migration Dynamics and Stock Mixing: Lake Erie White Bass

Results of spatial modeling for estimation of the YOY white bass population size in the Ohio waters of Lake Erie, confirmed the historical observations from trawl surveys that substantial populations of white bass were present in both the Western and Central Basins during August (Figure 8). The best model had a RMSPE of 54.39. The model estimated that 56.6% of the total Ohio white bass population was located in the Western Basin during August while the remainder of the population was located in the Central Basin. The model estimated a juvenile white bass population size in August of 1,200,477 for the Ohio waters of Lake Erie (Table 1). Combination of the of the August Central basin population SCA, which indicated that 80.4% of the August Central Basin population was comprised of individuals with origins in the Sandusky system, and the assumption that none of the white bass in the Western Basin were produced in the Sandusky system, resulted in the estimation that the Sandusky spawning stock contributed 34.6% of the total Ohio juvenile white bass population in August 2011.

DISCUSSION

Water Chemistry

I found significant differences in water Sr:Ca ratios of Maumee Bay, Sandusky Bay, and the open waters of Lake Erie in 2011. Inter-annual variation in Sr chemistry has been observed in these systems due to annual variations in precipitation patterns. However, over an eighteen year time series the same Sr chemistry hierarchy has remained intact (Pangle et al. 2010). The Sandusky watershed produces the highest Sr concentration of all Lake Erie tributaries, the Maumee produces a moderate Sr concentration, and the Detroit water mass consistently produces low Sr concentrations. Strontium is known to be incorporated into the $CaCO_3$ matrix of the otolith in proportion to the ambient elemental concentrations found in the environment (Fowler et al. 1995, Collingsworth et al. 2010). Thus, fish which have major spawning stocks that utilize the Maumee and Sandusky rivers for reproduction, such as white bass and walleye, lend themselves to investigations of stock structure and migration dynamics through the utilization of otolith micro-chemical analyses.

Spawning Stock Elemental Signatures - Maumee and Sandusky Watersheds 2011

The characterization of juvenile white bass otolith micro-chemical signatures produced in the Sandusky and Maumee Bays during 2011 confirmed the conclusions of other studies in Lake Erie. That is, significant differences in water chemistry (specifically Sr concentration) between the Sandusky and Maumee water masses produce significantly different otolith micro-chemical signatures in fish with natal origins in these different spawning areas (Bigrigg 2006, Pangle et al. 2010, Hayden et al. 2011). Sr:Ca ratios in otoliths of white bass produced in the Sandusky water mass were nearly double those of white bass produced in the Maumee water mass. This difference in Sr concentration allowed me to predict the natal origins of white bass spawned in the Sandusky system with great confidence (LDFA, near 100% discrimination, P <0.0001).

Stock Composition Analysis of the August Central Basin White Bass Population

The 2011 spawning season was characterized by being one of the highest discharge springs on record (USGS NWIS 2012). The Sandusky spawning stock produced the majority of white bass that recruited to the Central Basin population. In August 2011, 80.4% of the white bass that were sampled in the Central Basin of Lake Erie were produced in the Sandusky system. The differentially greater production of recruits emanating from this system suggests that the Sandusky spawning-stock experienced favorable conditions for survival during the early life stages. The hydrodynamic and physical characteristics of this system may have been the reason for differentially greater contributions during this extreme flow year. If larvae produced in the Sandusky system were retained within the turbid and productive Sandusky Bay nursery habitat this likely resulted in increased growth and survival by individuals. Increased survivorship of individuals likely resulted in the cumulative increase in proportional contributions to the year class by this spawning stock.

The larval life stage of *Morone spp.* is prone to extremely high mortality. In a mark recapture study of larval striped bass (*Morone saxatalis*) over three days in the Patuxent River mortality exceeded 70% (Secor et al. 1995). Many factors are involved in the survival of larval and juvenile fish (Letcher et al. 1996). Larvae must be transported to nursery habitat that provides ample supplies of zooplankton after the yolk sac is absorbed and predation must be avoided (Scharf et al. 2000, Jones et al. 2003). Several authors have suggested that high river discharge may have a negative effect on larval survival due to turbulent destruction and egg suffocation caused by high sediment loads which are typically associated with high discharge events (Limburg 1996, Mion et al. 1998). In contrast, other studies have found that low discharge during larval transport in Lake Erie tributaries may have a negative effect on recruitment due to starvation suffered during increased river residence times and increased predation in nursery areas due to lower turbidity (Jones et al. 2003, Reichert et al. 2011). It has also been suggested that the mortality response by larval fish to discharge perturbations may vary depending on the nature of the system; where threshold levels for and responses to abiotic forcing are dictated on a system by system basis (Limburg et al. 1999).

Emigration Dynamics

To test the hypothesis that juvenile white bass utilized the Sandusky nursery area for considerable durations of time, even during the extreme flows that characterized the 2011 season, data was combined from the otolith micro-chemical analyses with a micro-structural analysis. This approach allowed estimation of the length at which individuals emigrated from their respective water masses of origin. These results indicated that of the individuals that survived to recruit to the August Central Basin population, the mean length at emigration from the Sandusky water mass was 56.5 mm. Contrastingly, the mean length at emigration of surviving individuals from the Maumee spawned stock was 10.2 mm.

Recent work in Lake Erie has shown that larval and juvenile fish which remain in the warm, productive, and turbid river plumes, such as the the Maumee and Sandusky nursery habitats, experience improved chances of survival (Reichert et al. 2010). These authors suggest that high turbidity environments like those found in river discharge plumes reduces top-down predation pressure and that is a major factor influencing differential survival. Bottom-up processes have also been hypothesized to have effects on the survival of larval and juvenile fish (Ludsin et al. 2001). Turbid river plumes are often high in nutrients which can sustain large zooplankton communities (Grimes and Kingsford 1996). As turbidity increases the amount of thermal energy absorbed from sunlight also increases (Kara et al. 2003). Water temperature can directly and indirectly effect recruitment due to both top-down and bottom-up processes. Several studies have found that water temperature plays a strong role in the recruitment success of *Morone spp*. Increased water temperature can lead to earlier production of prey resources (Richardson 2008). Simultaneously, increased water temperature increases metabolic rates and growth of larval and juvenile fish, which in turn shortens the amount of time that individuals are highly susceptible to predation (Rutherford and Houde 1995, Secor and Houde 1995, Limberg et al. 1999). The majority of individuals that recruited to the August Central Basin population remained in the turbid and productive Sandusky water mass for substantial periods of time before emigration occurred. The results here confirm the findings of other studies which show increased recruitment due to utilization of turbid river plumes (Reichert et al. 2010). Further, results here demonstrate that the Sandusky system is able to retain larval and juvenile fish during extreme discharge events.

The Sandusky Bay acts like an estuary hydrodynamically; there is inflow of lake water caused by wind driven seiche events (Brant and Herdendorf 1972). During seiche events, where lake water invades the lower bay, an estuarine turbidity maximum (ETM) is created at the lake:bay water interface (Bedford 1992). The ETM zone in Sandusky Bay was characterized by high turbidity and a change in sediment type due to the scouring action at the interface between water masses, about 2 km into the lower bay (Bedford 1989).

Several studies have documented the effects of ETM zones on the retention, recruitment, feeding, and growth of *Morone* larvae in estuarine environments (North and Houde 2003, Shoji et al. 2005, North and Houde 2006, Maartino et al. 2007). In the Chesapeake Bay the ETM zone is characterized by high turbidity and an abundance of zooplankton because sediment and organisms are concentrated where the river outflow meets the tidal inflow (North and Houde 2003). This hydrodynamic characteristic also makes it more likely that larval fish are not exported from the system; rather, they are retained in the ETM zone. The ETM zone acts as refugia from predators due to high turbidity, it is rich in zooplankton prey, and has a high warming rate (North and Houde 2006). These studies also found that during years of high discharge the strength and extent of the ETM zone was greater, due to more frequent storm events causing a greater degree of wind forcing. The strength of the ETM zone in the Chesapeake Bay had a significant positive relationship with feeding rate, growth rate, and recruitment of *Morone* larvae (North and Houde 2001, Shoji et al. 2005). The presence of a strong ETM zone in the Sandusky Bay during years of high storm activity may allow larval fish to be retained in the system and respond with lower mortality rates than larvae produced in other Lake Erie production areas. The combination of the Sandusky Bay's propensity for retention of larval and juvenile fish and favorable growth and survival factors associated with remaining in a warm turbid nursery habitat for extended periods, allowed the Sandusky spawning stock of white bass to prosper under the extreme flow conditions of 2011.

