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SAGINAW BAY Multiple Stressors Summary Report

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- Provide critical support for NOAA's Mission

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SAGINAW BAY Multiple Stressors Summary Report

1. INTRODUCTION

1.1 Purpose of report

This report synthesizes results obtained during a five-year study (2008-2012) on Saginaw Bay, a large embayment on the southwest side of Lake Huron. The report is a summary of findings relevant for management decision making regarding issues related to the fishery and water quality of Saginaw Bay. Because the report is intended as an overview, detailed descriptions of the approaches and methods used are omitted, but can be found in papers published in the peer-reviewed literature, including a special issue in the *Journal of Great Lakes Research*, scheduled for publication in late 2013.

The project was sponsored by the National Oceanic and Atmospheric Administration Center for Sponsored Coastal Ocean Research (NOAA CSCOR), administered through the NOAA Great Lakes Environmental Research Laboratory (GLERL) and builds on previous research in Saginaw Bay conducted by NOAA GLERL from 1991 to 1996. The organizing project concept was an "Adaptive Integrated Framework" (AIF) in which models and data are used interactively to inform one another and guide the research approach. While the project was headquartered at NOAA GLERL, the research team included partners from Michigan State University, the University of Michigan, Purdue University, Wayne State University, Western Michigan University, Eastern Michigan University, Case Western Reserve, the University of Akron, Duke University, LimnoTech, Inc., and the Michigan Departments of Natural Resources and Environmental Quality.

From the early conceptual stages of the project, our intent was to focus on research to inform pending management decisions. To help achieve this goal, project team members had numerous meetings with personnel from the MI DNR and DEQ, before the project proposal was written, to discuss the major uncertainties regarding fisheries and water quality management issues in Saginaw Bay. Additionally, representatives from both agencies were included as co-investigators on the proposal. Once the proposal was funded, we held additional meetings and a workshop to further refine our research agenda. Throughout the project, we tried to maintain an open communication with the participating management agencies.

After considerable consultation, our research agenda centered on issues related to phosphorus inputs and eutrophication symptoms including harmful algal blooms, benthic algal production and beach fouling (aka "muck"), invasive species and their influence on foodweb dynamics, and concerns regarding walleye and yellow perch production. Previous research had established a set of monitoring locations in the bay, our new project incorporated a subset of these stations and also included nearshore transects where divers conducted various monitoring activities (Figure 2.1). The results included herein highlight findings from our ambient monitoring as well as insights gained from related quantitative modeling efforts.

2. MANAGEMENT ISSUE FINDINGS AND IMPLICATIONS

2.1 Water Quality / HABs / beach issues ("muck")

Saginaw Bay has a long history of eutrophication-related symptoms including drinking water taste and odor problems associated with high cyanobacteria levels (Bierman et al. 1980) and decaying organic matter deposits along the beaches. Excessive algal production around the Great Lakes catalyzed an extended debate from the 1960s into the 1970s about the primary cause of eutrophication, which was largely resolved by the mid-1970s with the recognition that phosphorus was the primary limiting nutrient in most freshwater ecosystems (Schindler and Vallentyne 2008), and that excess phosphorus loading was the cause of eutrophication symptoms in Saginaw Bay and other areas of the Great Lakes.

The earliest known phosphorus data from Saginaw Bay, collected in 1956, indicated total phosphorus concentrations as high as 70 ug/L, with average inner bay concentrations ranging from 37 to 45 ug/L, and average outer bay concentrations ranging from 13 to 24 ug/L (Beeton et al. 1967). A 1974 report indicated that data were insufficient to evaluate historical

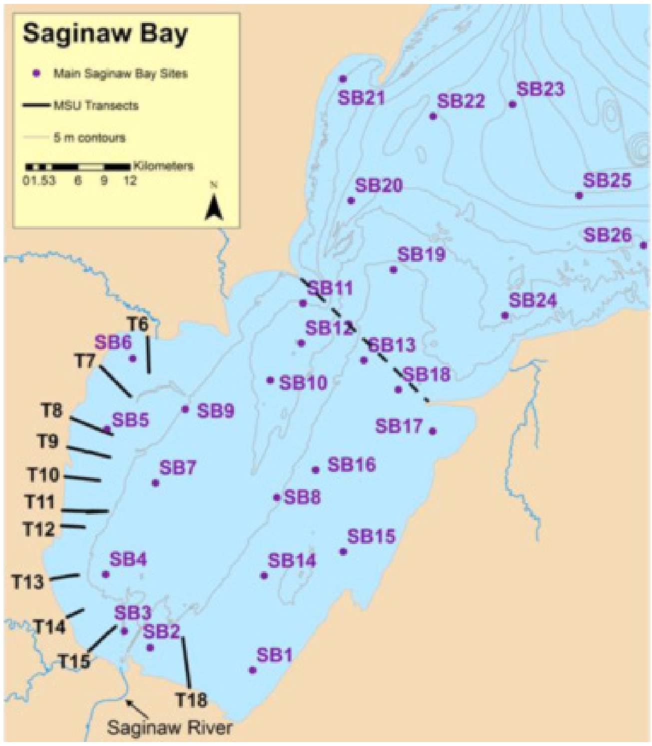

Figure 2.1 - Saginaw Bay station location map.

phosphorus trends, but concentrations were sufficiently high to support excessive algal growth, and *Microcystis* and *Aphanizomenon* were described as "common" (Freedman 1974).

Few detailed historical observations exist about the composition of shoreline detritus in Saginaw Bay. A 1961 Michigan Department of Natural Resources (MDNR) memorandum described the wash-up as a "grey-black substance" composed of zooplankton (primarily ostracods and cladocerans), aquatic plant material, *Fragillaria* pieces, and *Cladophora* (Fetterolf 1961). Similar observations were made in an MDNR memorandum in 1978 (Kenaga 1978). However, more recent observations suggest that beach "muck" is composed primarily of decomposing metaphytonic chlorophytes (benthic autotrophs), including *Zygnematales*, *Oedogonium*, diatoms, *Cladophora*, and vascular hydrophytes (macrophytes) (Pillsbury et al. 2002).

To mitigate the problems associated with high phosphorus levels, the 1978 amendments to the Great Lakes Water Quality Agreement (GLWQA) included a 440 tonnes/year total phosphorus target load for Saginaw Bay, which was based on conclusions from four mathematical models (International Joint Commission 1978). A 1979 phosphorus conference to establish a phosphorus management strategy for the Great Lakes included a recommendation that the "spring area-wide mean total phosphorus concentrations in Saginaw Bay should not exceed 15 ug/L". The report also included proposed objectives to correspond with a 15 ug/L total phosphorus concentration including a 3.6 ug/L chlorophyll a concentration, a 3.9 m secchi depth, and the goal of a mesotrophic state (Thomas et al. 1980). Assessments following the establishment of target phosphorus loads (Bierman et al. 1984, DePinto et al. 1986) indicated general improvements in water quality; concurrently, management emphasis shifted from eutrophication to concerns with toxic contaminants. As a result, active monitoring for phosphorus and other eutrophication indicators lapsed for a number of years.

Under the 1987 Protocol amending the GLWQA, the Saginaw River/Bay was designated as 1 of 43 Areas of Concern (AOC) due to impairment of 12 of the 14 possible Beneficial Use Impairments (BUIs) including:

- Restrictions on fish and wildlife consumption
- Eutrophication or undesirable algae
- Tainting of fish and wildlife flavor
- Restrictions on drinking water consumption, or taste and odor
- Degradation of fish and wildlife populations
- Beach closings
- Degradation of aesthetics
- Bird or animal deformities or reproduction problems
- Degradation of benthos
- Degradation of phytoplankton and zooplankton populations

- Restriction on dredging activities
- Loss of fish and wildlife habitat

Since 1988, seven Remedial Action Plans (RAPs) have been developed for the Saginaw River/Bay AOC, detailing a list of activities to address the sources contributing to these BUIs and the progress that has been made to restore the AOC. Two of the 12 BUIs were removed in 2008, including the fish and wildlife tainting, and drinking water taste and odor impairments (MI Department of Environmental Quality 2012). The removal of the taste and odor BUI was based on meeting treatment and water quality standards at the point of distribution into the water system. However, taste and odor problems associated with cyanobacteria growth still occur periodically, thus the two Bay City drinking water intakes are listed as not supporting the public water supply designated use under the Clean Water Act.

Invasive dreissenid mussels were discovered in Saginaw Bay in 1991. Zebra (*Dreissena polymorpha*) and quagga (*Dreissena rostriformis bugensis*) mussels are believed to alter phosphorus cycling and promote the growth of cyanobacteria (Vanderploeg et al. 2001, Bierman et al 2005) as well as nuisance benthic algae including *Cladophora*. The "nearshore shunt hypothesis" posits that dreissenid mussels intercept influent phosphorus near tributary mouths limiting offshore phosphorus transport and increasing phosphorus availability in benthic nearshore regions (Hecky et al. 2004). In many areas around the Great Lakes, there has been a resurgence of beach fouling resulting from the deposition of decaying *Cladophora*, a problem that had diminished following implementation of phosphorus reduction strategies in the late 1970s. Beach "muck" continues to be an active concern in some areas around Saginaw Bay.

Annex 4 of the Great Lakes Water Quality Protocol of 2012 (the protocol amending the 1978 GLWQA) establishes an interim total phosphorus concentration target of 5 ug/L for the open waters of Lake Huron, and carries forward the 440 tonnes/year total phosphorus load for Saginaw Bay as an interim target. The protocol also requires development of target phosphorus concentrations for nearshore waters of the Great Lakes and calls for load reduction targets for watersheds that have a "significant localized impact" on nearshore waters of the Great Lakes with consideration for "the bioavailability of various forms of phosphorus, related productivity, seasonality, fisheries productivity requirements, climate change, invasive species, and other factors, such as downstream impacts, as necessary" (Great Lakes Water Quality Protocol 2012).

2.2 Project Findings

2.2.1 Phosphorus Inputs

Phosphorus load estimation is limited by the availability of both flow (volume/time) and phosphorus concentration (mass/volume) measurements in the tributaries entering Saginaw Bay. An important consequence of this sparse data record is that annual total phosphorus load estimates are highly uncertain. To calculate annual loads and quantify their uncertainty, we developed a Bayesian hierarchical model for the Saginaw River (Cha et al. 2010). The Saginaw River is the largest tributary entering Saginaw Bay, has the best data record, and has been previously estimated to contribute ~78% of the total phosphorus load into the Bay (Canale and Squire 1976). Our results are consistent with previous reports (Bierman et al. 1984, DePinto et al. 1986) that documented TP load decreases following the GLWQA; however by the early 1990s the declines ceased, with considerable yearly variability since then. Even when only the Saginaw River is considered, the 440 tonnes/year target TP load has rarely been met (Figure 2.2). If annual estimates for the Saginaw River are increased by 25% to approximate the total load from all tributaries, then only in 2003 is there a > 50% probability that the target load was met.

Initial load decreases resulted from declining total phosphorus concentrations in the Saginaw River; current yearly variability results primarily from annual river flow fluctuations. Saginaw River flow fluctuates yearly but shows no consistent long-term trend (Figure 2.3). The lowest annual TP loads occurred in the late 1990s- early 2000s, a period when the river was experiencing slightly lower flows. Although annual flow exhibits no obvious trend, there is some indication that seasonal changes may be occurring. In particular, early spring flow (March-April) has declined since the 1990s, whereas flow in May has generally increased.

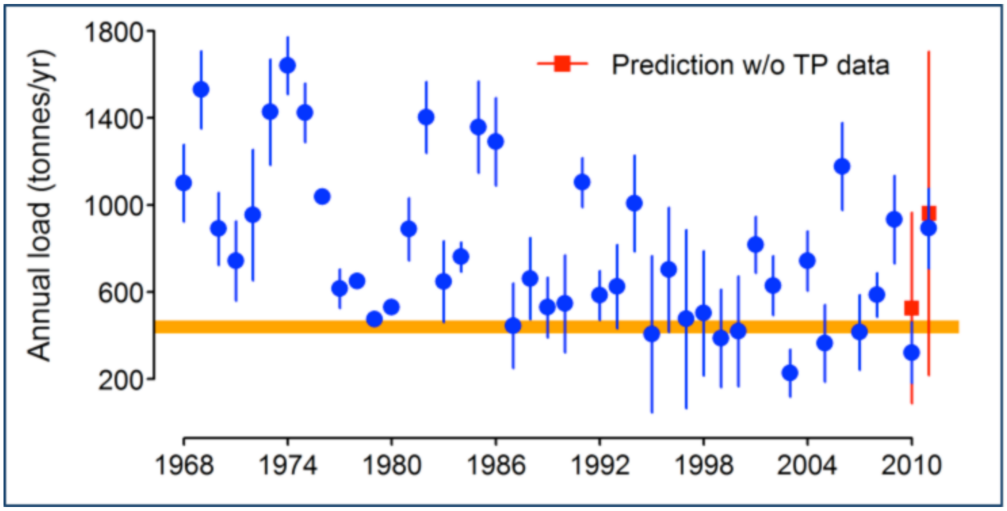

Figure 2.2 - Estimates of the Saginaw River total phosphorus load. Blue dots represent the mean of the Bayesian predictive distribution, bars represent ± 2 standard deviations. Red dots and lines indicate estimates for 2010 and 2011 using Saginaw River flow data without total phosphorus concentration data. Horizontal orange line denotes 440 tonnes target established in the GLWQA.

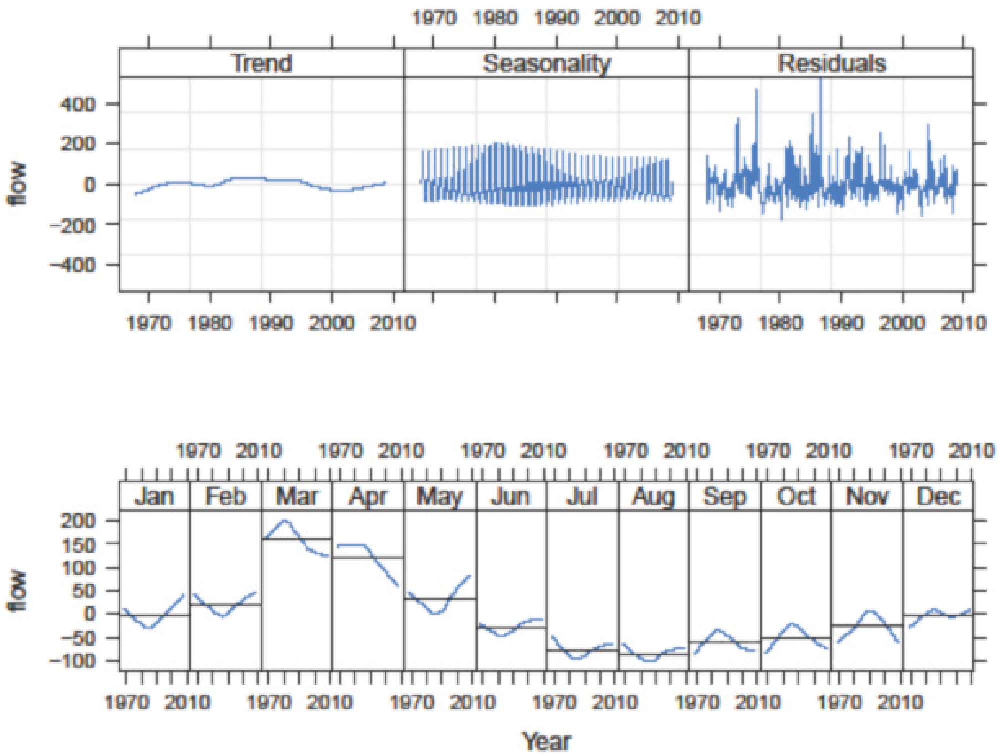

Figure 2.3 – Depiction of the Saginaw River long-term flow pattern produced with a technique known as "season trend decomposition using loess" (Cleveland 1993). The data are broken into three components: a smoothed long-term trend (top left), an oscillating seasonal pattern (top middle), and residual (top right). Smoothed long-term monthly patterns (bottom) indicate departures (blue line) from the long-term mean (horizontal black line).

Inputs from the tributaries outside of the Saginaw River basin are not well-monitored for either flow or phosphorus concentration. Limited sampling (n=28) in 2009 in the Kawkawlin, Rifle, Pine, and Aus Gres Rivers indicated total phosphorus concentrations ranging from 19 to 221 ug/L with a sample average of 70.6 ug/L, and soluble reactive phosphorus concentrations ranging from 0.72 to 89.5 ug/L with a sample average of 21.6 ug/L. The highest concentrations occurred in the Kawkawlin River.

The wetlands around the Shiawassee National Wildlife Refuge just southwest of Saginaw partially mitigate the loads originating in the Flint River, Shiawassee River, Tittabawasse River, and other smaller tributaries, with an average reduction of approximately 13%. This estimate was derived by calculating the difference of the average 1997-2010 loads at the outlets of Tittabawasse, Shiawassee, Flint, and Cass Rivers with the Saginaw River load just upstream of Saginaw. These loads were estimated using regression models developed using available total phosphorus values from 1998 to 2008 and observed flows from 1997 to 2010.