Spatial Model of Migration Dynamics and Stock Mixing: Lake Erie White Bass

The spatial modeling of the 2011 juvenile white bass population illuminated the importance of the Sandusky spawning stock on a lake wide basis. I estimated that during the extreme flows characteristic of the 2011 spawning season the Sandusky spawning stock produced 34.9% of the total August recruitment contribution to the Ohio juvenile white bass population.

During 2011 there was a significant difference in the mean size of juvenile white bass between the West and Central basin populations during August (73.7 and 110.8 mm mean SL, respectively) (J. Tyson personal communication 3-7-2012). Predation mortality has been shown to have much greater consequences for smaller individuals due to gape limitation in piscivorous predators (Sougard 1997). If spawning stock specific differential mortality occurred after the August survey the estimate of the Sandusky spawning stocks total recruitment contribution as identified by the spatial model would actually be an underestimate.

Annual variation in spawning-stock specific recruitment contributions

Clearly, the Sandusky spawning stock was a substantial contributor to the Lake Erie white bass population under the extreme high discharge conditions that were experienced during the 2011 spawning season. This was likely due to the hydrodynamic properties of the Sandusky Bay which allowed it to retain early life stages in productive habitat. However, the 2011 spawning season produced a very weak overall year class. The West Basin District 1 2011 mean CPHT was 67.4% below the 20-year mean and the Central Basin District 2 mean CPHT was 61.7% below the 20-year mean (ODNR-DOW 2012). During years characterized by less extreme discharge conditions other spawning stocks may produce greater proportional contributions to the lake wide population. Cumulatively, greater inputs from multiple spawning stocks likely results in strong year classes. Thus, during highly successful recruitment years the proportional contribution from the Sandusky spawning stock is likely less dominant.

Conclusions

In 2011 the Sandusky spawning group of white bass was able to make substantial contributions to the year class, even during record discharge conditions. It is likely that this was made possible by the unique hydrodynamics of the Sandusky system. A combination of high productivity and protection from advection due to ETM zone physics made it possible for Sandusky origin larval and juvenile white bass to remain in optimal nursery habitat for extended periods of time before emigration to the Central Basin. Migration was delayed until juvenile white bass were larger, and thus, better able to avoid predation and more successfully feed piscivorously. Results herein suggest that delayed emigration had positive influences on recruitment. This study underscores the importance of managing and maintaining the distinct spawning-stocks that utilize different habitats in Lake Erie as distinct groups. In the presence of increasing environmental stochasticity caused by global climate change, maintaining a diverse inventory of spawning stocks buffers Lake Erie fisheries from total losses of year classes. Under differing abiotic conditions some stocks may fail to produce recruits while others thrive; thus, the inherent unpredictability of abiotic conditions dictates that a diverse suite of spawning stocks is critical to maintaining healthy fish populations.

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FIGURES:

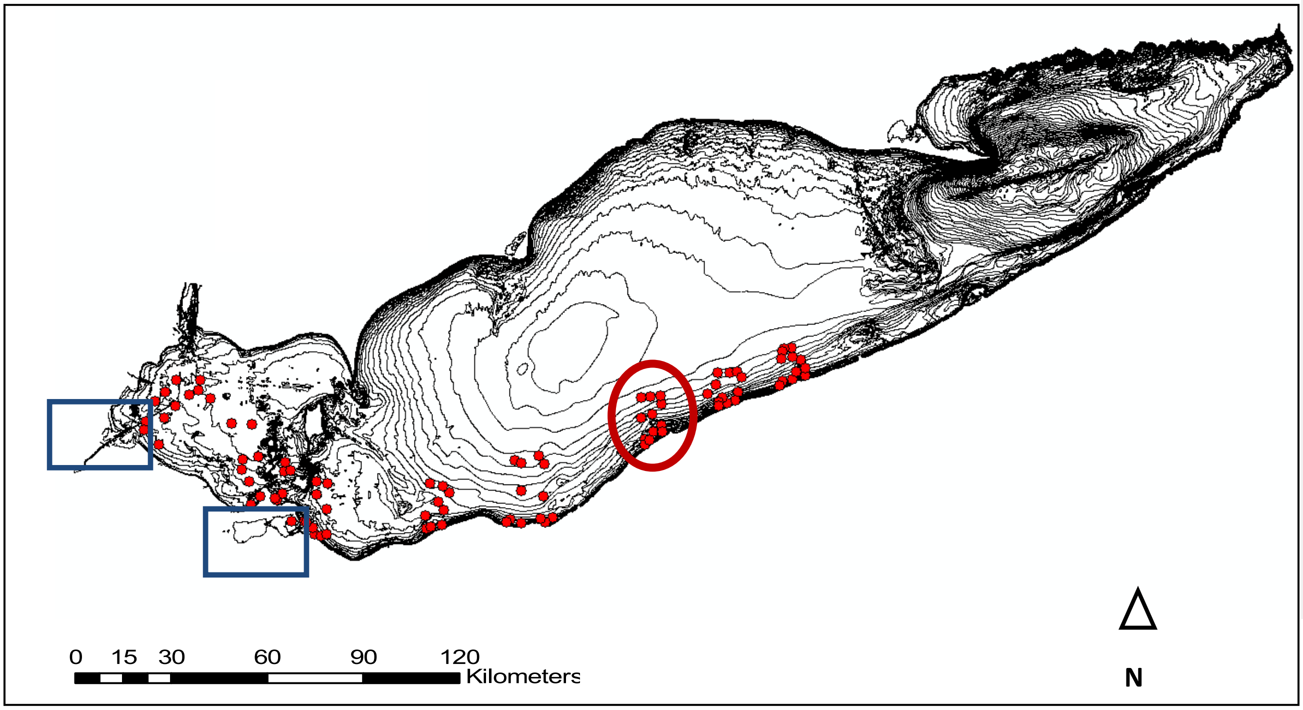

Figure 1. Locations of Maumee and Sandusky bays (left and right rectangles respectively). Early-juvenile white bass were collected here in June 2011 to determine micro-chemical signatures produced in these production areas. Standard trawl sampling sites (red dots) surveyed by the ODNR-DOW in August 2011 and subset of trawl sites (red circle) where late-juvenile white bass were collected for SCA analyses (n=51).