Based on a tally of discharge monitoring reports from National Pollutant Discharge Elimination System (NPDES) permitted facilities, urban and industrial point sources totaled approximately 178 and 163 metric tons of phosphorus in 2004 and 2005, respectively, two average years, 194 and 177 metric tons in 2006 and 2009, respectively, two wet years, and 115 metric tons P in 2010, a dry year. In each of these years, the proportion originating in the Saginaw River basin was approximately 80-90% of the total reported discharge. The contribution of retention treatment basins (RTBs) in each of these years was approximately 14-19 metric tons phosphorus. Based on the ratio between reported discharges and summer low flow river load, we estimate that approximately 50% of the total point-source phosphorus load is exported to the bay. Thus, the contribution of NPDES permitted point sources to the total load to the bay ranges from approximately 9% in wet years to approximately 16% in dry years. Contributions of RTBs range from approximately 1.5 to 4.5% of the total phosphorus load.

2.2.2 Physical Processes

Inner Saginaw Bay has generally been regarded as well-mixed and vertically isothermal. However, thermistor strings deployed in 2009 at two sites (Figure 2.4a) revealed sporadic short-term summer stratification (Figure 2.4b). In 2010, 2011, and 2012, GLERL deployed a Realtime Coastal Observation Network (RECON) buoy, in the deep area (~11 m) of inner-Saginaw Bay, equipped with sensors that measure surface and bottom characteristics including temperature, pH, dissolved oxygen, and current profiles. These measurements are logged and simultaneously transmitted in near real-time for web-based access (http://www.glerl.noaa.gov/res/recon/station-sbb.html). Periodic, albeit generally weak, stratification has also been documented at this location (Figure 2.5a), possibly resulting as cold water pulses from the outer bay enter the inner bay. Additionally, periods of rapid oxygen depletion occur regularly near the bottom (Figure 2.5b), with oxygen concentrations occasionally dropping below 2 mg/L. Because there is only one oxygen sensor, located approximately 20-50 cm from the bottom, neither the vertical or horizontal extent of these dynamics are currently known. We anticipate deploying a RECON buoy at this site for several years into the future to better document these dynamics.

Numerical modeling conducted for ice-free seasons in 1991-1996 and 2008-2010 advanced our knowledge of circulation and water exchange with the main lake, revising existing views on hydrodynamics of Saginaw Bay. In particular, we found that some existing current maps (Bratzel et al. 1977) inaccurately depict circulation in the outer bay. Model results

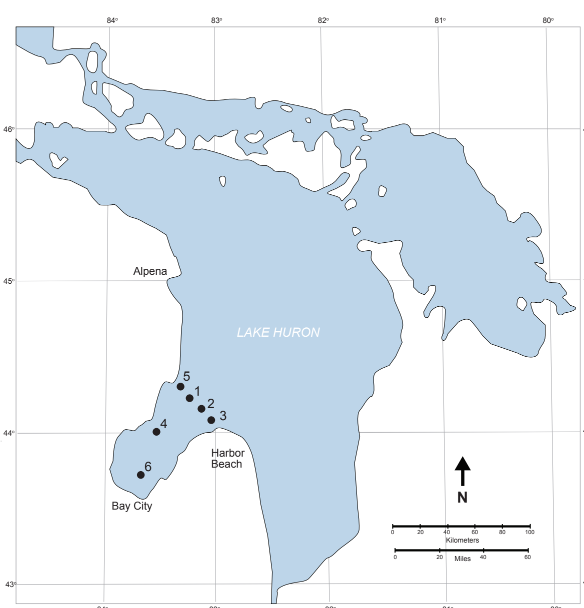

Figure 2.4a – Location of thermistors in Saginaw Bay.

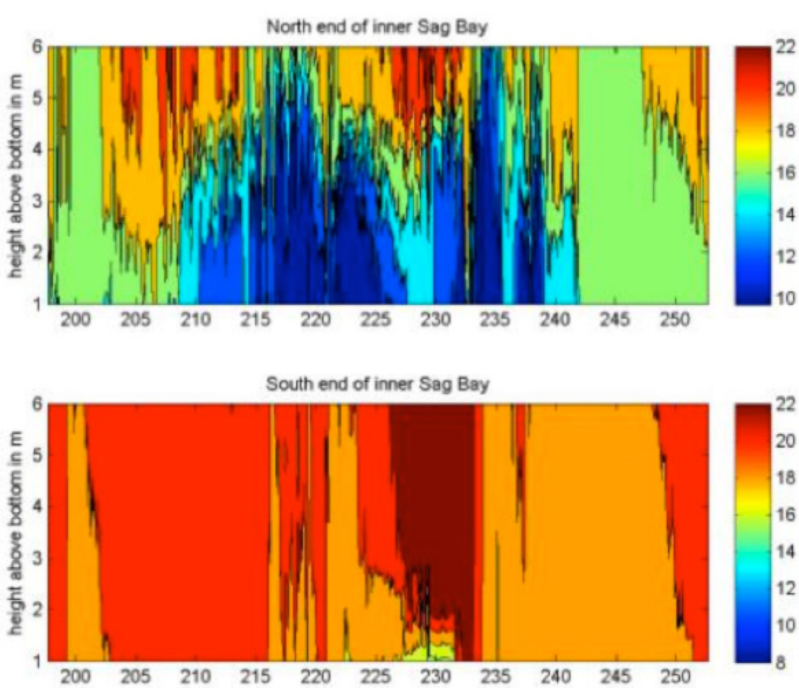

Figure 2.4b – Temperature profiles from each location. Temperatures in degrees C, horizontal axis in Julian days.

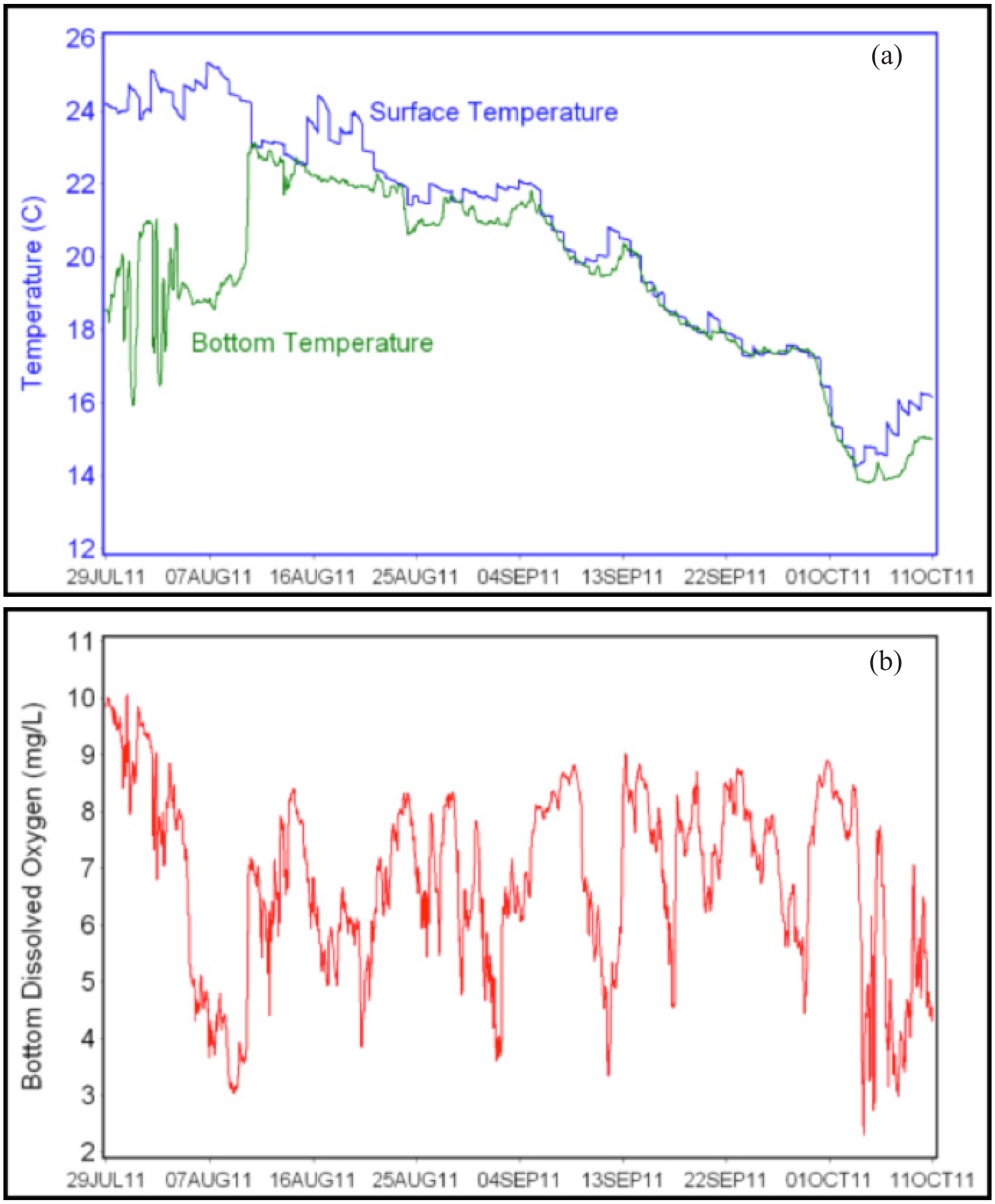

Figure 2.5. - (a) Surface and bottom temperatures recorded by RECON buoy deployed in 2011 near site 10, and (b) corresponding bottom oxygen concentrations.

for 1991-96 and 2008-10 show a persistent anticyclonic gyre, rather than a cyclonic gyre, near the mouth of the outer bay, limiting water and constituent exchange with Lake Huron (Figure 2.6). Real-time, high-resolution circulation patterns can be viewed at http://www.glerl.noaa.gov/res/glcfs/currents/, and nowcasts depicting Saginaw River plume dynamics are available at http://www.glerl.noaa.gov/res/glcfs/sb/.

Previous studies (Dolan 1975) showed that water exchange driven by lake circulation resulted in an estimated riverine flushing time of the inner bay of approximately 3.7 months. New model results, based on a 2-dimensional particle transport model, which was run from spring to late summer for 9 years, revealed considerably longer flushing times, ranging from ~7 months in the mid-late summer and exceeding 10 months in the spring.

2.2.3 Water Quality/Harmful Algal Blooms (HABs)

To evaluate temporal total phosphorus and chlorophyll a concentration patterns in the inner bay, we acquired extant data from numerous sources (Cha et al. 2011). A broad view considering the data from all of these sources, indicates that both total phosphorus and chlorophyll a declined in the late 1970s to the early 1980s (Figure 2.7), approximately in concert with decreasing total phosphorus loads (Figure 2.2). However, since approximately the mid-1980s, concentrations of both have been fairly stable.

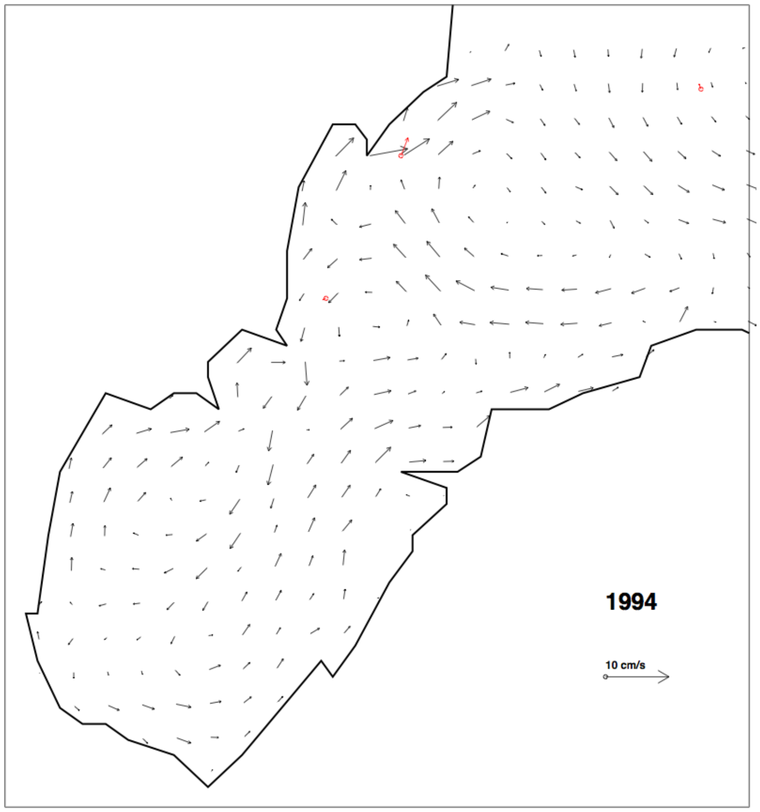

Figure 2.6 – Average Saginaw Bay circulation pattern in 1994.

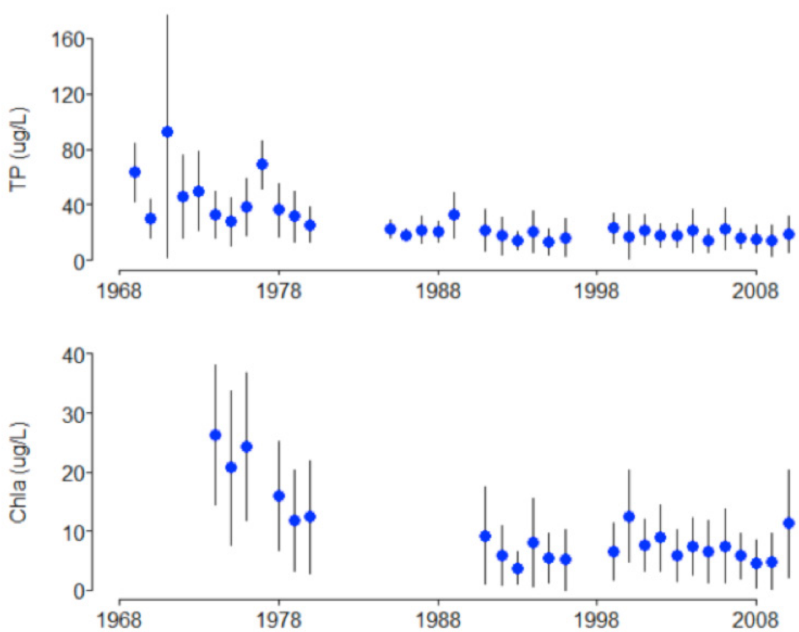

Figure 2.7 – Data from numerous extant sources depicting Saginaw Bay total phosphorus (top) and chlorophyll a concentrations vs time. Sample average (dots) ± 1 standard deviation (vertical bars).

A more-focused examination considering only the data collected by NOAA GLERL from 1991 to 1996 and 2008 to 2010 offers a different perspective. High-resolution hydrodynamic models of the bay indicate that, generally, the Saginaw River plume flows counter-clockwise and most strongly influences water quality on the southeast side of the inner bay. Generally, both total phosphorus and chlorophyll a concentration are higher in the plume-influenced samples than the non-plume samples. When the ambient monitoring stations are separated into three groups: inner-bay stations within the river plume, inner-bay stations outside of the river plume, and outer-bay stations, temporal patterns become more discernible (Figure 2.8). In the inner bay, within the Saginaw River plume, there is little difference between the distributions of TP concentrations from 1991 to 1996 and 2008 to 2010, and the sample averages are similar. However, within the inner bay, outside of the river plume, TP concentration distributions are higher in 1991-1996 than 2008-2010, and sample averages reflect this difference. Similarly, outer-bay concentration distributions were also higher in 1991-1996 than 2008-2010. Thus, outside of the Saginaw River plume, TP concentrations demonstrate a slight decrease in the more recent data. Data distributions from the nearshore diver transects exhibit a pattern similar to the 2008-2010 ambient stations with slightly higher concentrations in the plume than the non-plume stations. Overall, outer-bay concentrations are considerably lower than inner-bay concentrations, while transect concentrations are consistent with current TP levels at the inner bay ambient stations. Recent (2008-2010) exceedance rates of the 15 ug/L TP target were 47% within the river plume and 32% in the non-plume samples, while no outer-bay samples exceeded the limit. Transect sample exceedance rates in and out of the river plume were 28% and 11%, respectively.

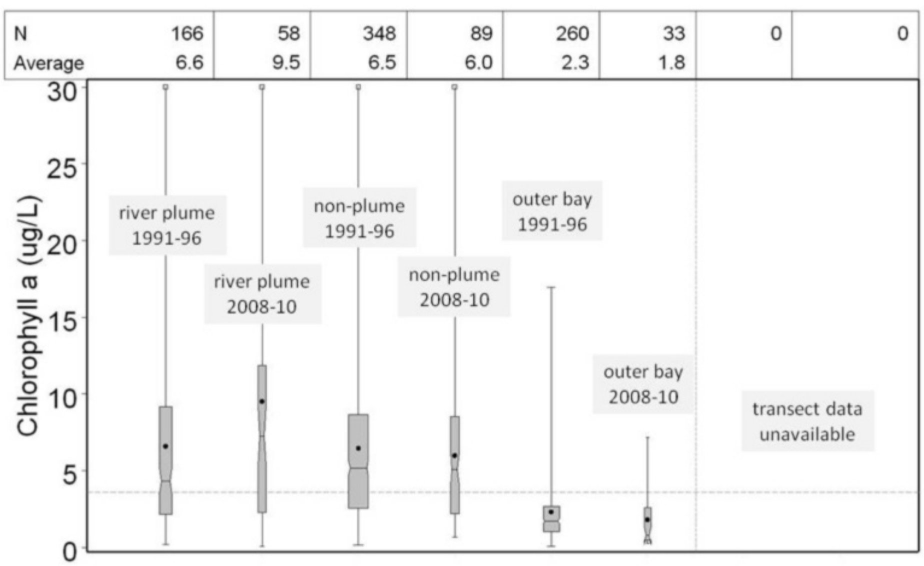

Figure 2.8 - Box and whisker plots depicting sample distributions of GLERL-collected total phosphorus in various time periods and locations in Saginaw Bay. Boxes indicate middle 50% of observations, dots indicate sample averages, horizontal lines indicate sample medians, notches depict 95% confidence intervals about the medians, whiskers indicate extreme values, box width is proportional to sample size. Sample sizes and sample averages for each group are shown above plot. Horizontal dashed line indicates 15 ug/L concentration objective.