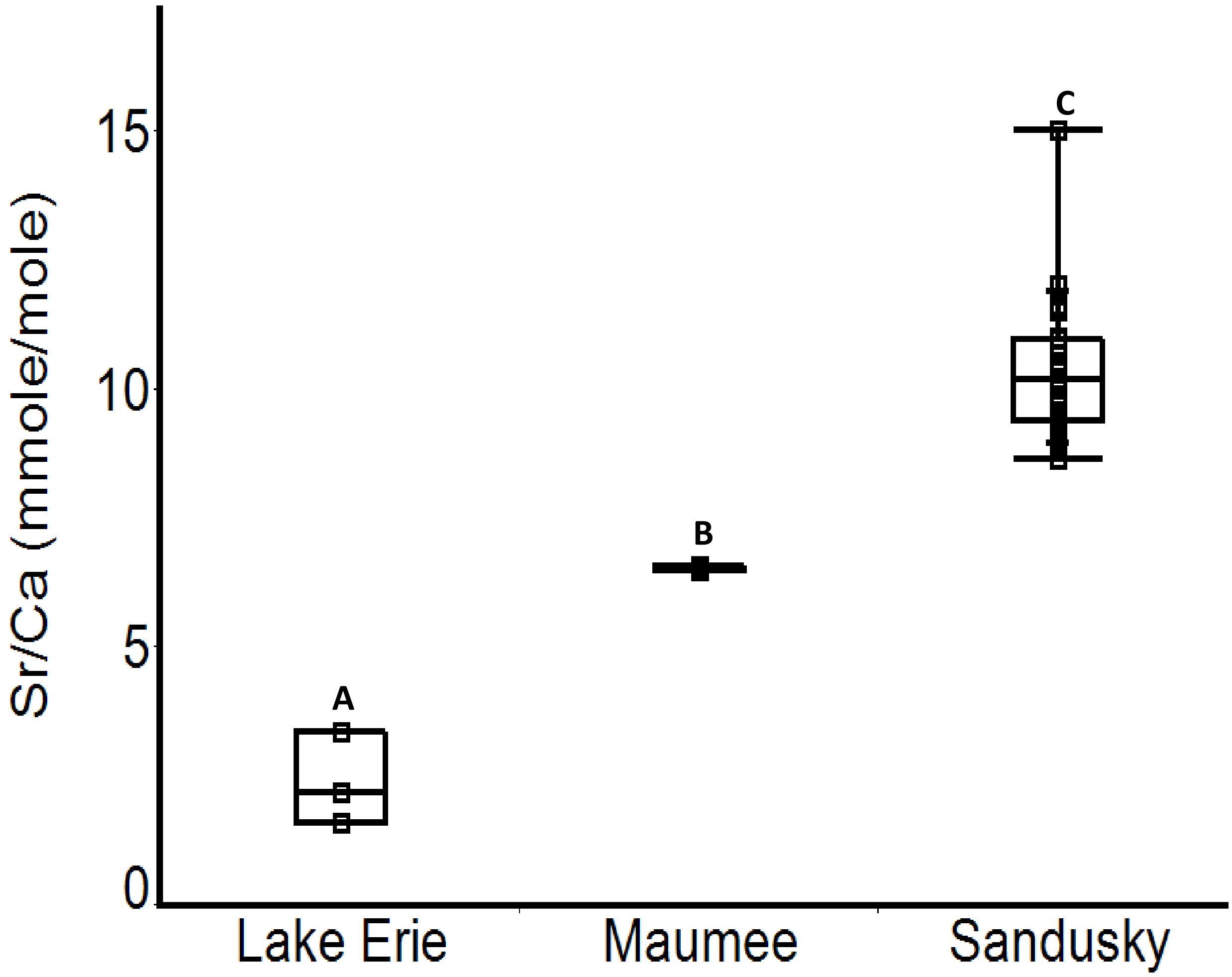

Figure 2. Boxplots of water Sr:Ca (mmole:mole) ratios observed in the Central Basin of Lake Erie (n=3), Maumee Bay (n=2), and Sandusky Bay (n=22) during spring 2011. Boxes represent 25th and 75th percentile, center horizontal line represents the median, minor hash marks represent the 10th and 90th percentiles, and whisker ends represent range. Significant differences in Sr:Ca ratio are denoted by different letters (one-way ANOVA with means comparison by Tukey's HSD F=54.75, df = 2, 24, $P<0.0001$).

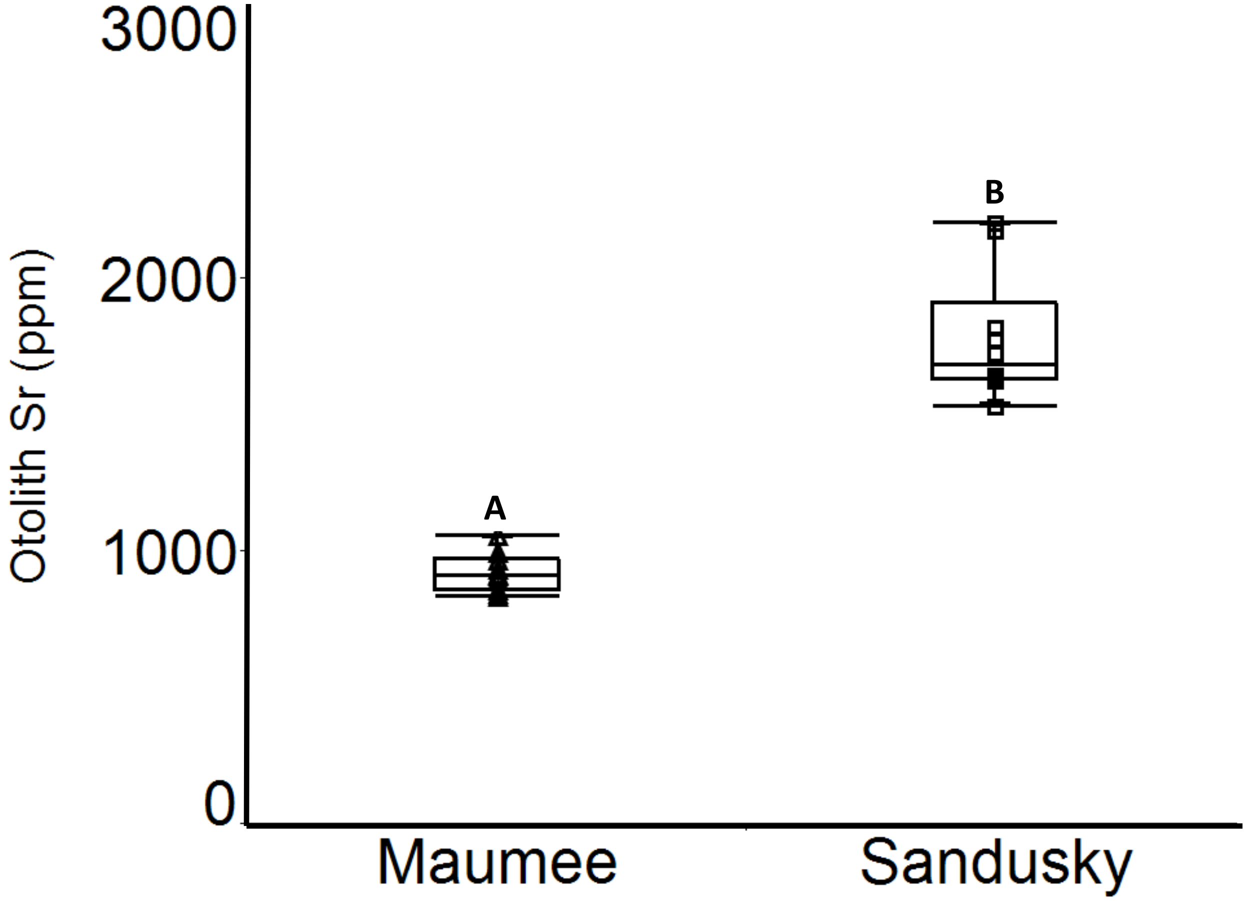

Figure 3. Box plots of otolith Sr concentration (ug Sr:g^{-1} Otolith) of known-origin juvenile white bass sampled in the Maumee River (n=10) and Sandusky River (n=10) during June 2011. Boxes represent 25th and 75th percentile, center horizontal line represents the median, minor hash marks represent the 10th and 90th percentiles, and whisker ends represent range. Different letters denote significant differences (one-way ANOVA ; F=123.169, df 2,18 P<0.0001).