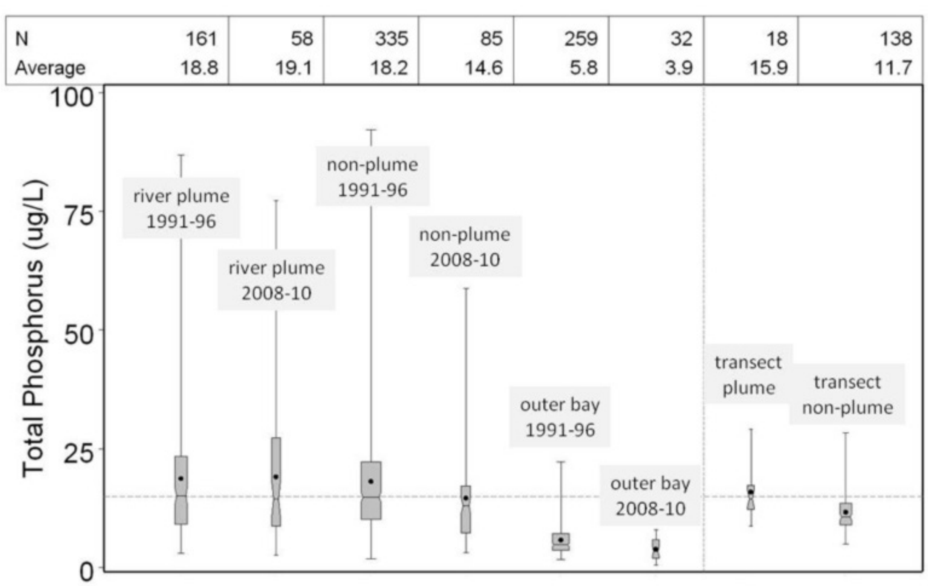

Figure 2.9 - Box and whisker plots of GLERL-collected data depicting sample distributions of chlorophyll a in various time periods and locations in Saginaw Bay. Boxes indicate middle 50% of observations, dots indicate sample averages, horizontal lines indicate sample medians, notches depict 95% confidence intervals about the medians, whiskers indicate extreme values, box width is proportional to sample size. Sample sizes and sample averages for each group are shown above plot. Horizontal dashed line indicates 3.6 ug/L concentration objective.

Chlorophyll a concentration patterns (Figure 2.9) are not as pronounced as those exhibited by TP, although outer bay concentrations are still notably lower than inner bay concentrations, as they are for phosphorus. Within the river plume, the overall distribution of CHLA is similar in 1991-1996 and 2008-2010, although the sample average is slightly higher in the later period. Within the inner bay, outside of the river plume, the overall concentration distributions are also similar as are the sample averages. High extremes are less apparent in the outer bay in 2008-2010 than 1991-1996, while the sample averages are similar. Exceedance probabilities of the 3.6 ug/L objective in 2008-2010 were 64%, 52%, and 14% in the plume, non-plume, and outer bay samples, respectively.

Secchi depth sample distributions (Figure 2.10) within the inner bay do not differ markedly, although the 2008-2010 non-plume readings exhibit slightly higher averages than the plume readings in both the ambient and nearshore transect stations. Nearshore transect measurements somewhat under-represent the actual water clarity, as these measurements were generally in shallow water; approximately 30% hit bottom, and the reading was set to the water depth. Outer bay measurements exhibit much greater secchi distributions than the inner bay, and the 2008-2010 samples indicate greater depths than the 1991-1996 samples. Only 10% of the inner bay measurements from 2008 to 2010 met the 3.9 m objective, whereas the objective was met in 78% of the outer bay readings.

There is a well-defined relationship between chlorophyll a and total phosphorus concentration (Figure 2.11), implying phosphorus continues to limit phytoplankton production. The relationship, on a log-scale, is similar among inner- and outer-bay stations and between the 1991-1996 and 2008-2010 time periods. A rigorous quantification of this relationship may be useful guidance for developing enforceable, numerical phosphorus "Substance Objectives" (USEPA 2010, GLWQP 2012).

Process-based model simulations confirm that phosphorus is limiting primary production in Saginaw Bay. It is also clear that reduction in phosphorus inputs from the watershed will reduce algal growth. However, at this time, the model has not been explored via diagnostic scenarios to be able to recommend optimal spatial and temporal strategies (i.e., focus on Saginaw River or minor tributaries directly feeding into nearshore zones of the bay) for this load reduction. Further, the model has not been exercised to develop a quantitative load-response relationship for these endpoints.

Model-based simulations indicate that wind-driven resuspension in the shallower areas of the inner bay contributes significantly to water column total phosphorus concentration on an event basis. Simulation of total phosphorus in the bay would not match observations very well if sediment resuspension is not included in the simulation. However, it is not clear that sediment resuspension of particulate phosphorus contributes significantly to algal growth.

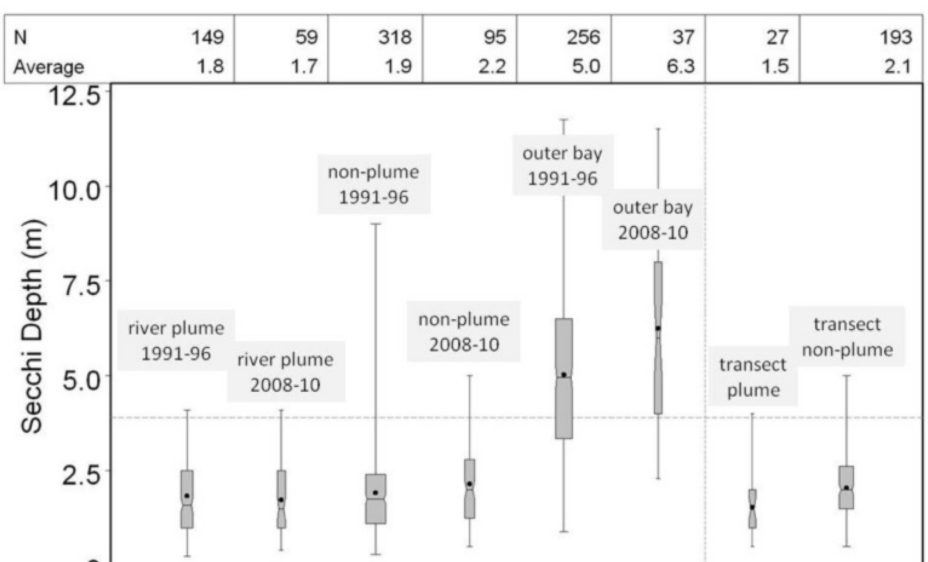

Figure 2.10 - Box and whisker plot depicting sample distributions of GLERL-collected secchi depth measurments in various time periods and locations in Saginaw Bay. Boxes indicate middle 50% of observations, dots indicate sample averages, horizontal lines indicate sample medians, notches depict 95% confidence intervals about the medians, whiskers indicate extreme values, box width is proportional to sample size. Sample sizes and sample averages for each group are shown above plot. Horizontal dashed line indicates 3.9 meter objective.

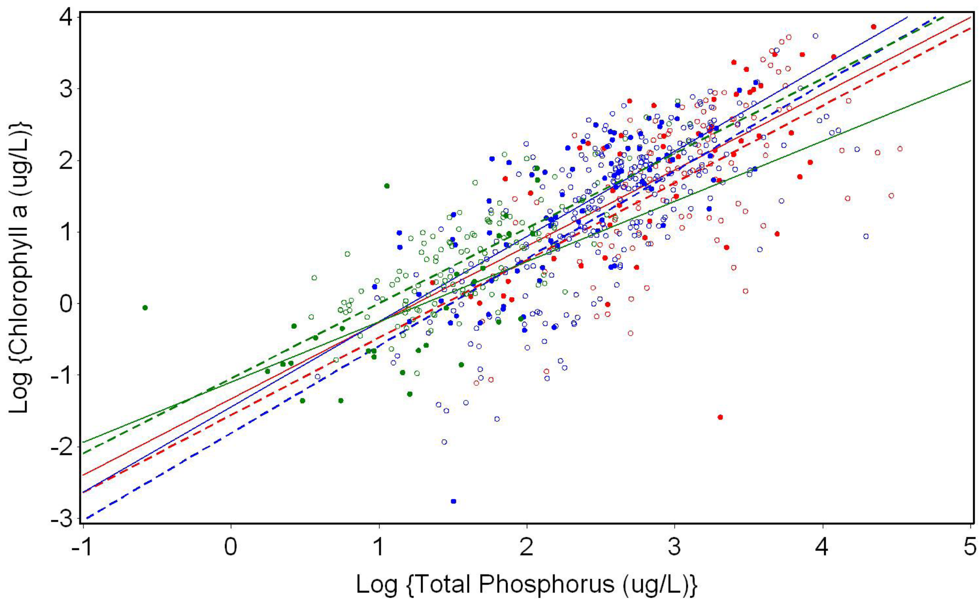

Figure 2.11 – Chlorophyll a vs total phosphorus in surface water samples and corresponding simple linear regression lines. Red = river plume, blue=non-plume, green=outer bay, circle = 1991-1996, dot = 2008-2010, dashed line = 1991-1996, solid line = 2008-2010.

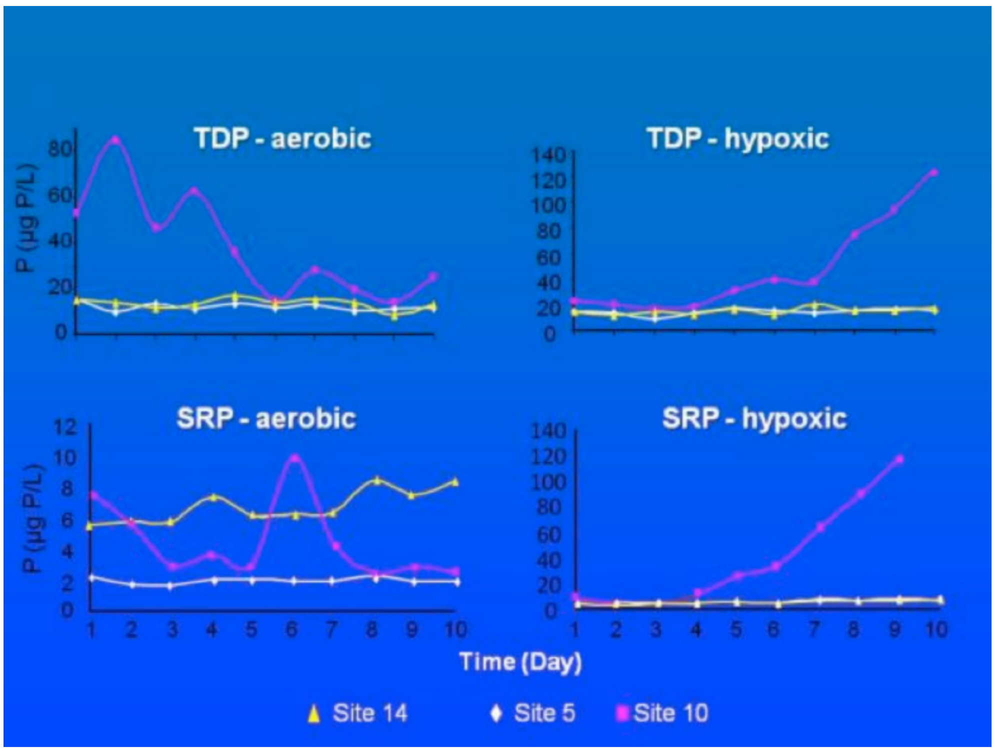

Figure 2.12 – Changes in phosphorus concentration in intact sediment cores from sites 5, 14, and 10 under differing oxygen levels.

Incubated sediment cores from site 10, in the deep area of the inner bay, exhibit high phosphorus flux to the water column under low oxygen conditions (Figure 2.12). This is in the same area where low bottom-water oxygen conditions have been recorded (Figure 2.5b), indicating the potential for periodic sediment phosphorus release. However, because low oxygen conditions have not been documented to persist, and ambient bottom-water phosphorus concentrations from site 10 are generally similar to surface concentrations, it seems unlikely that sediment phosphorus release is a consistent driver of phytoplankton production.

Phytoplankton biovolume measures show a mix of diatoms and cyanobacteria. On a cell-density basis, cyanobacteria are dominant at most times of the year (Figure 2.13a), whereas on a biovolume basis, Bacillaryophyta (diatoms) generally dominate (Figure 2.13b). While there are no enforceable numerical criteria for cyanobacteria, these levels are not particularly high by comparison to other lakes. For example, a target cyanobacteria concentration of 2 uL/L (20 x 10^8 μm^3 L^{-1}) has been considered in Lake Mendota, WI, (Stow et al. 1997); the levels reported here are generally below that target.

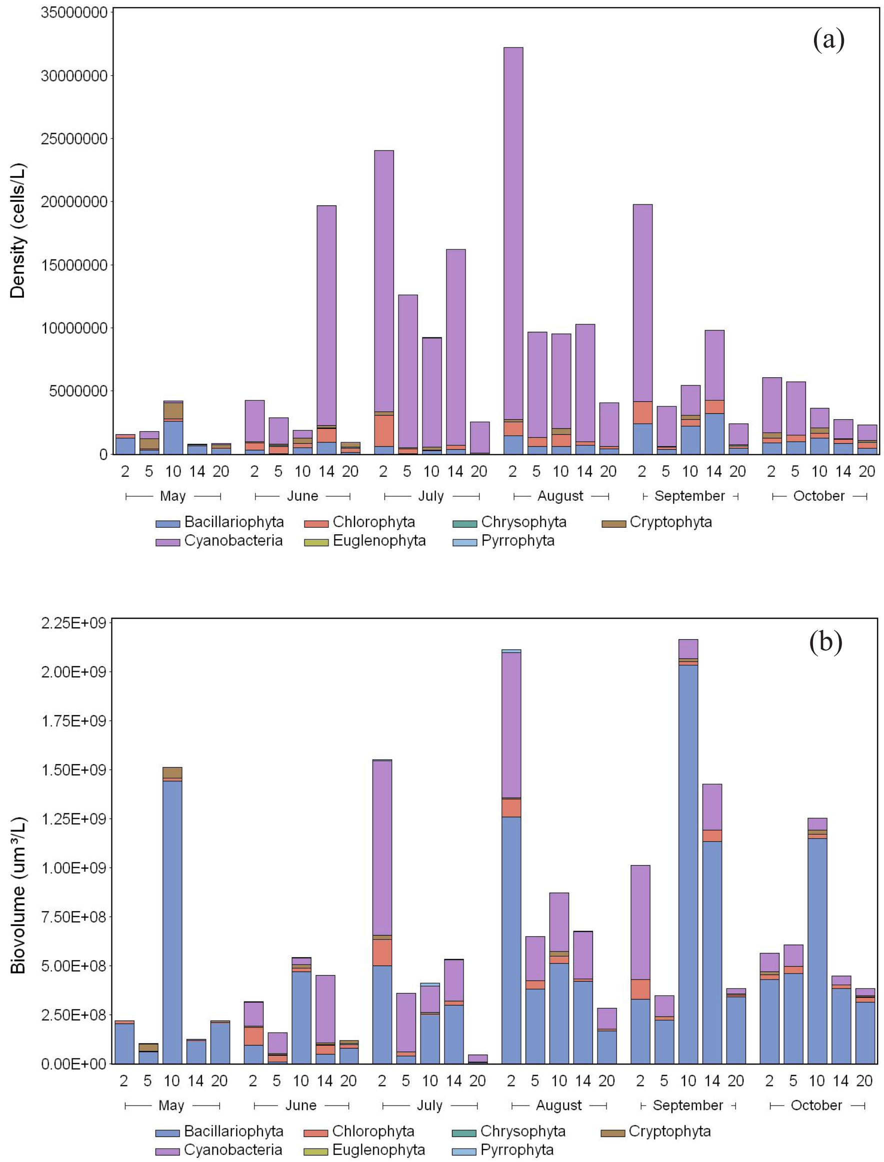

Figure 2.13 – 2010 data depicting phytoplankton species by density (top) and biovolume (bottom) in surface samples from sites 2, 5, 10, 14, and 20.