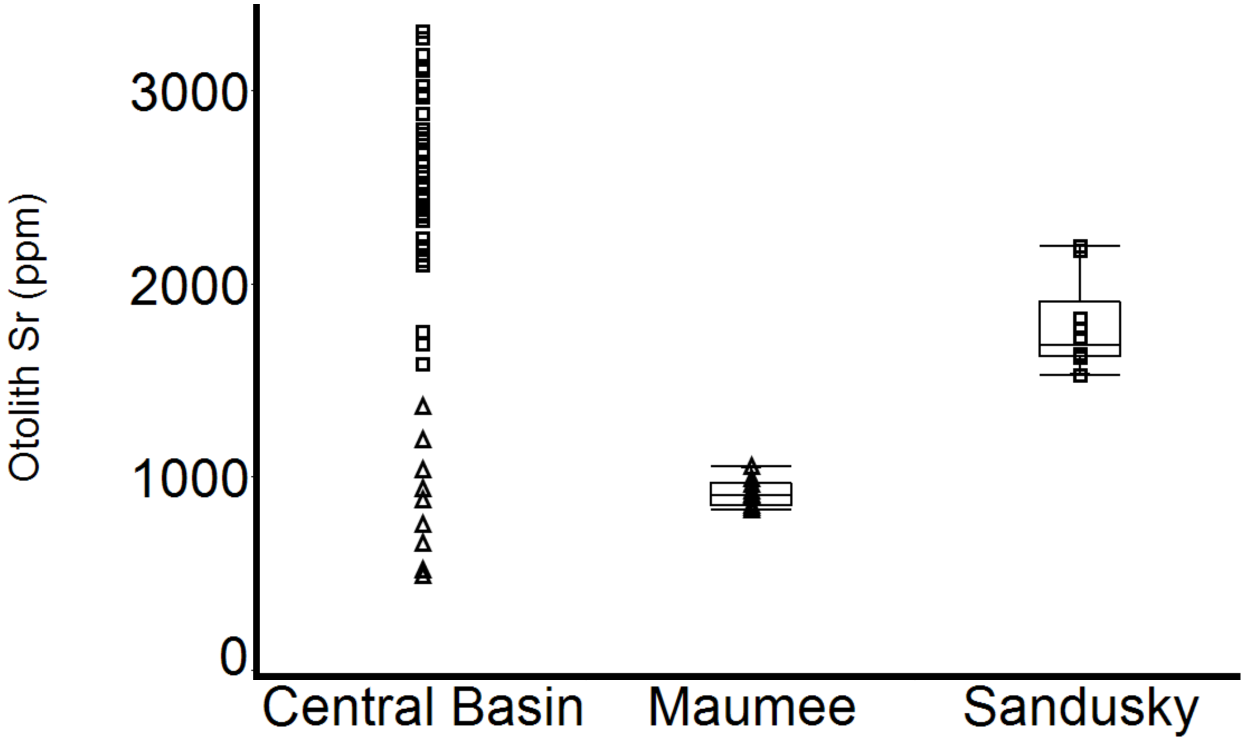

Figure 4. August 2011 Central Basin individuals with unknown-origins (n=51) were classified to spawning stock of origin based on otolith Sr concentrations (ug Sr:g^{-1} Otolith) using LDFA. Squares indicated classification to the Sandusky spawning-stock (n=41). Triangles indicate classification to the Maumee spawning-stock (n=10). Known-origin Maumee and Sandusky individuals are shown to the right with quantile plots for reference (Figure 3).

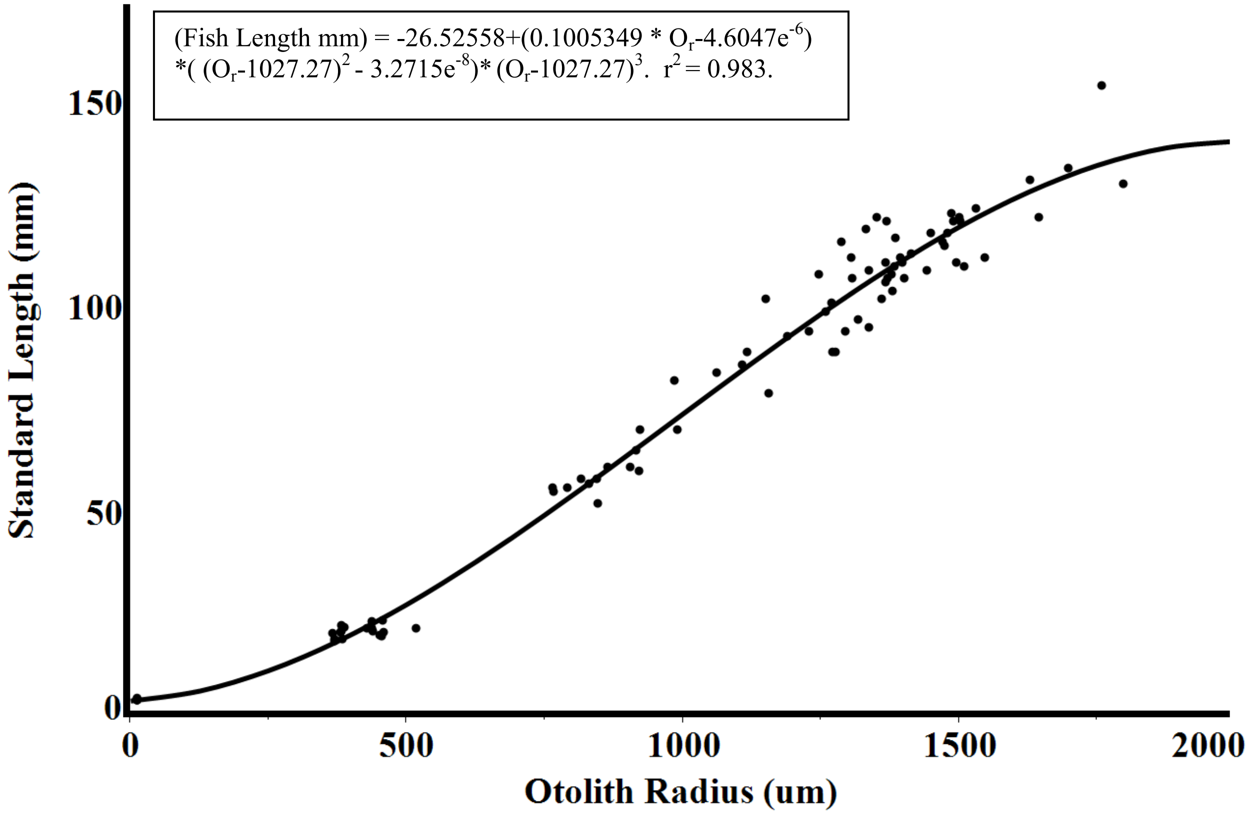

Figure 5. Polynomial regression model of the relationship between white bass length (SL mm) and otolith radius (um from core to edge of rostrum tip). The slope of the regression parameter changes following ontogenetic changes that occur in the somatic size: otolith size relationship during the transition from the larval to the juvenile life stages (n=72).