Cyanobacteria composition is mixed; species of *Merisomopedia* and *Microcystis* generally dominate in the summer (Figure 2.14). Summer *Microcystis* blooms continue to occur, driven by a combination of warm water column temperatures and elevated levels of available phosphorus. Ambient microcystin concentrations were variable; approximately 19% of the 145 measurements exceeded the 1 ug/L World Health Organization drinking water concentration, mostly in the late summer (Figure 2.15). All samples analyzed for microcystin were untreated lake water and do not reflect concentrations in polished drinking water.

Diver-conducted dreissenid mussel surveys at hard-substrate sites indicate that mussel densities are lower than levels recorded in the 1990s (Figure 2.16). An 11-year monitoring gap makes it difficult to know if current levels represent a long-term decline or if densities experience large fluctuations over time-scales of 5-10 years. In the 1990s, zebra mussels (*D. polymorpha*) were the only dreissenids collected. In 2008-2010, samples consisted of approximately 20% zebra and 80% quagga mussels (*D. rostriformis bugensis*). Though densities at these sites were lower than in the 1990s, mussels were observed to be widely distributed, and quickly colonized equipment that was deployed for extended periods (Figure 2.16). Simple mass-balance model results indicate that, since the mussels first invaded, the proportion of influent phosphorus retained in the bay has remained relatively high (Cha et al. 2011), supporting the idea that mussel filtration is still influential even at lower densities. Additionally, the complement of phytoplankton species observed (Figure 2.13) is consistent with a community that would be promoted by the ability of mussels to selectively reject unpalatable algal forms

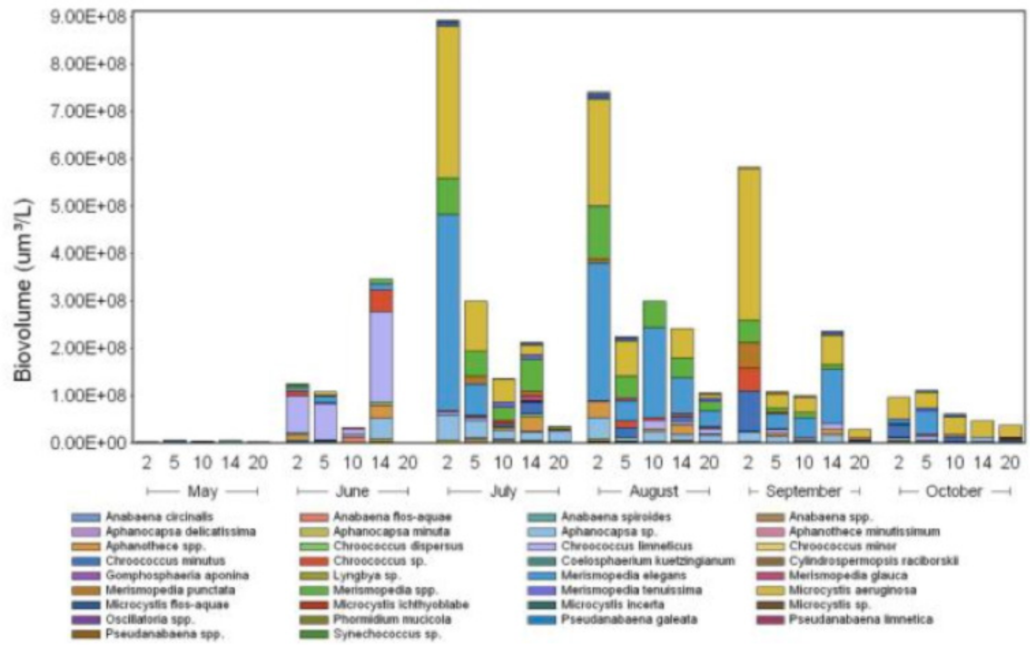

Figure 2.14 - 2010 data depicting cynobacteria species in surface samples from sites 2, 5, 10, 14, and 20.

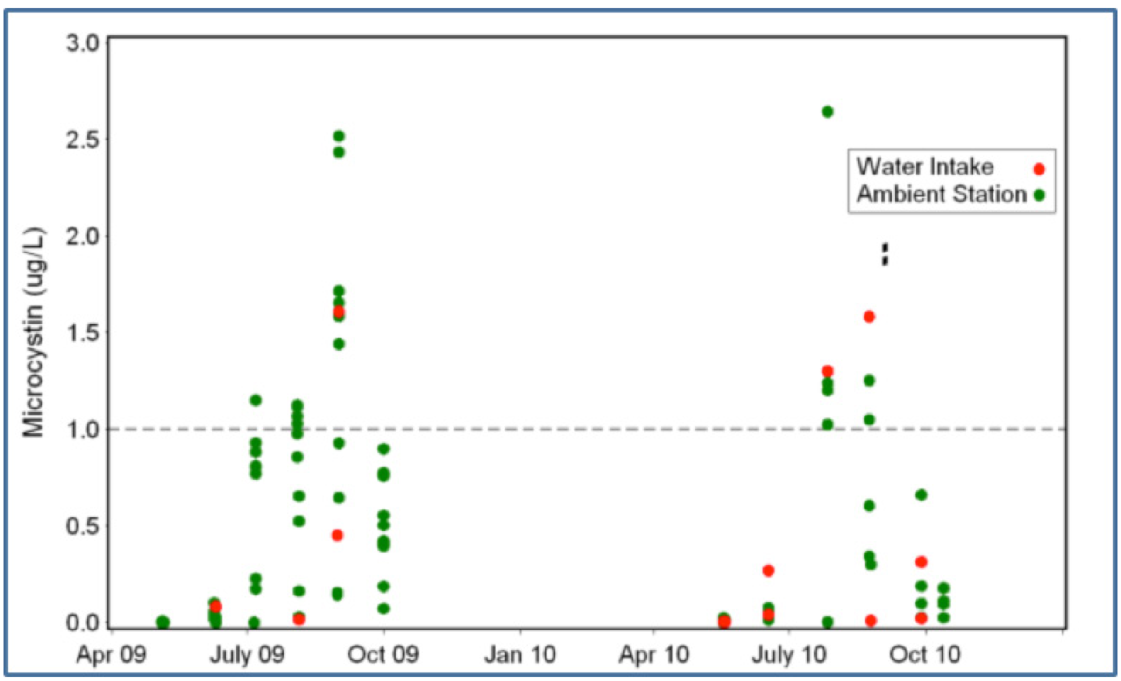

Figure 2.15 – Microcystin concentrations from 2009 to 2010. Horizontal dashed line depicts World Health Organization drinking water standard. All samples were of raw water, not polished drinking water.

(Vanderploeg et al. 2001). Thus, it is likely that these invasive mussels still strongly influence ambient water quality and may be responsible for the total phosphorus declines observed outside of the Saginaw River plume (Figure 2.8).

2.2.4 Muck and Beach Fouling

BCRA Park Ranger Logs

Reduced phosphorus levels following the 1978 GLWQA are believed to have significantly reduced beach fouling in the 1980s-1990s along most Great Lakes shorelines, prior to the proliferation of dreissenid mussels (Bootsma et al. 2004, Higgins et al. 2008a, Auer et al. 2010). However, park ranger logs from the Bay City Recreation Area (BCRA), located northwest (NW) of the mouth of Saginaw River, reveal that muck was a regular problem in Saginaw Bay throughout the 1980s and early 90s. A few example entries include:

June 18, 1978 - Considerable time was spent removing muck from the swimming area. Our muck problem is very bad again this year.

June 10, 1979 - Our muck problem is very severe at the present time. The muck is about a foot deep and extends along the entire beach and approximately 25 feet from the shoreline out into the bay.

June 22, 1980 - Offshore winds and rains moved our muck from the beach area and we have the best swimming conditions we have had for several seasons.

June 20, 1982 - The prevailing NW winds have piled up the muck on our beach to the extent our bombardier tractor can't push it. With settled water conditions we may again make some progress in clearing our swimming area.

Aug 5, 1984 - Muck on the beach is very thick.

May 21, 1989 - We have a very low water level in the bay and a very big concentration of muck.

Extensive entries throughout this period describe "thick, stinky muck", and winds are sometimes mentioned as the cause of accumulation on the beach. Overall, these descriptions indicate that the phosphorus reductions attained in Saginaw Bay did not cause a decrease in beach muck comparable to what other Great Lakes beaches experienced after the 1978 target phosphorus loads became effective.

2.2.5 Field Study – Beach Survey

Each summer from 2009 to 2012 we conducted an observational study of 7-10 sites along the southwestern Saginaw Bay shoreline, between the Saginaw River and Linwood, MI, where the volume, frequency, and composition of detrital

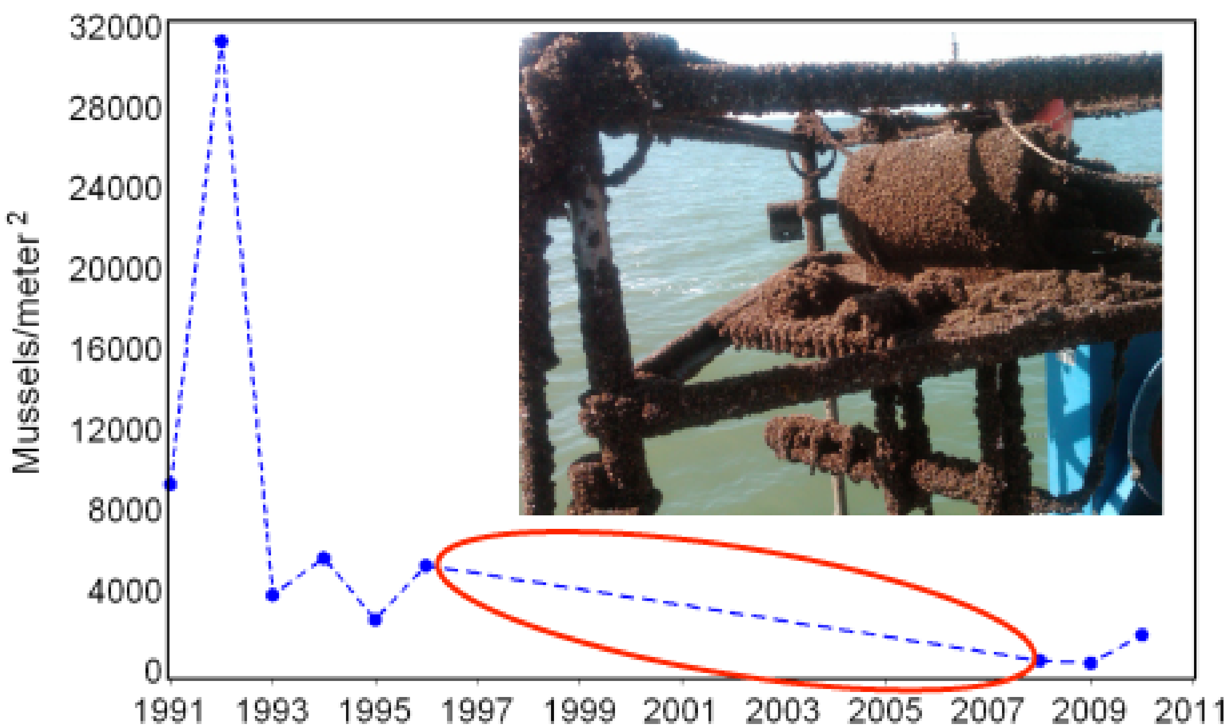

Figure 2.16 – Average dreissenid mussel densities vs time. Inset shows mussel colonization on an instrumentation tripod that was deployed from April-September in 2009. Red ellipse highlights the 11 year monitoring gap.

wash-up was monitored. Sites were chosen based on a preliminary study assessing areas of moderate to severe shoreline deposition (Figure 2.17). Results suggest that muck composition differs across the summer season and between years; *Cladophora*, *Mougeotia, Oedogonium, Spirogyra*, *Zygnema, Chara,* macrophytes, and wood chips have all been observed in varying proportions. For example, in 2009, instances of *Spirogyra*, *Cladophora*, and macrophyte deposition were observed all at different times in the summer months. In 2011, an early, severe deposition of macrophytes and a small amount of filamentous green algae was observed, measuring over 60 cm in depth in some areas along the BCRA. *Mougeotia*, *Ulothrix*, and diatoms were observed in early 2012. This varied composition suggests a more complex underlying process than most other Great Lakes areas where shoreline fouling is usually attributed to deposits of *Cladophora*.

The state of decay of the beach detritus, and thus our ability to identify the main constituents, differed over the study period. Along areas of severe deposition, primarily near the BCRA, fresh muck deposition (i.e. identifiable composition) occurred early in the season and only occasionally thereafter. More often, deposition events contained material so badly decomposed that the composition was indeterminate. However, as we moved north along the shoreline, the detritus was less decomposed and more consistently identifiable. Figure 2.18 compares photos taken at a public access on the end of Cottage Grove Road (Linwood, MI; one of our northern sites) versus a photo taken at the Bay City Recreation Center (Bay City, MI; one of our southern sites) on the same day. We also typically saw a late season (late July, early August) deposition of macrophytes that was consistent across nearly all sites, though this late season deposition was often much smaller in volume than early season (April, May) deposition events.

We also observed a pattern in muck movement and evidence as to the source of the muck precursors. First, muck appears to collect most heavily in inlets and coves along the shoreline, which are areas protected from heavy wind and wave scour. Additionally, the general direction of muck movement is north to south with the most severe areas of deposition located in

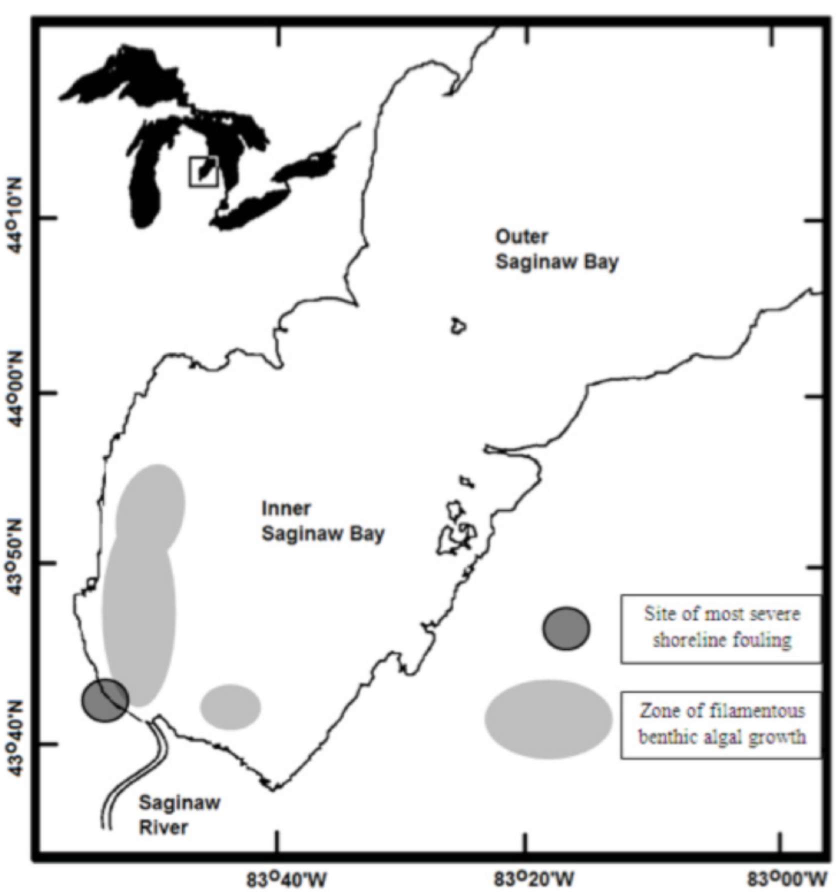

Figure 2.17 – Depiction of the location on Saginaw Bay that experiences frequent, severe shoreline fouling events and the region of benthic algal growth identified by our bay-wide observations. Sampling sites were established in this zone of high deposition.

Figure 2.18 – Comparison of beach detritus between a location north of the Bay City Recreation Area (Linwood, MI) versus the wash-up at the Bay City Recreation Area (Bay City, MI) on the same day. Detritus at northern sites were less decomposed and more identifiable than material at the BCRA sites.

the BCRA. Fine-scale circulation models confirm that currents run in a north to south pattern parallel to the shoreline and indicate that currents regularly converge just north of the river mouth, usually during periods of northerly winds (http://www.glerl.noaa.gov/res/glcfs/currents/). The location of the convergence is in the same area as the areas with heaviest muck deposition. Also, the circulation models suggest that the source of the detritus comes from the southwest portion of the inner bay, which is supported by our field work, explained below.

2.2.6 Fecal Indicator Bacteria

Wet muck samples collected near the water's edge displayed high fecal indicator bacteria (FIB) levels, and nearshore water in the vicinity of muck deposits had higher FIB counts than water from control sites (Figure 2.19). Levels in dry muck samples collected further up on the beach, and levels in beach sand were lower than levels in the wet muck. Wet muck samples experimentally exposed to sunlight for several days showed declining FIB levels with time (Figure 2.20). These results suggest that wet muck harbors FIB and may be a bacteria source to nearby areas.