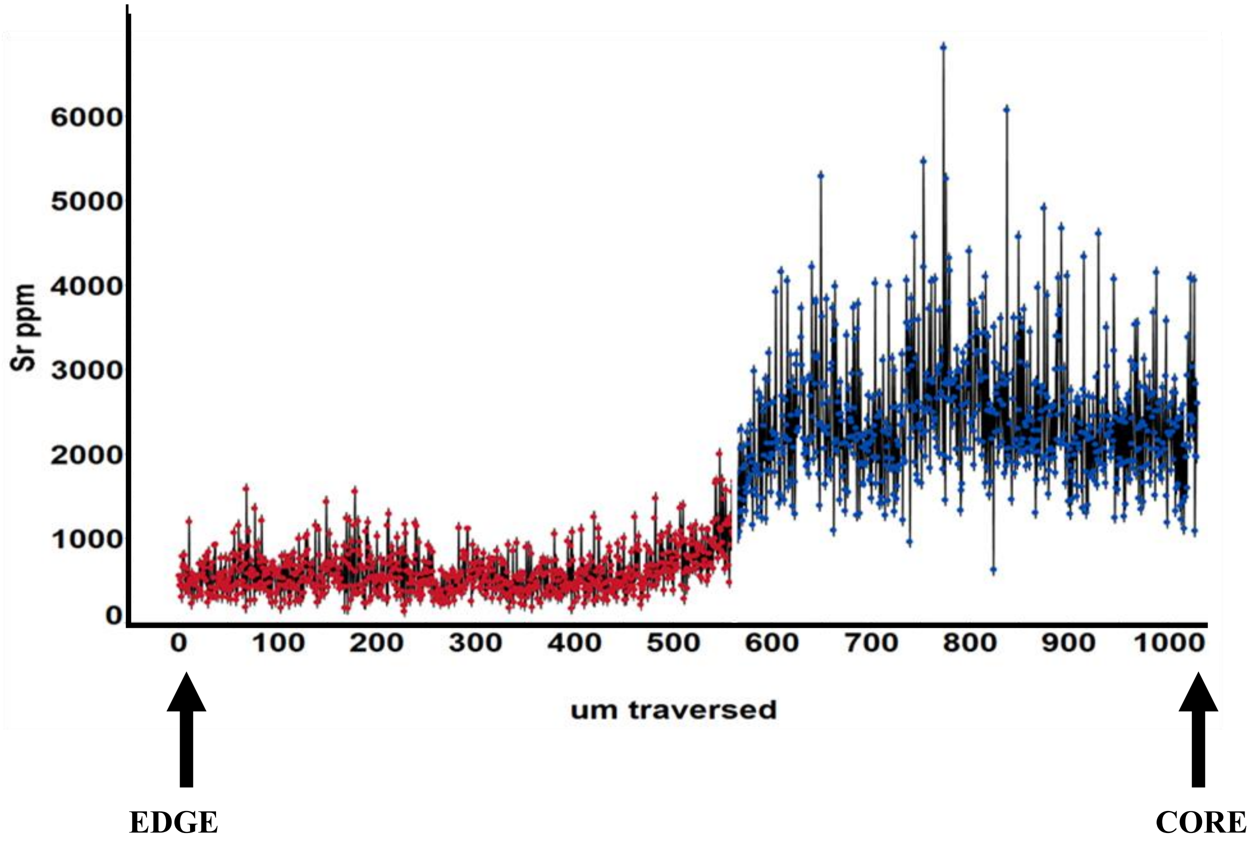

Figure 6. Laser ablation traverse from core to edge (right to left) on juvenile white bass otolith sampled in the Central Basin of Lake Erie in August 2011. Elevated Sr concentrations near the core indicate this individual was produced at the Sandusky spawning site. The Sr chemistry regime shift that corresponds with emigration into the Central Basin was identified by a recursive partitioning model(blue to red). The model estimated that this individual left the Sandusky water mass with an otolith radius of 564um. These data were then input into the fish length: otolith size model (Fig 5) to estimate fish size at emigration for each individual collected.

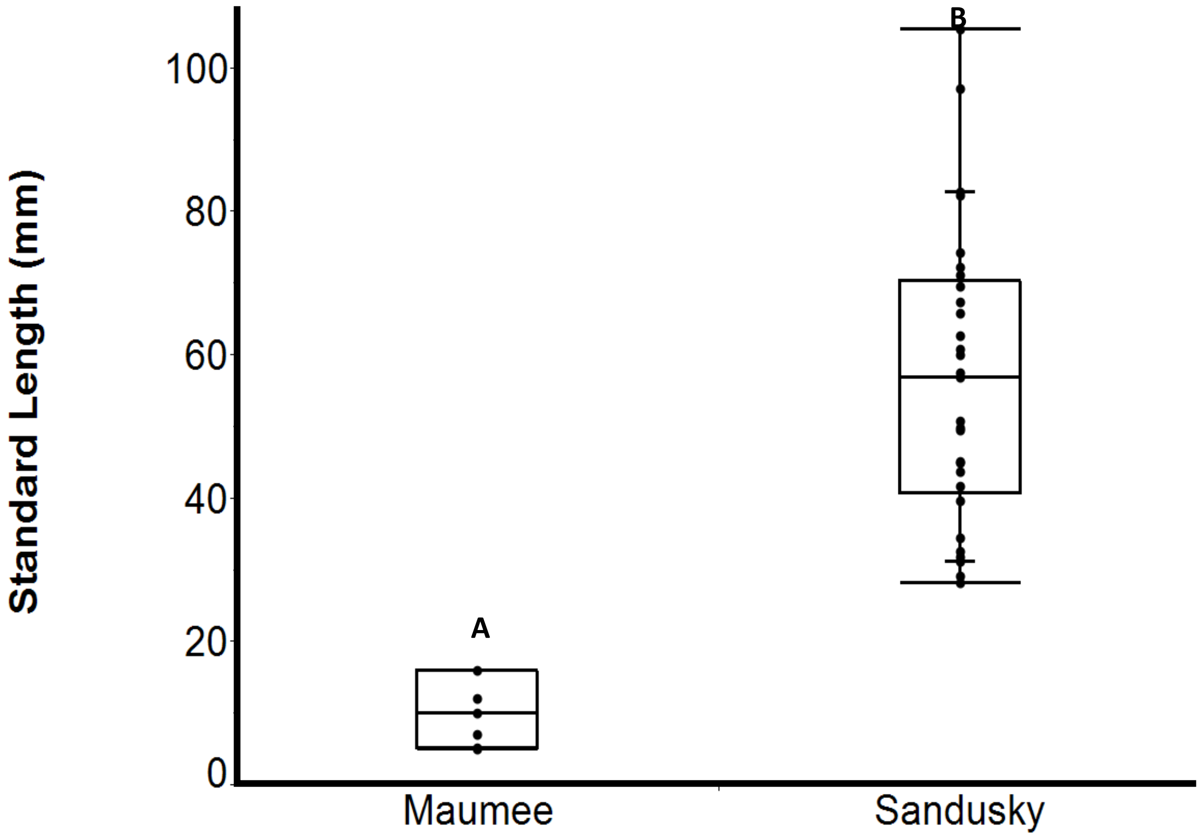

Figure 7. Length (mm SL) at emigration from the Sandusky (n=41) and Maumee (n=7) water masses for white bass sampled from the August 2011 Central Basin population. Boxes represent 25th and 75th percentile, center horizontal line represents the median, minor hash marks represent the 10th and 90th percentiles, and whisker ends represent range. Different letters denote significant differences (one-way ANOVA ; df 2,50 F=35.279, P<0.0001). Individuals identified from the Maumee (n=7) reached a mean size at emigration of 10.2 mm (SL, SE=1.70). Individuals classified as Sandusky origin (n=41) reached a mean size of 56.5mm (SE=3.77) before emigration.

August 2011

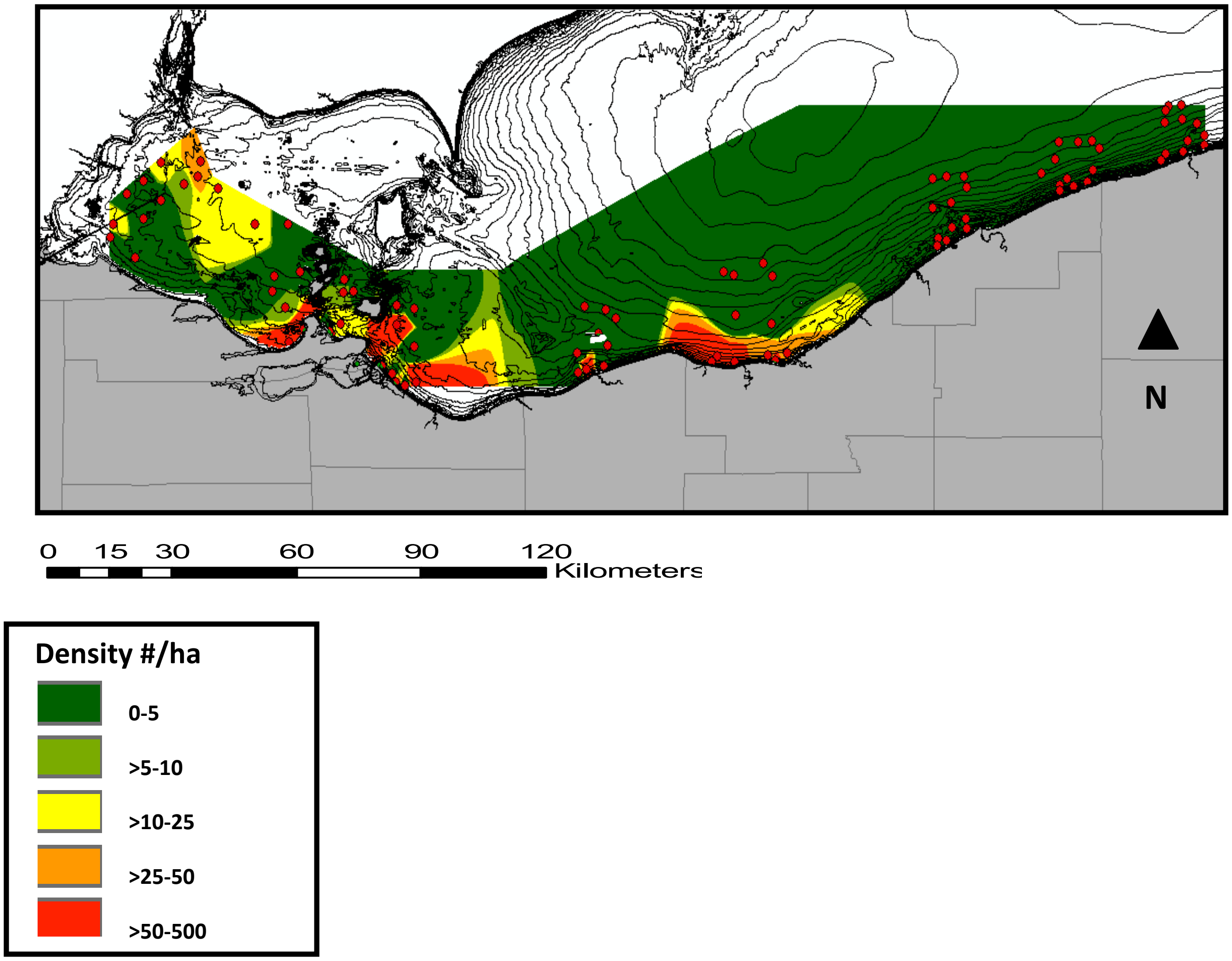

Figure 8. Inverse Distance Weighted (IDW) interpolation of juvenile white bass density estimated from August 2011 trawl survey point data. Map shows distinct concentrations of juvenile white bass in the Western and Central Basins of Lake Erie during August 2011.