2.2.7 Field Study – Saginaw Bay Survey

In 2009 and 2010, we conducted a survey to determine the location, composition, and limits to growth of the benthic filamentous algal community of Saginaw Bay. An oblong region, approximately 20 km long and 3.5 km wide (70 km^2), was identified in the southwest region of the inner bay, which extended from 5 km west of the Saginaw River to the northern reach of Pinconning, MI, ranging from 2.0 to <5.0 m depth (Figure 2.17). This region was chosen for accessibility and because simulation models suggested that conditions for *Cladophora* and similar benthic filamentous green algal species production in the inner bay seem to be optimal in the shallow (~2 m depth) areas of the west and southeast portions of the inner bay. The greatest benthic growth was observed in the middle of this region and declined to nearly no growth at the edges, both parallel and perpendicular to the shoreline (for an example of high coverage, see Figure 2.21). In July 2009, sloughed *Cladophora* was observed at multiple locations, in some areas causing 100% coverage of the benthos. During this same time, beach observations indicated that a deposition event included substantial amounts of degraded *Cladophora*. We did not see sloughed *Cladophora* elsewhere in the bay or near agricultural drains, thereby supporting the idea that the decaying *Cladophora* on the beach originated in our sampling area. Additionally, a fine-scale circulation model indicated that currents moving over this area of heavy algal growth converge north of the Saginaw River, where muck deposition is most severe. Therefore, our results support the source of muck precursors to be located in the southwest region of the bay.

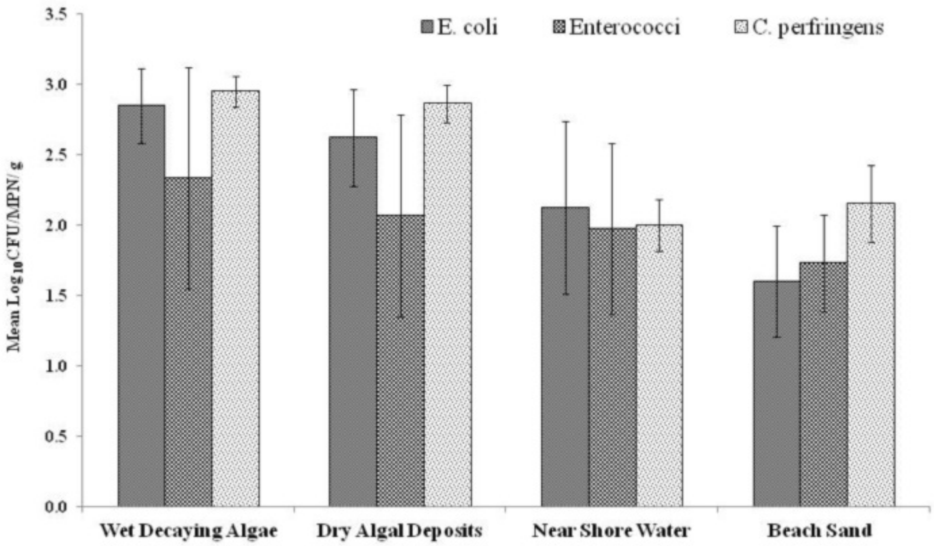

Figure 2.19 - Mean Log_{10} concentrations (± Standard Error) of *E. coli, Enterococci,* and *C. perfringens* concentrations in wet decaying algae (muck), dry algal (muck) deposits, nearshore water, and beach sand. The means represent six samples collected between June and August 2010 on a biweekly basis.

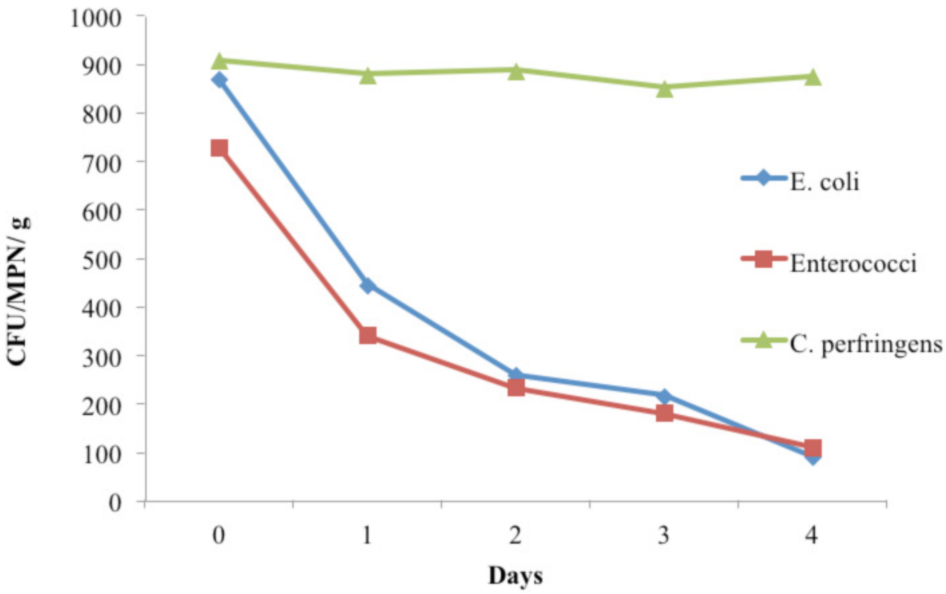

Figure 2.20 – Effect of 96 hrs sunlight exposure on the persistence (survival) of several Fecal Indicator Organisms (FIBs; *E. coli, Enterococci,* and *C. perfringens*) within freshly deposited wet muck collected from Tobico Beach, at the Bay City State Recreation Area. Upon moving a mat of muck to an area of direct sunlight and away from possible contamination from wave action, the muck was spread to a thickness of 15 cm, and 5 g was collected daily from the start of the experiment August 27-31, 2010 and analyzed for FIB following methods by Whitman et al. 2003.

Figure 2.21 – Underwater photos of benthic green filamentous algal growth at transect 9 (near Pinconning, MI), 4.0 m depth on 6/14/2010.

Benthic algal growth was also observed in the localized nearshore areas near agricultural drains and other potential phosphorus sources (Figure 2.22), but we have reason to believe these zones do not provide a majority of the detritus we see in shoreline fouling events. In 2012, muck and nearshore water samples were collected south of an agricultural drain experiencing a large *Cladophora* sloughing event. However, the samples did not show any *Cladophora*, suggesting that the detritus source was not the agricultural drain.

We assessed algae collected from the southwest quadrant of the bay to understand which natural levels of light and phosphorus elicited both the healthiest and least healthy algae in unaltered habitats. Benthic light and tissue phosphorus measurements were made on algal samples collected from a variety of light and phosphorus conditions. Measurements were compared to published light and phosphorus levels documented to cause light and phosphorus stress. At all sites, internal phosphorus measurements were below 1.6 mg P/g dwt, the threshold at which reductions in tissue phosphorus have been reported to reduce algal growth rates (Wong and Clark 1976, Auer and Canale 1982, Higgins et al. 2008; Figure 2.23). The relative light saturation coefficient, a measure of how different the actual light environment is from the required light environment, was below 0 at 14 of 18 sites, indicating that a majority of the samples were light stressed (Figure 2.24). Therefore, our results indicate that the algal muck precursors in the southwest quadrant of the bay are both light and phosphorus stressed.

2.3 Knowledge/Data Gaps – Research Needs

The uncertainty of the annual load estimate in a given year is inversely proportional to the number of TP concentration measurements collected. For most recent years, there are approximately 10-12 concentration measurements available. Managers should evaluate whether the precision available from this level of monitoring is adequate for decision-making. A monitoring schedule consistent with the level of precision appropriate for decision-making should be developed. The load estimation method developed in this study is useful for estimates at the annual scale. If finer-temporal scales are of interest additional methods should be explored and should be supported with data at an appropriate temporal scale.

Our calculations indicate that point sources currently contribute a relatively low proportion of the total annual phosphorus load to the bay. However, the distribution of non-point sources within the watershed is not well-characterized. Dreissenid mussel densities are now much lower than they were in the 1990s, and the community is currently dominated

Figure 2.22 – Photo of algal growth near Rosebud Agricultural Drain, Linwood Michigan on 6/7/2010.

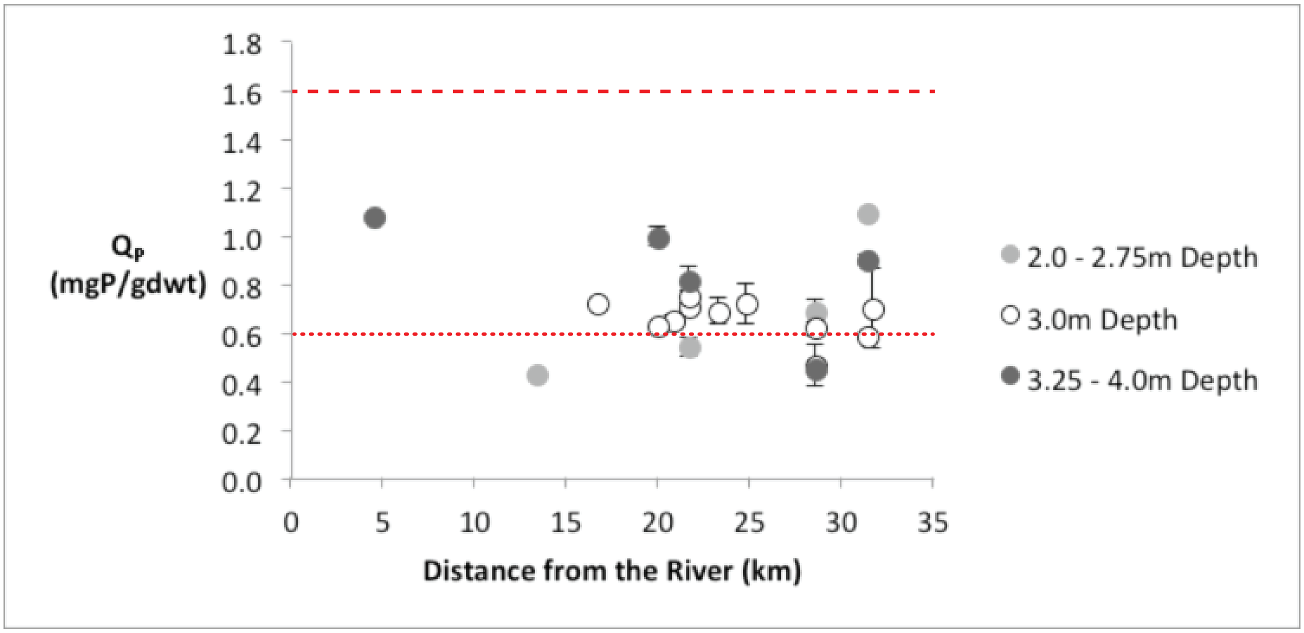

Figure 2.23 – Tissue phosphorus (mg P/g dwt) of benthic filamentous algae in the inner bay of Saginaw Bay, Lake Huron in 2009 compared to published values of phosphorus-limiting tissue concentrations (n = 21). 1.6 mg P/g dwt is the level below which phosphorus is limiting. Based on this threshold, 100% are P-limited. P-starvation 0.6 mg P/g dwt is the critical growth requirement. 26% of the samples are below this threshold, indicating P deficiency. The data is averaged across sample site. Error bars indicate standard error and are based on multiple measurements at a single sample site.

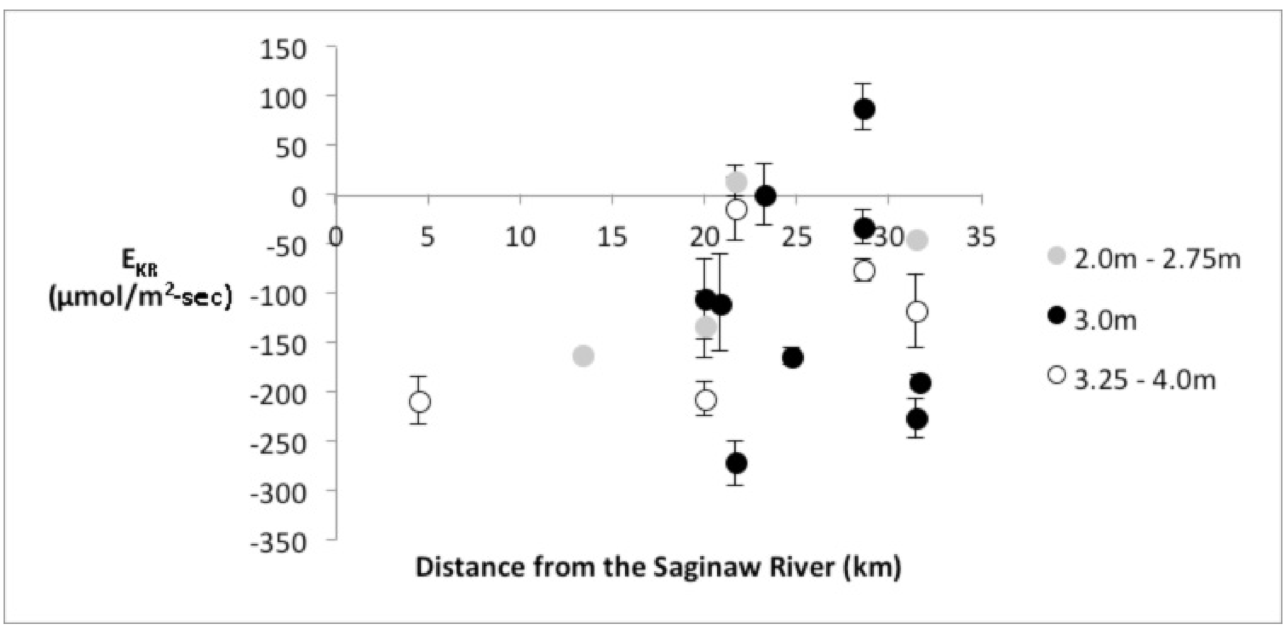

Figure 2.24 – The difference between midday benthic light (µmol/m^2-sec) and the light saturation index (E_K, µmol/m^2-sec), also known as relative E_K, or E_{KR}. Data below 0 indicates subsaturating light conditions. The data is averaged across sample site. Error bars indicate standard error and are based on multiple measurements at a single sample site.

by quagga rather than zebra mussels. However, it is unclear if mussel densities are trending lower or if they just vary over periods of years. The relative role of the mussels in promoting benthic algal production, if further phosphorus reductions occur, is unclear.

Although we have an approximate understanding of the makeup of both beach detritus and the benthic algal community, we do not have estimates of the proportion of detrital material produced that actually washes onto the beaches. If this proportion is small, significant reductions may be needed to noticeably affect beach deposition.

We still have low predictive power as to the timing and severity of major shoreline fouling events. High-resolution, near real-time hydrodynamic models are under active development. Coupling these models with future beach surveys may provide a useful predictive tool to managers and residents of pending deposition events.

The origin of the fecal bacteria observed in association with the beach muck is unknown as is its health risk and association with pathogenic organisms.

Although observed microcystin levels were relatively low, *Microcystis* was observed regularly in the warmer months, and the relationship between *Microcystis* abundance and microcystin production remains unclear. The development of simple empirical models to predict microcystin may be useful to provide an early warning to beach and drinking water managers.

2.4 Management Implications

The 440 tonnes/year target total phosphorus load originally developed for the 1978 GLWQA has almost never been met, and ambient total phosphorus and chlorophyll a concentrations and secchi depth objectives are regularly exceeded in the inner bay. While there is some evidence for episodic sediment phosphorus reintroduction to the water column, the observation that the highest phosphorus and phytoplankton levels consistently occur in the Saginaw River plume make it unlikely that periodic sediment phosphorus release is an important promoter of algal growth. Water-column primary production appears to be phosphorus-limited as does benthic algal growth, thus it is likely that further phosphorus reductions will result in reduced algal production. Point-source total phosphorus discharges constitute a relatively low proportion of the current total phosphorus load; a focus on reducing non-point phosphorus inputs will be necessary to promote further improvements in eutrophication symptoms.

However, the effect of further phosphorus reductions on beach fouling is unclear. Because muck was a consistent occurrence in the 1980s, before dreissenid mussels appeared, it cannot be considered a resurgent problem resulting from the mussel invasion, as it is in other areas around the Great Lakes. Unlike many other Great Lakes beaches, where *Cladophora* is the primary constituent of beach muck, the composition varies near the Bay City Recreation Area. Although benthic algal production, including *Cladophora*, is extensive in the Bay, the observed beach detritus often contains other filamentous algae as well as significant amounts of decaying macrophytes. Phosphorus reductions are unlikely to limit the production of macrophytes, which obtain phosphorus from deposited sediments. Currents in the bay are also important. Our results indicate a significant source of muck precursors in the southwest region of the bay; it is likely that decaying vegetation circulates in large gyres in the inner bay, and is pushed ashore at under appropriate wind conditions.

Published reports in the 1980s, following efforts to reduce phosphorus loading, indicated water quality improvements associated with declining phosphorus inputs. Shortly thereafter, management priorities shifted, and active phosphorus surveillance languished for an extended period. During that time, phosphorus loads stabilized above the 440 tonnes/year target, and dreissenid mussels became established, altering phosphorus cycling and the composition of the algal community. The lapse in active monitoring has made it difficult to fully understand the changes that have occurred over this period. Although invasive mussel densities are currently much lower than they were in the 1990s, they are still widespread, and their future population trajectory is unknown. Additionally, the composition of the mussel community has shifted from exclusively zebra mussels to approximately 75% quagga mussels; their role in nutrient cycling and algal productivity may continue to evolve as conditions in the bay change. To reduce future uncertainties, an active Adaptive Management Strategy, including regular monitoring and routinely updated modeling, should be developed and implemented. The Adaptive Management concept was in its nascent stage at the time of the 1978 Great Lakes Water Quality Agreement but is the basis of Annex 10 of the 2012 Protocol Amending the Agreement.