LOCATION	**HECTARES**	**MIN CPHT**	**MAX CPHT**	**MEAN of SAMPLES**	**STDEV of MEANS**	**TOTAL WHITE BASS**
West Basin	**316,897**	**0**	**378**	**26.8**	**65.13**	**679,983**
Central Basin	**705,012**	**0**	**56.8**	**6.05**	**16.02**	**520,494**
TOTAL						**1,200,477**

Table 1. Abundance estimates by lake basin for juvenile white bass in August 2011 using Inverse Distance Weighted (IDW) interpolation of August trawl survey point data. Results of the SCA analyses estimated the Sandusky Spawning-stock contributed 80.4% (≈418,000 individuals) to the August Central Basin population. This was 34.9% of the estimated total August 2011 juvenile white bass population in the Ohio waters of Lake Erie.

APPENDIX A GIS METADATA

Great Lakes State Boundaries

Format_Name: ARC/INFO Shape

Metadata_Reference_Information:

Metadata_Date: 01/15/2013

Metadata_Standard_Name: SCI Minimum Compliance Metadata

Metadata_Standard_Version: SCI Std 003-02

Originator: Bureau of the Census

Publication_Date: 20061002

Title: Great Lakes state boundaries

Publication_Place: Ann Arbor, MI

Publisher: Great Lakes Information Network (GLIN)

Online_Linkage: http://gis.glin.net/ogc/services.php#gl_state_boundaries

Description:

Abstract:

States are the primary governmental divisions of the United States. The District of Columbia is treated as a statistical equivalent of a state for decennial census purposes, as are Puerto Rico and the Island Areas: American Samoa, Guam, the Commonwealth if the Northern Mariana Islands, and the Virgin Islands of the United States.

Each state and statistically equivalent entity is assigned a two-digit numeric Federal Information Processing Standards (FIPS) code in alphabetical order by state name, followed in alphabetical order by the Island Areas and Puerto Rico. Each state and statistically equivalent entity also is assigned a two-letter FIPS/U.S. Postal Service code and a two-digit census code. The census code is assigned on the basis of the geographic sequence of each state within each census division; the first digit of the code identifies the respective division, except for Puerto Rico and the Island Areas, which are not assigned to any region or division.

Purpose: To delineate the boudaries of the Great Lakes states and region.

Supplemental_Information: Summary: State boundaries for the Great Lakes states

Bounding_Coordinates:

West_Bounding_Coordinate: -97.239212

East_Bounding_Coordinate: -71.856209

North_Bounding_Coordinate: 49.384361

South_Bounding_Coordinate: 36.970295

Use_Constraints: None. Acknowledgment of the U.S. Bureau of the Census would be appreciated for products derived from these files. TIGER, TIGER/Line, and Census TIGER are registered trademarks of the Bureau of the Census.

Contact_Person: Pete Giencke

Contact_Organization: GLC

Contact_Voice_Telephone: 7349719135

Contact_Electronic_Mail_Address: pgiencke@glc.org

Browse_Graphic:

Browse_Graphic_File_Name:

http://gis.glin.net/geoserver/wms?bbox=-97.239212,36.970295,-71.856209,49.384361&request=GetMap&layers=glin:gl_state_boundaries&width=600&height=400&srs=EPSG:4326&styles=line_black&format=image/png

Browse_Graphic_File_Description: WMS-based PNG preview of dataset at full extent

Browse_Graphic_File_Type: PNG

Native_Data_Set_Environment: GNU/Linux i686 i386

Originator: Bureau of the Census

Publication_Date: unknown

Metadata_Reference_Information:

Metadata_Date: 2009-12-30T11:38:14-04:00

Contact_Person: Pete Giencke

Contact_Organization: GLC

Contact_Voice_Telephone: 7349719135

Contact_Electronic_Mail_Address: pgiencke@glc.org

Metadata_Standard_Name: FGDC Content Standards for Digital Geospatial Metadata

Metadata_Standard_Version: FGDC-STD-001-1998

Distribution_Information:

Contact_Person: Pete Giencke

Contact_Organization: Great Lakes Commission

Contact_Position: Lead Systems Developer

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State_or_Province: MI

Postal_Code: 48104

Contact_Voice_Telephone: (734) 971-9135 x132

Contact_Facsimile_Telephone: (734) 971 - 9150

Contact_Electronic_Mail_Address: pgiencke@glc.org

Resource_Description: gl_state_boundaries

Distribution_Liability: Disclaimer. The Great Lakes Commission (GLC) and the Great Lakes Information Network (GLIN) cannot assume liability for any damages caused by any errors or omissions in the data, nor as a result of the failure of the data to function on a particular system. The Great Lakes Commission (GLC) and the Great Lakes Information Network (GLIN) make no warranty, expressed or implied, nor does the fact of distribution constitute such a warranty.

Format_Name: Shapefile

Format_Information_Content: State boundaries for the Great Lakes states

File_Decompression_Technique: Shapefile compressed with GNU zip

Network_Resource_Name: http://gis.glin.net/geoserver/wfs?request=getfeature&service=wfs&version=1.0.0&typename=glin:gl_state_boundaries&outputformat=shape-zip

Online_Computer_and_Operating_System: GNU/Linux i686 i386

Format_Name: GML

Format_Information_Content: State boundaries for the Great Lakes states

File_Decompression_Technique: Geographic Markup Language (GML) compressed with GNU zip

Geographic_Coordinate_Units: Decimal Degrees

Latitude_Resolution: 0.01757812

Longitude_Resolution: 0.01757812

Ohio County Boundries

Originator: Bureau of the Census

Publication_Date: 20061019

Title: oh county boundaries 2000

Publication_Information:

Publication_Place: Ann Arbor, MI

Publisher: Great Lakes Information Network (GLIN)

Online_Linkage: http://gis.glin.net/ogc/services.php#oh_county_boundaries_2000

Description:

Abstract: TIGER, TIGER/Line, and Census TIGER are registered trademarks of the Bureau of the Census. The Redistricting Census 2000 TIGER/Line files are an extract of selected geographic and cartographic information from the Census TIGER data base. The geographic coverage for a single TIGER/Line file is a county or statistical equivalent entity, with the coverage area based on January 1, 2000 legal boundaries. A complete set of Redistricting Census 2000 TIGER/Line files includes all counties and statistically equivalent entities in the United States and Puerto Rico. The Redistricting Census 2000 TIGER/Line files will not include files for the Island Areas. The Census TIGER data base represents a seamless national file with no overlaps or gaps between parts. However, each county-based TIGER/Line file is designed to stand alone as an independent data set or the files can be combined to cover the whole Nation. The Redistricting Census 2000 TIGER/Line files consist of line segments representing physical features and governmental and statistical boundaries. The Redistricting Census 2000

TIGER/Line files do NOT contain the ZIP Code Tabulation Areas (ZCTAs) and the address ranges are of approximately the same vintage as those appearing in the 1999 TIGER/Line files. That is, the Census Bureau is producing the Redistricting Census 2000 TIGER/Line files in advance of the computer processing that will ensure that the address ranges in the TIGER/Line files agree with the final Master Address File (MAF) used for tabulating Census 2000. The files contain information distributed over a series of record types for the spatial objects of a county. There are 17 record types, including the basic data record, the shape coordinate points, and geographic codes that can be used with appropriate software to prepare maps. Other geographic information contained in the files includes attributes such as feature identifiers/census feature class codes (CFCC used to differentiate feature types, address ranges and ZIP Codes, codes for legal and statistical entities, latitude/longitude coordinates of linear and point features, landmark point features, area landmarks, key geographic features, and area boundaries. The Redistricting Census 2000 TIGER/Line data dictionary contains a complete list of all the fields in the 17 record types.

Purpose: In order for others to use the information in the Census TIGER data base in a geographic information system (GIS) or for other geographic applications, the Census Bureau releases to the public extracts of the data base in the form of TIGER/Line files. Various versions of the TIGER/Line files have been released; previous versions include the 1990 Census TIGER/Line files, the 1992 TIGER/Line files, the 1994 TIGER/Line files, the 1995 TIGER/Line files, the 1997 TIGER/Line files, the 1998 TIGER/Line files, and the 1999 TIGER/Line files. The Redistricting Census 2000 TIGER/Line files were originally produced to support the Census 2000 Redistricting Data Program.

Supplemental_Information: Summary: 2000 Ohio county boundaries

Currentness_Reference: Date the file was made available to create TIGER/Line File extracts.

Maintenance_and_Update_Frequency: TIGER/Line files are extracted from the Census TIGER data base when needed for geographic programs required to support the census and survey programs of the Census Bureau. No changes or updates will be made to the Redistricting Census 2000 TIGER/Line files. Future releases of TIGER/Line files will reflect updates made to the Census TIGER data base and will be released under a version numbering system based on the month and year the data is extracted.

Spatial_Domain:

Bounding_Coordinates:

West_Bounding_Coordinate: -84.820160

East_Bounding_Coordinate: -80.518692

North_Bounding_Coordinate: 41.977524

South_Bounding_Coordinate: 38.403198

Use_Constraints: None. Acknowledgment of the U.S. Bureau of the Census would be appreciated for products derived from these files. TIGER, TIGER/Line, and Census TIGER are registered trademarks of the Bureau of the Census.

Contact_Person: Pete Giencke

Contact_Organization: GLC

Contact_Voice_Telephone: 7349719135

Contact_Electronic_Mail_Address: pgiencke@glc.org

Browse_Graphic:

Browse_Graphic_File_Name:

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Browse_Graphic_File_Description: WMS-based PNG preview of dataset at full extent

Browse_Graphic_File_Type: PNG

Native_Data_Set_Environment: GNU/Linux i686 i386

Originator: Bureau of the Census

Metadata_Reference_Information:

Metadata_Date: 2009-12-30T11:38:14-04:00

Contact_Person: Pete Giencke

Contact_Organization: GLC

Contact_Voice_Telephone: 7349719135

Contact_Facsimile_Telephone:

Contact_Electronic_Mail_Address: pgiencke@glc.org

Metadata_Standard_Name: FGDC Content Standards for Digital Geospatial Metadata

Metadata_Standard_Version: FGDC-STD-001-1998

Contact_Person: Pete Giencke

Contact_Organization: Great Lakes Commission

Contact_Position: Lead Systems Developer

Address_Type: Mailing and Physical

Address: 2805 S. Industrial Hwy, Suite 100

City: Ann Arbor

State_or_Province: MI

Postal_Code: 48104

Resource_Description: oh_county_boundaries_2000

Distribution_Liability: Disclaimer. The Great Lakes Commission (GLC) and the Great Lakes Information Network (GLIN) cannot assume liability for any damages caused by any errors or omissions in the data, nor as a result of the failure of the data to function on a particular system. The Great Lakes Commission (GLC) and the Great Lakes Information Network (GLIN) make no warranty, expressed or implied, nor does the fact of distribution constitute such a warranty.

Format_Name: Shapefile

Format_Information_Content: 2000 Ohio county boundaries

File_Decompression_Technique: Shapefile compressed with GNU zip

Network_Resource_Name:
http://gis.glin.net/geoserver/wfs?request=getfeature&service=wfs&version=1.0.0&typename=glin:oh_county_boundaries_2000&outputformat=shape-zip

Online_Computer_and_Operating_System: GNU/Linux i686 i386

Format_Name: GML

Format_Information_Content: 2000 Ohio county boundaries

File_Decompression_Technique: Geographic Markup Language (GML) compressed with GNU zip

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Horizontal_Coordinate_System_Definition:

Geographic:

Geographic_Coordinate_Units: Decimal Degrees

Latitude_Resolution: 0.01757812

Longitude_Resolution: 0.01757812

Entity_and_Attribute_Information:

Great Lakes Bathymetry

Originator: Great Lakes Environmental Research Laboratory

Originator: National Geophysical Data Center

Publication_Date: 20061108

Title: lake erie bathymetry

Publication_Information:

Publication_Place: Ann Arbor, MI

Publisher: Great Lakes Information Network (GLIN)

Online_Linkage: http://gis.glin.net/ogc/services.php#lake_erie_bathymetry

Abstract:

A bathymetric layer for Lake Erie

NOAA is engaged in a program to compile Great Lakes bathymetric data and make them readily available to the public, especially to the communities concerned with Great Lakes science, pollution, coastal erosion, response to climate changes, threats to lake ecosystems, and health of the fishing industry. This program is managed by NGDC and it relies on the cooperation of NOAA/Great Lakes Environmental Research Laboratory, NOAA/National Ocean Service, the Canadian Hydrographic Service, other agencies, and academic laboratories.

Compilation of new bathymetry for the Great Lakes is an important part of this program, being carried out cooperatively between NOAA (NGDC and GLERL), and the Canadian Hydrographic Service. This new bathymetry provides a more detailed portrayal of lakefloor topography, and reveals some lakefloor features seen for the first time.

Supplemental_Information: Summary: A bathymetric layer for Lake Erie

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West_Bounding_Coordinate: -83.571671

East_Bounding_Coordinate: -78.769493

North_Bounding_Coordinate: 42.910305

South_Bounding_Coordinate: 41.363583

Contact_Person: Pete Giencke

Contact_Organization: GLC

Contact_Voice_Telephone: 7349719135

Contact_Electronic_Mail_Address: pgiencke@glc.org

Browse_Graphic_File_Name:

http://gis.glin.net/geoserver/wms?bbox=-83.571671,41.363583,-78.769493,42.910305&request=GetMap&layers=glin:lake_erie_bathymetry&width=600&height=400&srs=EPSG:4326&styles=line_navy&format=image/png

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Browse_Graphic_File_Type: PNG

Native_Data_Set_Environment: GNU/Linux i686 i386

Cross_Reference:

Originator: Great Lakes Environmental Research Laboratory

Originator: National Geophysical Data Center

Metadata_Reference_Information:

Metadata_Date: 2009-12-30T11:38:14-04:00

Contact_Person: Pete Gienck

Contact_Organization: GLC

Contact_Voice_Telephone: 7349719135

Contact_Facsimile_Telephone:

Contact_Electronic_Mail_Address: pgiencke@glc.org

Metadata_Standard_Name: FGDC Content Standards for Digital Geospatial Metadata

Metadata_Standard_Version: FGDC-STD-001-1998

Distribution_Information:

Contact_Person: Pete Giencke

Contact_Organization: Great Lakes Commission

Contact_Position: Lead Systems Developer

Contact_Address:

Address_Type: Mailing and Physical

Address: 2805 S. Industrial Hwy, Suite 100

City: Ann Arbor

State_or_Province: MI

Postal_Code: 48104

Contact_Voice_Telephone: (734) 971-9135 x132

Contact_Facsimile_Telephone: (734) 971 - 9150

Contact_Electronic_Mail_Address: pgiencke@glc.org

Resource_Description: lake_erie_bathymetry

Distribution_Liability: Disclaimer. The Great Lakes Commission (GLC) and the Great Lakes Information Network (GLIN) cannot assume liability for any damages caused by any errors or omissions in the data, nor as a result of the failure of the data to function on a particular system. The Great Lakes Commission (GLC) and the Great Lakes Information Network (GLIN) make no warranty, expressed or implied, nor does the fact of distribution constitute such a warranty.