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3. INVASIVE SPECIES AND FOODWEB DYNAMICS

3.1 Brief history of Saginaw Bay invertebrate and vertebrate assemblages

The Saginaw Bay ecosystem has been impacted by a suite of anthropogenic stressors, including chemical contamination, over-fishing, nutrient enrichment, sedimentation habitat destructions, and invasions of non-indigenous species (Vollenweider et al. 1974, Verbrugge et al. 1995, Fielder 2002). Until the 1970s, the bay was considered highly degraded due to high nutrient loads, various chemical pollutants, and land-use related sedimentation (Schneider 1977). Saginaw Bay historically supported productive cool water fisheries for species such as yellow perch, walleye, and lake herring, because it is generally warmer and more eutrophic than the main basin of Lake Huron. However, overfishing and habitat degradation led to declines and extirpation of many native fish populations by the 1940s (Hile and Buettner 1959, Schneider and Leach 1977, Fielder et al. 2000). Degradation in overall water quality and fisheries led to the listing of Saginaw Bay as an Area of Concern (AOC) by the International Joint Commission in 1978 (International Joint Commission 1978).

Since the 1970s, the impacts of several environmental stressors on Saginaw Bay may have seemingly lessened, and environmental conditions may have improved. Nutrient abatement programs have led to a reduction in phosphorous loadings (Cha et al. 2010). Direct discharges of chemical contaminants have decreased, although many legacy impacts of contaminants still persist (Jude et al. 2010, Wan et al. 2010). Stocking of walleye, beginning in 1980, led to the reestablishment of this fish population (Fielder et al. 2007). However, since the 1970s, Saginaw Bay has experienced numerous invasions, including spiny water fleas (*Bythotrephes*), white perch (*Morone americana*), round goby (*Neogobius melanostomus*), and zebra/quagga mussels (*Dreissena polymorpha* and *D. bugensis*). In addition, alewife, an invasive fish species that was a dominant component of the ecosystem since the 1950's, crashed in 2003 (Schaeffer et al. 2004, Schaeffer et al. 2005, Roseman et al. 2006) and has since not fully recovered. For a timeline of some noteworthy events in Saginaw Bay see Figure 3.1.

Altered environmental conditions, species invasions, and shifts in dominant foodweb components have undoubtedly altered Saginaw Bay's foodweb. However, due in part to limited, long-term monitoring of physical conditions, nutrient loading (but see Cha et al. 2010), chemical concentrations and lower trophic levels, a complete understanding of foodweb responses is lacking. In contrast to many environmental variables, the Michigan Department of Natural Resources (MI-DNR) has maintained a long-term fish trawling program in Saginaw Bay from 1970 to present. This dataset facilitates evaluation of long-term changes to the Saginaw Bay fish community and inferences regarding potential environmental variables driving changes in this fish community.

We aim to describe current patterns and long-term changes in the Saginaw Bay foodweb through field surveys and analyses of historic data. While many previous biotic studies of Saginaw Bay have focused on yellow perch and walleye (i.e., key species targeted by recreational and commercial fisheries; see section 4), production of walleye and yellow perch is dependent on conditions of the entire foodweb. We collected zooplankton, benthic invertebrates, and fish to examine spatial and seasonal assemblage patterns and trophic connections. In addition, we used the long-term MI DNR trawling survey to evaluate changes at the fish assemblage level and we compared lower trophic level (zooplankton and benthic invertebrates) to patterns documented during the 1990s.

3.2 Project Findings

3.2.1 Data sources

Field Surveys: From April 2009 through June 2011, we conducted extensive field collections in Saginaw Bay. These surveys targeted a number of different research questions and aspects of the Saginaw Bay ecosystem (described elsewhere in this report). We collected zooplankton using vertical tows of 64 µm zooplankton nets. We collected predatory zooplankton (*Leptodora* and *Bythotrephes*) and ichthyoplankton primarily using surface and oblique tows of a bongo sampler (335 and 700 µm) mesh. We sampled benthic macroinvertebrates with a standard Ponar dredge (0.052 m^2 with

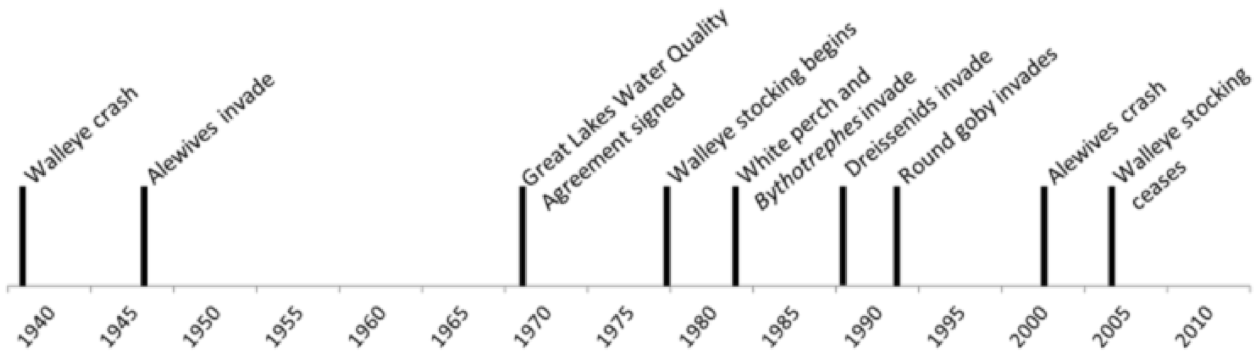


Figure 3.1 - Timeline of notable changes to the Saginaw Bay foodweb.

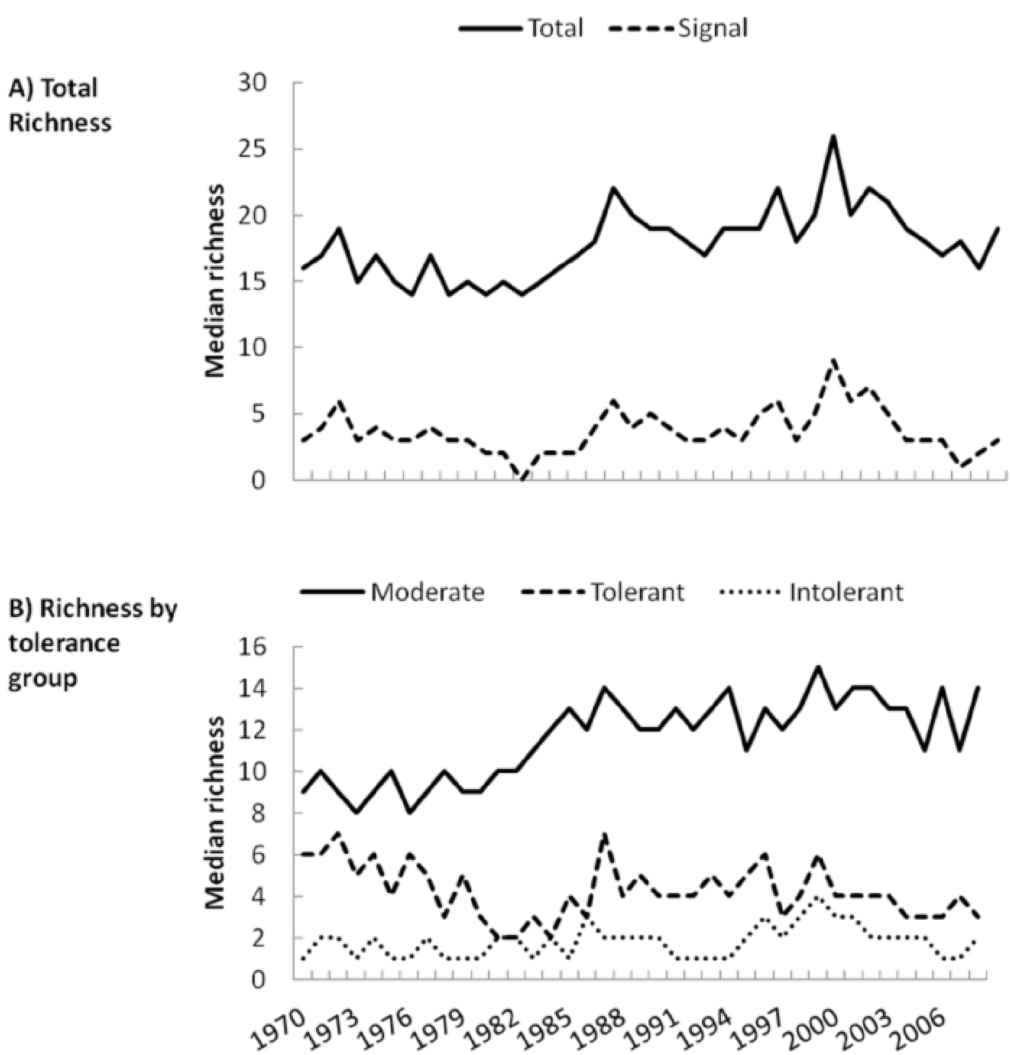


Figure 3.2 - Median richness in 10 trawls as determined by Monte Carlo simulations from the fall Saginaw Bay trawl survey (1970-2008) for A) total (rho=+0.57, p<0.05) and signal (relatively rare; see Ludsin et al. 2001) species richness (p>0.05) and B) tolerant (rho=-0.32, p<0.05), intolerant (rho=+0.32, p<0.05), and moderately tolerant (rho=+0.77, p<0.001) species richness.

500 μm mesh). Finally, we collected fish with a 7.6 m semi-balloon bottom trawl with a 13 mm stretched-mesh cod-end, which was towed for 10 min at approximately 1.29 ms^{-1}. Organisms were preserved on board and then identified, enumerated, and examined (length/mass measurement, diet analyses) in the laboratory.

Historical analyses: We also evaluated biotic patterns in Saginaw Bay by analyzing historic patterns of fish collected through a long-term MI DNR trawling program (1970-present). Compared to fish community assessments, long-term surveys of invertebrates in Saginaw Bay are lacking. Thus, we compared invertebrate patterns observed during 2009-2011 with patterns documented during the 1990s by NOAA GLERL (for description see: Nalepa et al. 1996, Johengen et al. 2000). These data from the 1990s represent a time period when zebra mussels proliferated in Saginaw Bay, alewives were still abundant, and round goby were not established.

3.2.2 Key Findings

Zooplankton: Our findings related to zooplankton community patterns are described in a recent paper by Pothoven et al. (2013). In brief, we found a substantial shift in the zooplankton community from the 1990s to 2009-2010. Calanoid copepods increased in proportional abundance, as did some large-bodied taxa, such as *Daphnia galeata*. Relatively small Bosminidae were the most abundant taxa during both time periods, but their proportional abundance was greater during the 1990s than 2009-2010. These shifts in zooplankton size structure coincided with the collapse of alewife in 2003. Alewives are voracious size-selective planktivores, capable of restructuring zooplankton size assemblages (e.g., Brooks 1968). Other shifts in the zooplankton assemblage (e.g., increased abundance of calanoid copepods) are suggestive of a shift towards oligotrophication. Similar patterns are evident for Lake Huron, where decreased nutrient loading and dreissenid filtering may contribute to a more oligotophic-indicative zooplankton assemblage (Barbiero et al. 2011). However, Saginaw Bay has remained relative productive since 1990, and hence the shift to a more oligotrophic assemblage is somewhat perplexing.

In addition to shifts in composition, Saginaw Bay's zooplankton community seems to have shifted phenologically. During the 1990s, zooplankton abundance was greatest in late spring and early summer (June), whereas during 2009-2010, zooplankton abundance was greatest during fall (September-October). This shift in abundance and the decreased abundance in late spring and early summer may have important implications for survival and subsequent recruitment of young fish, which may rely on zooplankton as prey during larval and early juvenile stages. However, the mechanisms underlying this temporal shift are unclear. Bottom up processes (e.g., reduced phytoplankton densities in spring/early summer) and shifts in planktivore composition may be contributing factors. Planktivory by young alewives may be greatest in late summer and early fall (Hewett and Stewart 1990). In contrast, consumption by young yellow perch may be greater in early summer than early fall (e.g., Hayward et al. 1991). Thus, a shift from abundant alewife to abundant age-0 yellow perch may have led to temporal shifts in zooplankton abundance.

Finally, not only herbaceous zooplankton, but also predatory zooplankton patterns shifted in Saginaw Bay from the 1990's to 2009-2010 (Pothoven et al. 2013). Two taxa of predatory zooplankton (*Leptodora* and *Bythotrephes*) were present in the system during both of these time periods. While densities of *Bythotrephes* increased significantly between the two time periods, *Leptodora* did not. Nonetheless, *Leptodora* densities decreased qualitatively: While *Leptodora* peaked in abundance during June in both 1991-1996 and 2009-2010, a subsequent peak in late summer was only evident in the 1990s. In contrast, *Bythotrephes* densities were consistently higher during the 2009-2010 period (0.9 m^{-3} vs 7.6 m^{-3}), with a small peak in abundance in the early summer and a much greater peak in the fall (Pothoven et al. 2013).

Benthic invertebrates: We collected benthic invertebrates on a monthly basis from several locations in Saginaw Bay and documented much greater spatial than temporal variation in benthic invertebrate assemblages (Foley et al. *in review*). Dominant taxa included quagga mussels (which have now almost entirely replaced zebra mussels in Saginaw Bay) and Chironomidae. For the most part, Saginaw Bay continues to be dominated by benthic invertebrate species tolerant of eutrophic and poor water quality conditions. However, we have found some more pollution sensitive taxa (*e.g., Hexagenia* and Trichoptera; Foley et al. *in review*, D. Kashian unpublished data) suggesting that the benthic community may be marginally responding to decreased nutrient loading and improved water quality.

The most noteworthy difference between benthic invertebrates collected during the 1990s and 2009-2010 was a significant decline in dreissenid mussel densities (Table 3.1). The mechanisms responsible for this decline are enigmatic. It is plausible that the densities observed during the 1990s followed a near exponential population growth that would inevitably lead to a compensatory reduction in sustainable density. Moreover, the shift from zebra to quagga mussels, slight decreases in nutrient loading, and potential predation by round gobies (see below) may all have contributed to this decline.

Table 3.1 - Mean density (no m^{-2}) of *Dreissena* in Saginaw Bay (from T. Nalepa).

Year	Inner Bay (5 sites)	Outer Bay (1 site)
1991	9,305	3,408
1992	31,334	4,695
1993	3,803	5,813
1994	5,633	9,925
1995	2,562	3,824
1996	5,261	6,981
Mean (91-96)	**4,314**	**6,636**
2008	**538**	**596**
2009	**421**	**411**
2010	**1,808**	

Fish community: Analyses of long-term sampling of the Saginaw Bay fish assemblage by the Michigan DNR (1970-2011) suggest that the community has shifted dramatically over the past four decades. We considered temporal changes in the fish assemblage using: 1) analyses of changes in richness metrics, 2) dynamic factor analyses (DFA) to fit long-term trend models of the most abundant fish species, and 3) non-metric multidimensional scaling (nMDS) to visualize differences in assemblage structure among different years. The median richness of fishes collected through Michigan DNR trawling increased marginally from the 1970s to present. In particular, richness of species classified as tolerant of eutrophic conditions decreased, whereas richness of species classified as marginally tolerant of eutrophic conditions increased. DFA and nMDS analyses which account for species-specific trends in relative abundance also suggest that the fish assemblage has shifted dramatically (for details see Ivan et al. *in revision*).

These shifts in the Saginaw Bay fish assemblage have occurred coincident with decreased nutrient loading and overall productivity in Saginaw Bay (Cha et al. 2010). In addition, the observed shifts in assemblage composition and structure (e.g., reductions in eutrophic tolerant species) are indicative that the fish assemblage has responded to improved water and habitat quality related to diminished eutrophy. We compared the ability of annual nutrient loading to explain assemblage patterns, versus the explanatory ability of other environmental variables (temperature, water levels, water flow). In so doing, we found that annual phosphorous loading was most strongly associated with shifts in assemblage patterns. However, the paucity of long-term environmental data made it difficult to rigorously evaluate a complete set of potential environmental variables, potentially structuring the Saginaw Bay fish community (for details see Ivan et al. *in revision*).

Fish species of note: Our surveys during 2009-2011 were primarily designed to describe yellow perch and walleye performance and interactions in Saginaw Bay (see other section of this report). However, we collected various other species during these surveys and below we point to some observations related to round goby, trout-perch and lake whitefish.

-*Round goby*: As described above, round goby invaded Saginaw Bay in the late 1990s and subsequently proliferated throughout the bay. They now represent an important diet item for piscivorous yellow perch and walleye (see walleye-perch section). In addition, they may play important roles as predator on benthic invertebrates and a competitor with benthivorous fishes. In many areas of the Great Lakes, round goby have been identified as contributing to altered spatial distributions, decreased abundance, and local extirpations of species such as johnny darter, logperch, and slimy sculpin. In fact, since the round goby invasion in Saginaw Bay, some small-bodied benthivorous species have become less common in annual trawl surveys (Fielder and Thomas 2006).