Format_Name: Shapefile

Format_Information_Content: A bathymetric layer for Lake Erie

File_Decompression_Technique: Shapefile compressed with GNU zip

Network_Resource_Name: http://gis.glin.net/geoserver/wfs?request=getfeature&service=wfs&version=1.0.0&typename=glin:lake_erie_bathymetry&outputformat=shape-zip

Online_Computer_and_Operating_System: GNU/Linux i686 i386

Format_Name: GML

Format_Information_Content: A bathymetric layer for Lake Erie

File_Decompression_Technique: Geographic Markup Language (GML) compressed with GNU zip

Spatial_Reference_Information:

Horizontal_Coordinate_System_Definition:

Geographic_Coordinate_Units: Decimal Degrees

Latitude_Resolution: 0.01757812

Longitude_Resolution: 0.01757812

Entity_and_Attribute_Information:

Lake Erie Nearshore

Originator: Natural Resources Research Institute

Publication_Date: 2007-09-20T17:08:02-04:00

Title: lake erie nearshore

Publication_Information:

Publication_Place: Ann Arbor, MI

Publisher: Great Lakes Information Network (GLIN)

Online_Linkage: http://gis.glin.net/ogc/services.php#lake_erie_nearshore

Description:

Abstract: A polygon dataset representing the nearshore environmental zone within the Lake Erie Basin. The zone is defined by water depth of more than 3 meters and less than 15 meters, queried from the NOAA National Geophysical Data Center bathymetry data. This data was developed in conjuction with the Lake Erie Millinium Network www.lemn.org .

Purpose: This data layer provides the basic geographic boundaries for the nearshore habitat zone in the Lake Erie Basin.

Supplemental_Information: Summary: Lake Erie nearshore habitat zone (3 - 15 meters depth)

Currentness_Reference: September 20, 2007

Maintenance_and_Update_Frequency: As Needed

Spatial_Domain:

Bounding_Coordinates:

West_Bounding_Coordinate: -83.542985

East_Bounding_Coordinate: -78.852086

North_Bounding_Coordinate: 42.921359

South_Bounding_Coordinate: 41.366085

Contact_Person: Tom Hollenhorst

Contact_Organization: Natural Resources Research Institute

Contact_Position: Research Fellow

Contact_Address:

Address_Type: Mailing and Physical

Address: 5013 Miller Trunk Hwy

City: Duluth

State_or_Province: MN

Postal_Code: 55811

Contact_Voice_Telephone: 218-720-4275

Contact_Electronic_Mail_Address: thollenh@nrri.umn.edu

Browse_Graphic:

Browse_Graphic_File_Name:

http://gis.glin.net/geoserver/wms?bbox=-83.542985,41.366085,-78.852086,42.921359&request=GetMap&layers=glin:lake_erie_nearshore&width=600&height=400&srs=EPSG:4326&styles=poly_gray&format=image/png

Browse_Graphic_File_Description: WMS-based PNG preview of dataset at full extent

Browse_Graphic_File_Type: PNG

Native_Data_Set_Environment: GNU/Linux i686 i386

Metadata_Reference_Information:

Metadata_Date: 2009-12-30T11:38:14-04:00

Contact_Person: Tom Hollenhorst

Contact_Organization: Natural Resources Research Institute

Metadata_Standard_Name: FGDC Content Standards for Digital Geospatial Metadata

Metadata_Standard_Version: FGDC-STD-001-1998

Resource_Description: lake_erie_nearshore

Distribution_Liability: Disclaimer. The Great Lakes Commission (GLC) and the Great Lakes Information Network (GLIN) cannot assume liability for any damages caused by any errors or omissions in the data, nor as a result of the failure of the data to function on a particular system. The Great Lakes Commission (GLC) and the Great Lakes Information Network (GLIN) make no warranty, expressed or implied, nor does the fact of distribution constitute such a warranty.

Format_Name: Shapefile

Format_Information_Content: Lake Erie nearshore habitat zone (3 - 15 meters depth)

File_Decompression_Technique: Shapefile compressed with GNU zip

Network_Resource_Name: http://gis.glin.net/geoserver/wfs?request=getfeature&service=wfs&version=1.0.0&typename=glin:lake_erie_nearshore&outputformat=shape-zip

Online_Computer_and_Operating_System: GNU/Linux i686 i386

Spatial_Reference_Information:

Horizontal_Coordinate_System_Definition:

Geographic_Coordinate_Units: Decimal Degrees

Latitude_Resolution: 0.01757812

Longitude_Resolution: 0.01757812

Lake Erie Offshore

Originator: Natural Resources Research Institute

Publication_Date: 2007-09-20T17:15:12-04:00

Title: lake erie open lake - offshore

Publication_Place: Ann Arbor, MI

Publisher: Great Lakes Information Network (GLIN)

Online_Linkage: http://gis.glin.net/ogc/services.php#lake_erie_open_lake_-_offshore

Description:

Abstract: A polygon dataset representing the open lake - offshore environmental zone within the Lake Erie Basin. The zone is defined by water depth of more than 15 meters, queried from the NOAA National Geophysical Data Center bathymetry data. This data was developed in conjuction with the Lake Erie Millinium Network www.lemn.org .

Purpose: This data layer provides the basic geographic boundaries for the open lake - offshore environmental zone within the Lake Erie Basin.

Supplemental_Information: Summary: Boundaries for the open lake - offshore habitat zone in the Lake Erie Basin.

Currentness_Reference: September 20, 2007

Maintenance_and_Update_Frequency: As Needed

Spatial_Domain:

Bounding_Coordinates:

West_Bounding_Coordinate: -82.402019

East_Bounding_Coordinate: -78.962412

North_Bounding_Coordinate: 42.845572

South_Bounding_Coordinate: 41.523578

Access_Constraints: None

Use_Constraints: None. Acknowledgement to LEMN www.lemn.org

Contact_Person: Tom Hollenhorst

Contact_Organization: Natural Resources Research Institute

Contact_Position: Research Fellow

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Address_Type: Mailing and Physical

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City: Duluth

State_or_Province: MN

Postal_Code: 55811

Contact_Voice_Telephone: 218-720-4275

Contact_Electronic_Mail_Address: thollenh@nrri.umn.edu

Browse_Graphic:

Browse_Graphic_File_Name:

http://gis.glin.net/geoserver/wms?bbox=-82.402019,41.523578,-78.962412,42.845572&request=GetMap&layers=glin:lake_erie_open_lake_-_offshore&width=600&height=400&srs=EPSG:4326&styles=poly_black&format=image/png

Browse_Graphic_File_Description: WMS-based PNG preview of dataset at full extent

Browse_Graphic_File_Type: PNG

Native_Data_Set_Environment: GNU/Linux i686 i386

Originator: Natural Resources Research Institute

Metadata_Reference_Information:

Metadata_Date: 2009-12-30T11:38:14-04:00

Contact_Person: Tom Hollenhorst

Contact_Organization: Natural Resources Research Institute

Contact_Electronic_Mail_Address: thollenh@nrri.umn.edu

Metadata_Standard_Name: FGDC Content Standards for Digital Geospatial Metadata

Metadata_Standard_Version: FGDC-STD-001-1998

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Resource_Description: lake_erie_open_lake_-_offshore

Distribution_Liability: Disclaimer. The Great Lakes Commission (GLC) and the Great Lakes Information Network (GLIN) cannot assume liability for any damages caused by any errors or omissions in the data, nor as a result of the failure of the data to function on a particular system. The Great Lakes Commission (GLC) and the Great Lakes Information Network (GLIN) make no warranty, expressed or implied, nor does the fact of distribution constitute such a warranty.

Format_Name: Shapefile

Format_Information_Content: Boundaries for the open lake - offshore habitat zone in the Lake Erie Basin.

File_Decompression_Technique: Shapefile compressed with GNU zip

Network_Resource_Name: http://gis.glin.net/geoserver/wfs?request=getfeature&service=wfs&version=1.0.0&typename=glin:lake_erie_open_lake_-_offshore&outputformat=shape-zip

Online_Computer_and_Operating_System: GNU/Linux i686 i386

Format_Name: GML

Format_Information_Content: Boundaries for the open lake - offshore habitat zone in the Lake Erie Basin.

File_Decompression_Technique: Geographic Markup Language (GML) compressed with GNU zip

Spatial_Reference_Information:

Horizontal_Coordinate_System_Definition:

Geographic:

Geographic_Coordinate_Units: Decimal Degrees

Latitude_Resolution: 0.01757812

Longitude_Resolution: 0.01757812