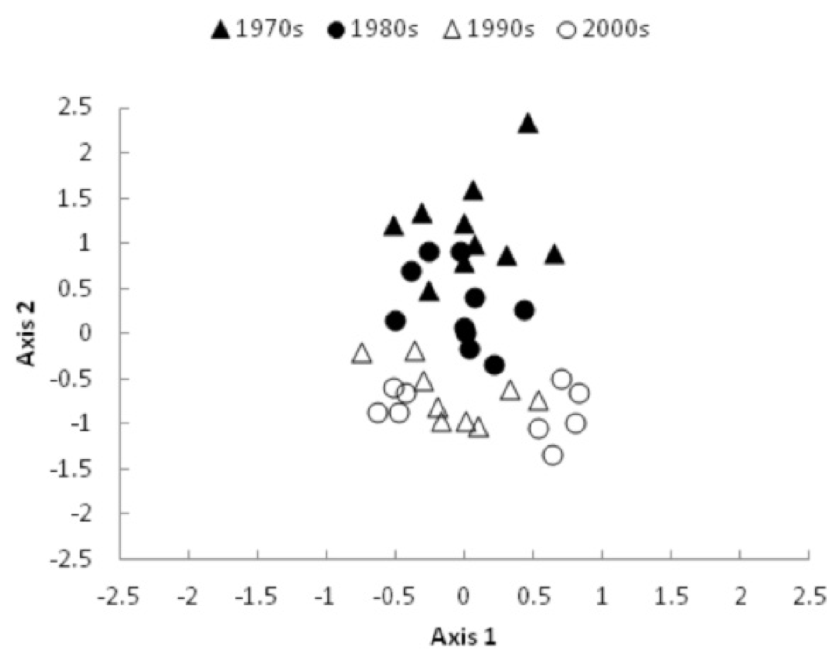
We found that round goby preferentially consumed Chironomidae larvae in Saginaw Bay (Figure 3.4). Since these prey are also targeted by several ecologically and economically important native species (e.g., young walleye, yellow perch, lake whitefish, trout-perch, etc), round goby have the potential to compete for prey resources (if these resources are limited).

As described above, abundance of dreissend mussels in Saginaw Bay declined from the mid 1990s to the late 2000s. As a potential predator on dreissenid mussels, round goby may have contributed to this decline. We found that relative consumption of dreissenids by round gobies increased with size (Figure 3.4) and tended to be highest in the fall. In addition, the size of dreissenids consumed increased with round goby size (Figure 3.5). Foley et al. (*in prep*) compared the size of dreissenids in the environment with the size of dreissenids in the guts of gobies and suggested that size-selective predation by gobies could partially explain dreissenid size distributions in the environment. However, preliminary bioenergetics analyses (based on maximum consumption rates and observed goby densities) suggest that the potential for goby consumption to limit dreissenid abundance is low.

-*Trout-perch*: Trout-perch are a native but largely understudied species in the Great Lakes. Due to their relative high abundance (third most abundant species collected in our bottom trawls), trout-perch likely play an important role in the Saginaw Bay foodweb. Our findings related to trout-perch interactions are described in a recent paper by Blouzdis et al. (2013). In brief, we found that trout-perch primarily consume Chironomidae larvae, and often display strong positive selection for Chironomidae and Amphipoda (a less abundant benthic prey). In contrast, dreissenid mussels, the most abundant benthic invertebrates in Saginaw Bay, were entirely absent from trout perch diets.

Despite their high abundance, trout-perch were very rare in the diets of potential piscivorous yellow perch and walleye; trout-perch constituted 5 out of 1370 piscine diet items (0.4%), while they constituted 15% of fish collected in bottom trawls (Blouzdis et al. 2013).

Figure 3.3 - Results of a preliminary non-metric multidimensional scaling analysis to visualize changes in the relative abundances of the Saginaw Bay fish assemblage, based on Michigan Department of Natural Resources trawling data from 1970 to 2008.



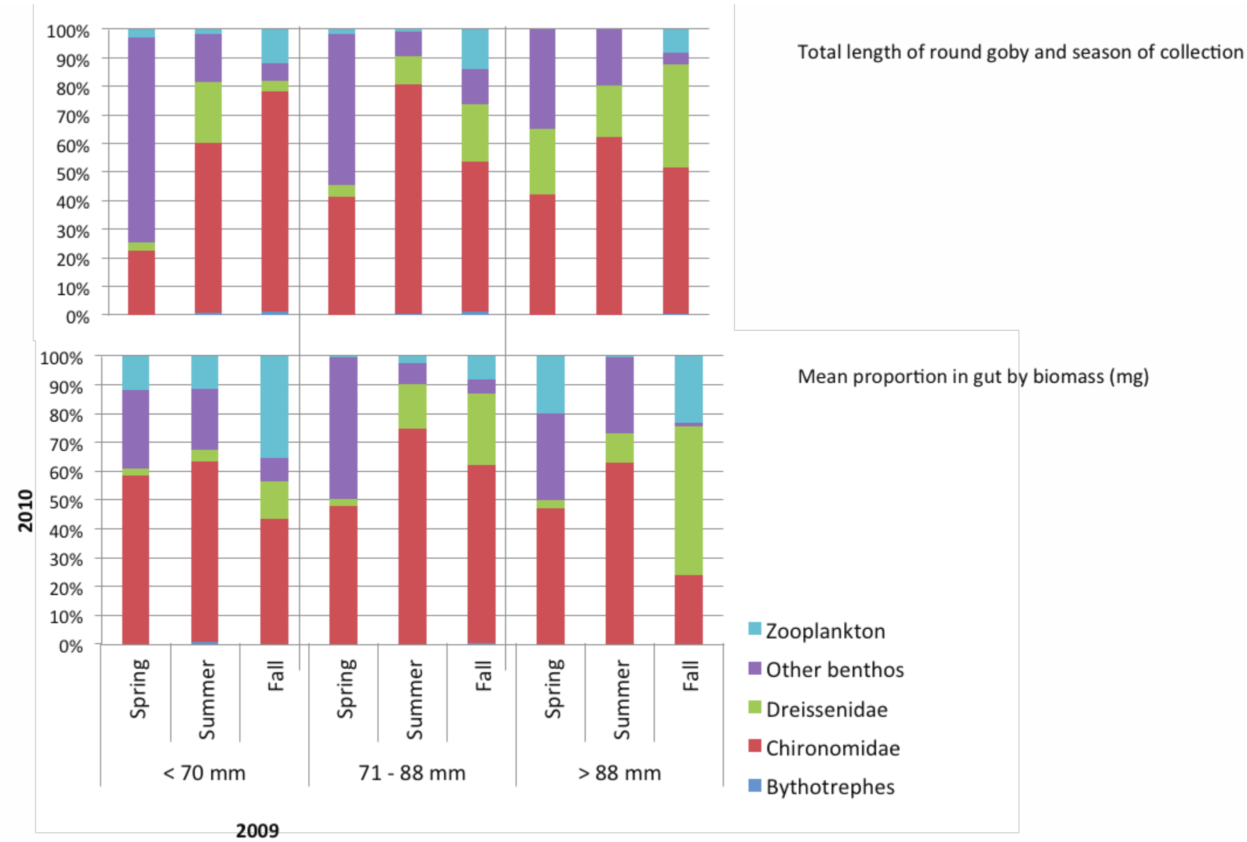


Figure 3.4 - Gut contents of round gobies, summarized by size, season collected, and year. Chironomid larvae (red) make up large proportions of the gut contents regardless of size, season or year. Dreissenids (green) make up increasingly larger proportions of items consumed as fish length increases or the season progresses. Even the smallest gobies rely on dreissenids to some degree. Zooplankton (turquoise) are dominated by ostracods. Other benthos (purple) are dominated by mayfly larvae, chironomid pupae and amphipods.

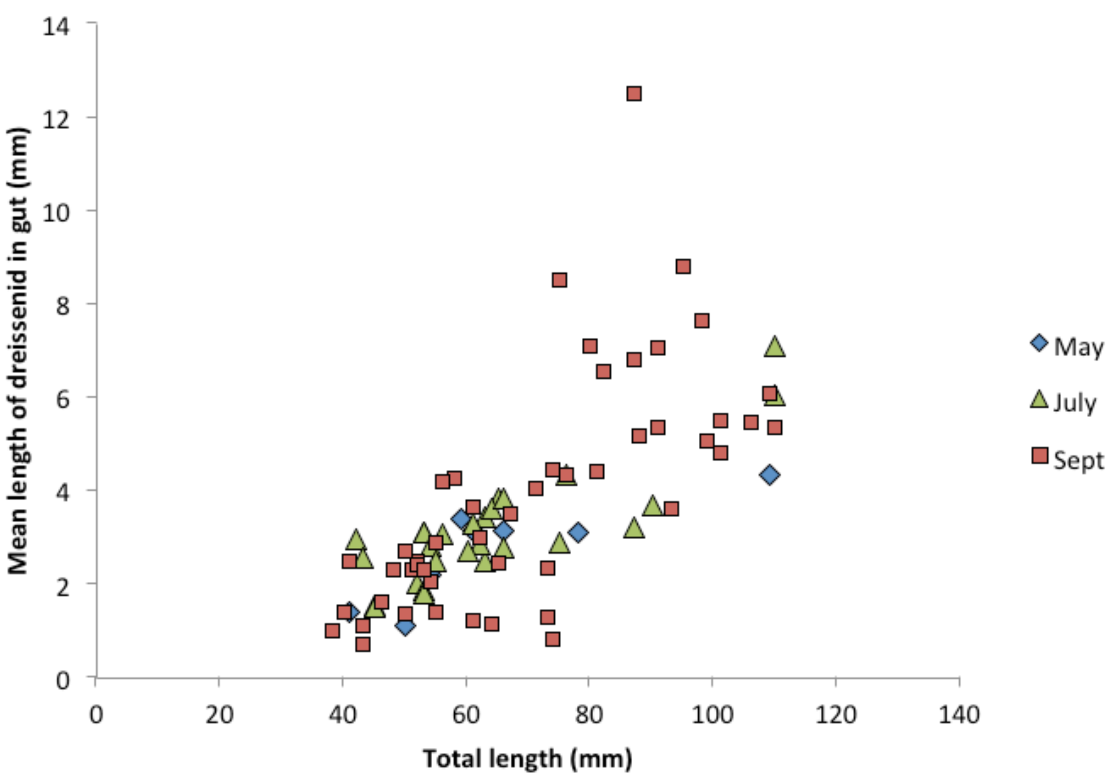


Figure 3.5 - Mean length of dreissenids found in different-sized round gobies. Larger gobies consume larger dreissenids regardless of time of year, while few gobies tend to consume dreissenids that are larger than 10 mm.

-Lake whitefish: Lake whitefish support important commercial fisheries in outer Saginaw Bay and in the main basin of Lake Huron. Lake whitefish spawn in inner Saginaw Bay and given the high productivity of inner Saginaw Bay, this habitat may allow for rapid growth of young whitefish and represent an important source of lake whitefish production for other regions of Lake Huron. We collected larval lake whitefish during April-June in both 2009 and 2010, and subsequently collected young-of-year lake whitefish in bottom trawls from June-November (for details see Pothoven et al. *in review*). Age-0 lake whitefish shifted from initially feeding on cyclopoid copepods to subsequently target cladocerans and then benthic prey (Chironomidae, Chydoridae and Sphaeridae). While we did not directly measure growth rates of young lake whitefish, the high abundance (relative to main basin of Lake Huron) of their preferred prey suggests that the potential for growth of young whitefish in Saginaw Bay is high (Pothoven et al. 2013). Also, it is worth noting that we did not find any young lake whitefish in diets of potential piscovorous fish.

3.3 Research Needs and Management Implications

Eutrophication and biotic responses: Saginaw Bay's biota appears to have partially responded to long-term reductions in nutrient loading and improved water quality. A variety of patterns point to such responses including: 1) a more oligotrophic zooplankton assemblage, 2) reemergence of some sensitive benthic invertebrates, and 3) a shift in the fish assemblage from species highly tolerant of eutrophic conditions to species moderately tolerant of eutrophic conditions. Nonetheless, many tolerant invertebrate and fish species remain highly abundant in Saginaw Bay and more sensitive species remain a minor component of overall communities. Thus, while our findings point to positive biotic responses, continued efforts to reduce nutrient loading/sedimentation and improve water quality are likely necessary for Saginaw Bay's biotic composition to continue to shift towards more sensitive species.

Invasive species: Several of the taxa that seem to have responded to ecosystem level changes in Saginaw Bay are not actively managed, and hence the taxa-specific management implications of some of our findings are not straightforward. For example, while it is clear that several invasive species play important roles in the Saginaw Bay's foodweb (e.g., quagga mussels, *Bythotrephes*, round gobies) it is not obvious how to control these species.

While invasive species are generally considered negatively, some invaders are contributing to production of desirable native fish species in Saginaw Bay. *Bythotrephes* are consumed by age-0 walleye and are strongly selected as preferred prey by age-1 and older yellow perch in Saginaw Bay. Similarly, round goby are consumed by piscivrous walleye (from age-0 through the end of life) and age-1 and older yellow perch.

Coregonids: To our knowledge, there have been limited previous studies of lake whitefish in Saginaw Bay. We found evidence that inner Saginaw Bay supports relatively fast growth of young whitefish, and we found no evidence that young lake whitefish are targeted by piscivorous walleye or yellow perch. We speculate that due to high availability of invertebrate prey (both zooplankton and benthic invertebrates), inner Saginaw Bay may constitute a high quality nursery source for adult lake whitefish, which in turn support fisheries in outer Saginaw Bay and main basin of Lake Huron.

The strong performance of young lake whitefish in Saginaw Bay may suggest that physiologically similar species may also thrive in Saginaw Bay. The potential for reestablishment of abundant stocks of native cisco (lake herring) in Lake Huron has received strong support. In the absence of alewife, this planktivore may now be able to fill an important ecological role in both Saginaw Bay and main basin of Lake Huron.

While growth conditions appear to be suitable for young coregonids, spawning habitat may constitute a potential bottleneck for increased lake whitefish and cisco production in Saginaw Bay. Past studies suggest that many potentially suitable spawning sites in Saginaw Bay have been lost through sedimentation. It is an open question where lake whitefish are currently spawning in inner Saginaw Bay. We suggest that future surveys could evaluate (a) whether coregonid spawning habitat is truly limited, and (b) the potential for creation of additional spawning habitat in Saginaw Bay.

Temporal shifts of invertebrates: We documented some temporal shifts (both within and across years) in invertebrate densities which are not straightforward to explain, but may have important implications. First, we found that zooplankton peak densities occur much later in the year now, than they did historically. This may have important implications for young fish that rely on abundant zooplankton as prey during early, critical life stages. Although we speculate that both bottom-up and top-down changes may have contributed to this shift (see above), we are unable to robustly evaluate the mechanistic underpinnings. Given the potential importance of this change in zooplankton density cycles, we suggest that future studies should more fully explore the mechanisms.

Second, we also documented a decline in dressenid abundance from the 1990s to late 2000s. This trend is opposite to patterns observed in many systems, where dreissenids have continued to increase over time. While some patterns (i.e., dreissenid size structures) suggest that goby predation may influence dreissenid populations, our preliminary bioenergetics estimates of goby consumption suggest that such predatory control is unlikely. Future efforts to understand the mechanisms of dreissenid declines would be useful and may help inform management efforts in several other systems, where control of dreissenids would be highly desirable.

Long-term monitoring: Finally, we believe that our studies in Saginaw Bay demonstrate the value of long-term monitoring. Many aspects of the Saginaw Bay ecosystem (e.g., water quality, invertebrate assemblages) have not been routinely monitored over a long time period, making it difficult to document historic trends and consider potential mechanisms underlying changes. In contrast, the Michigan Department of Natural Resources long-term (1970-present) trawling program in Saginaw Bay represents an invaluable resource for exploring historic biotic responses. In many aquatic systems, data availability is the converse of Saginaw Bay (i.e., long-term data on environmental conditions, but limited data on upper trophic levels like fishes). The Michigan DNR should be applauded for maintaining this program and we hope that it will continue indefinitely.

3.4 Section 3 References

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4. FISH AND FISHERY MANAGEMENT IN SAGINAW BAY

4.1 Brief History of Saginaw Bay Walleye and Perch Fishery

Yellow perch and walleye presently and historically represent the most important fisheries in Saginaw Bay (Fielder and Thomas 2006). Successful production of harvestable walleye and yellow perch requires survival from hatching to a size suitable for harvest. As is the case for most fish species, walleye and yellow perch are highly fecund and produce large numbers of young most of which die during early life. Large initial cohort sizes imply that the greatest capacity for altering fish population production relates to changes in vital rates (survival and growth) during early life. These early life determinants of walleye and perch recruitment have evidently varied dramatically over time in Saginaw Bay.

Prior to the middle of the 20th Century, the Saginaw Bay walleye stock consistently supported the second largest commercial fishery in the Great Lakes (i.e., during this time there was consistent successful natural reproduction; Schneider and Leach 1977, Mrozinski et al. 1991). However, due to a variety of factors (including over-exploitation, invasive species, and intensive eutrophication) the stock collapsed. Even though the Michigan Department of Natural Resources (MDNR) was able to reestablish (and subsequently maintain) an adult walleye population (Keller et al. 1987), until recently, this population has been almost entirely dependent upon stocking (i.e., limited evidence of successful natural reproduction; Mrozinski et al. 1991, Fielder 2002).

The Saginaw Bay yellow perch population, on the other hand, has persisted despite dramatic changes to the ecosystem and without intensive stocking efforts, and in fact, continues to support both commercial and sport fisheries. However, growth rates of this population have varied dramatically over time: during the 1980's, growth rates of Saginaw Bay yellow perch were anomalously low (likely owing to insufficient benthic invertebrate prey resources; Schaeffer et al. 2000), but following a severe decline in population abundance from 1989 to 1991, growth rates increased markedly (Fielder et al. 2000).

Interestingly, during the past few years, MDNR early fall survey trawling has documented large numbers of age-0 walleye and yellow perch in Saginaw Bay (Fielder and Thomas 2006). However, the young fish that constitute these abundant cohorts have experienced poor growth rates and obtained relatively small body sizes by the fall (Fielder and Thomas 2006). In turn, these small individuals may have limited energy reserves and high mass-specific metabolic rates potentially leading to high starvation mortality during winter (a period of resource scarcity) and prolonged susceptibility to gape limited predators. In fact, recent MDNR collections of age-1 walleye and yellow perch indicate that survival rates from age-0 to age-1 are low for walleye and extremely low for yellow perch.

These differential survival rates of young percids suggest that the bottlenecks limiting recruitment of walleye and yellow perch in Saginaw Bay have changed over time. Prior to 2003, fall age-0 walleye abundance was low (Fielder et al. 2007), indicating poor survival during larval and early juvenile planktivorous ontogenetic stages. During this time, invasive alewives dominated the Lake Huron fish community (Dobiesz et al. 2005) and were seasonally abundant in Saginaw Bay (i.e., adults were abundant during spawning migrations in late spring and early summer, while age-0 alewives utilized Saginaw Bay as a nursery habitat during summer and early fall). Alewives are voracious planktivores capable of restructuring zooplankton communities (Brooks and Dodson 1965, Wells 1970, O'Gorman et al. 1991, Scavia et al. 1986, Evans 1992) and thereby competing with young planktivorous walleye and perch. In addition, there is a plethora of evidence from a variety of systems that alewives are potentially important predators on percid early life stages (e.g., Brandt et al. 1987, Mason and Brandt 1996). It is thus not surprising that coincident with the recent collapse of the Lake Huron alewife population (Fielder et al. 2007), early life survival rates of walleye and perch increased dramatically (Fielder and Thomas 2006), such that growth conditions during the late summer and fall (when young walleye and perch rely primarily upon piscivory and invertivory, respectively) may now more strongly affect recruitment success (Fielder and Thomas 2006).

While it is apparent that recruitment bottlenecks for walleye and yellow perch in Saginaw Bay have changed over time, it is not clear how the suite of stressors affecting the Saginaw Bay ecosystem (nutrient loading, river discharge, invasive species, and climate change) have (in the past) and will (in the future) interactively impact annual production and recruitment of these two species. An empirical (regression) analyses evaluating the effects of various biological and physical potential determinants of walleye recruitment (based on MDNR fall trawling surveys) suggests that from the period including 1993-2005, adult alewife abundance in Lake Huron was the single best predictor of walleye recruitment (fall abundance of wild and hatchery age-0 walleye; Fielder et al. 2006). This and other empirical analyses are useful for identifying potentially important determinants of recruitment success and for generating hypotheses regarding recruitment mechanisms, but such analyses are less useful for rigorously evaluating such hypotheses. Further, given that (1) ecosystems are characterized by strong non-linear relationships (which are difficult to account for through empirical analyses), (2) a multitude of temporally correlated natural and anthropogenic forcing factors can influence temporal trends in population biomass and growth, and (3) the Saginaw Bay ecosystem may have undergone a regime shift leading to potential non-stationarity in causal relationships; empirical relationships may have limited predictive power beyond the time-period represented by their underlying data sets. This is especially true if future values of predictive variables extend beyond the range of values upon which the relationship was established.

We therefore explore mechanisms of walleye and perch recruitment in Saginaw Bay by evaluating their early-life dynamics (growth, survival, and food-web interaction) from hatching through survival to the following spring. During this time, these fish are expected to change from consuming primarily zooplankton to consuming primarily benthic invertebrates and fish. Thus, depending upon how nutrients move through the ecosystem (to zooplankton vs. benthos), different life stages (larvae, late-stage juveniles) may be growth limited (population bottlenecks) during this period. In turn, growth rates will have clear implications for survival (due to size-dependent predation pressure and size-dependent over-winter mortality), and survival rates will also vary independent of growth, as abiotic conditions can dramatically mediate predation pressure.

4.2 Project Findings

Historical analyses: To appreciate dynamics structuring early-life performance of yellow perch and walleye in Saginaw Bay, we initially analyzed historical data (1970-2008) collected as part of the Michigan Department of Natural Resources' long-term trawling program in Saginaw Bay. These analyses are largely described by Ivan et al. (2011).

Walleye have been stocked in Saginaw Bay since 1980, and hence, our historical analyses of walleye covered the period 1980-2008. During this time period, we found weak evidence of density-dependent controls on walleye growth. That is, while the mean lengths of young (ages 0-2) walleye cohorts in the fall were negatively associated with the relative abundances of these cohorts, these relationships were weak and insignificant. In addition, our analyses suggest that walleye year-class strength (both in terms of abundance and mean size) are set by fall of age 0. Relative abundances of age-0 walleye were strongly, positively related to the relative abundances of age-1 and age-2 walleye 1 and 2 years in the future, respectively. Similarly, mean lengths of age-0 walleye were strongly, positively related to the mean lengths of age-1 and age-2 walleye 1 and 2 years in the future, respectively. In short, these analyses suggest that factors influencing growth and survival of walleye before fall of their first year of life are strong determinants of year-class strength (Table 4.1).

Our analyses suggest that for the period 1970-2008, growth of young yellow perch cohorts in Saginaw Bay are negatively related to density of a particular cohort (particularly strong correlations for ages 0 and 2), suggesting that growth is influenced by compensatory density-dependence. Moreover, these analyses suggest that yellow perch year-class strength (both in terms of abundance and mean size) are set by fall of age 1. That is, for the period 1970-2008 the relative abundance and mean length of age-1 yellow perch were strongly, positively related to the relative abundance and mean length (respectively) of age-2 yellow perch the following year. In contrast, while relative abundance and mean length of age-0 yellow perch were positively related to the relative abundance and mean length (respectively) of age-1 yellow perch the follow year, relative abundance and mean length of age-0 yellow perch were unrelated to relative abundance and mean length of age-2 yellow perch 2 years later. In short, these analyses suggest that factors influencing growth and survival of yellow perch before fall of their first year of life are insufficient to explain subsequent year-class strength; however, processes occurring before fall of their second year of life do seem to define year-class strength (Table 4.1).

Table 4.1 - From Ivan et al. (2011): Age-specific correlations of walleye and yellow perch surveyed through the Michigan DNR's annual trawling surveys in Saginaw Bay. (a) Yellow perch display strong compensatory density-dependent effects on growth, while such effects are weaker for walleye. (b-c) Year-class strength (b) in terms of mean length; (c) in terms of abundance) of walleye are set by fall of age-0, while year-class of perch appear to be set by fall of age-1.

Walleye (1980-2008)				Yellow perch (1970-2008)		
a) Correlations between annual age-specific mean CPUE and mean length.						
	age-0	-0.44			-0.53*	
	age-1	-0.28			-0.18	
	age-2	-0.10			-0.65*	
b) Correlations between annual age-specific mean lengths [age (x) in year (t) vs. age (x+1) in year (t+1)].						
		age-1	age-2		age-1	age-2
	age-0	+0.64*	+0.70*		+0.66*	+0.04
	age-1		+0.62*			+0.78*
c) Correlations between annual age-specific CPUE [age (x) in year (t) vs. age (x+1) in year (t+1)].						
		age-1	age-2		age-1	age-2
	age-0	+0.64*	+0.79*		+0.35*	+0.18
	age-1		+0.72*			+0.78*

Analyses of these long-term time series may provide insights to factors structuring past recruitment of walleye and yellow perch in Saginaw Bay. Fielder et al. (2007) evaluated the effects of various potential biological and physical determinants of walleye recruitment (based on MDNR fall trawling surveys) and suggested that from 1993 to 2005, adult alewife abundance in Lake Huron was the single best predictor of walleye recruitment (fall abundance of age-0 walleye). We conducted similar analyses evaluating yellow perch recruitment during the period 1970-2008. Since yellow perch recruitment seems to be set by fall of age-1, we used relative abundance of age-1 yellow perch in fall trawling surveys as a measure of recruitment. In addition, we developed models to explain variation in age-0 yellow perch production. Long-term (i.e., 1970-present) annual environmental data are lacking for Saginaw Bay, and we were thus limited in the number of explanatory variables we could consider. We used annual measures of temperature and model-derived estimates of P loading and flow rates in the Saginaw River as potential environmental explanatory variables, and we used spawning stock biomass (SSB) of female yellow perch as a measure of spawning stock size (Figure 4.1). In addition, we considered non-stationarity in recruitment models by evaluating potential models with different parameters for separate blocks of years. Ultimately, models including such non-stationarity were far more successful at describing variation in yellow perch production and recruitment than models assuming fixed model parameters and models incorporating the influence of environmental variables. Specifically, since 1995, yellow perch production and recruitment appear to be influenced by differential processes than earlier time periods (Figure 4.2). In addition, during these later years, the spawning stock biomass of yellow perch in Saginaw Bay has been consistently low. On the one hand, this may be of concern given that low SSB has been accompanied with poor recruitment of age-1 yellow perch. On the other hand, the recent time period has been characterized by relatively high abundances of age-0 yellow perch, suggesting that low SSB is not a key limiting factor in production of young yellow perch.

Field Surveys: From April 2009 through June 2011, we conducted extensive field collections in Saginaw Bay. These surveys targeted a number of different research questions and aspects of the Saginaw Bay ecosystem (described elsewhere in this report). In terms of walleye and yellow perch, field surveys were designed to track two annual cohorts (2009 and 2010) from just after hatching through survival to the following spring. We aimed to describe the prey base underlying

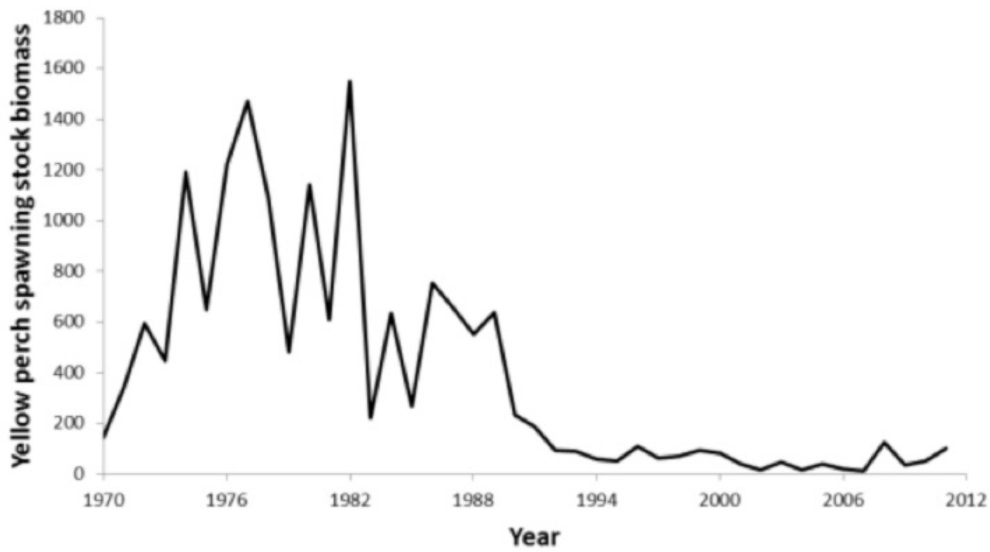


Figure 4.1 - Spawning stock biomass of yellow perch in Saginaw Bay, 1970-2011.

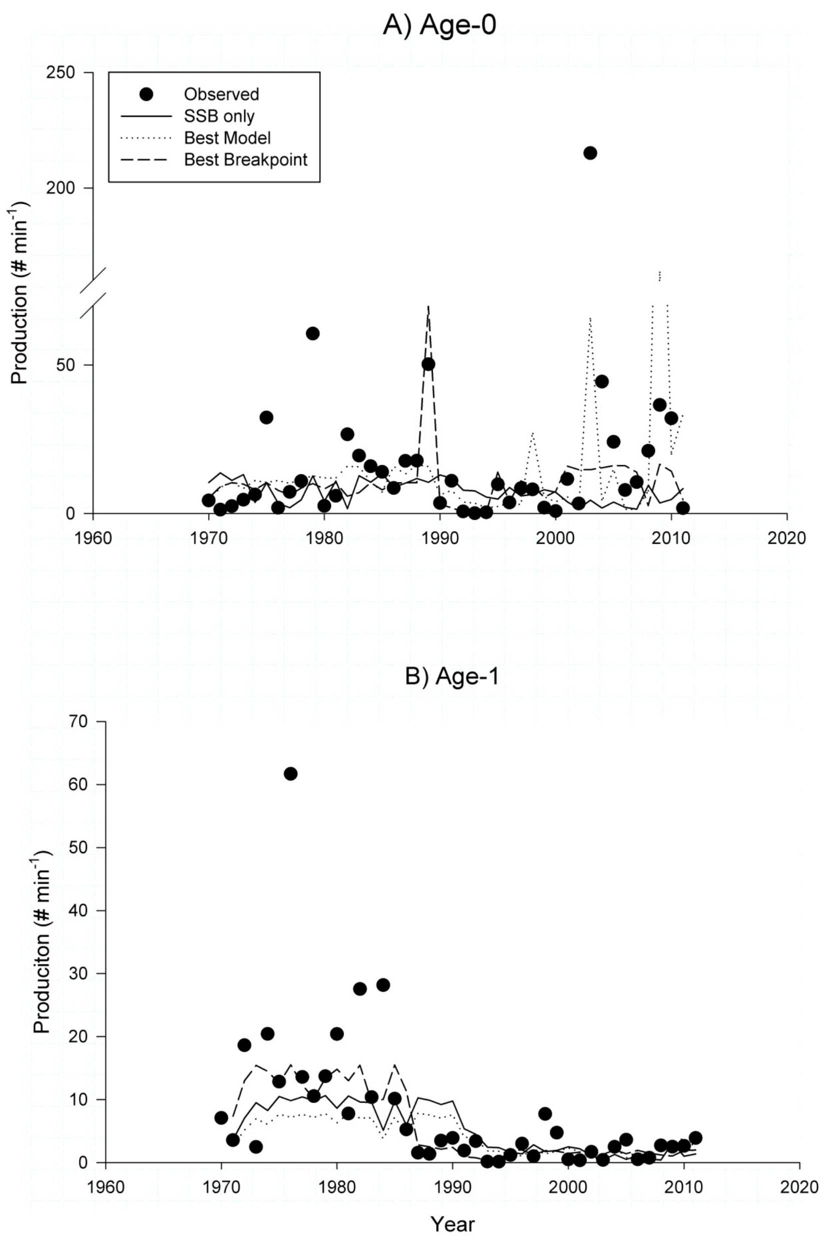


Figure 4.2 - (A) Production of age-0, and (B) recruitment of age-1 yellow perch in Saginaw Bay, including observed CPUE (*Obs*: mean catch per minute of fall assessment trawling by the Michigan DNR), predicted (based on Ricker stock-recruitment model with spawning stock biomass as the sole predictor), and best model (based on Ricker stock-recruitment model with spawning stock biomass as predictor and assuming non-stationarity).

walleye and yellow perch production in the altered Saginaw Bay ecosystem and identify potential impediments to early life survival for young percids.

Walleye: During both 2009 and 2011, we initially collected young walleye near the mouth of the Saginaw River (Figure 4.3). This is a relatively warm area of inner Saginaw Bay, and a past study indicated that the Tittabawasee River (a tributary to the Saginaw) was the major contributor of walleye recruits to Saginaw Bay (Fielder 2002). Hence, initial detection of young walleye in this area was not surprising. However, in subsequent weeks, we also collected young, recently hatched larvae (2 days or less post-hatch based on otolith increment counts) in other areas of Saginaw Bay. Some initial simulations using hydrodynamics and particle transport models suggest that it is highly unlikely that young walleye collected in these other areas would have originated from the Saginaw River, suggesting that other habitats are also potentially important contributors of walleye recruits.

Young walleye grew rapidly from larvae to juveniles. Larval walleye fed on a diversity of zooplankton prey, with cladocerans and dreissenid veligers serving as important prey (Figure 4.4). Juvenile walleye transitioned from feeding primarily on zooplankton, to larger invertebrates (predatory zooplankton, *Bythotrephes* and *Leptodora;* and benthic invertebrates, Chironomidae), and then fish (rainbow smelt, shiners and round goby; Figure 4.5). A dearth of previous data makes it difficult to compare young walleye diets to historical Saginaw Bat diet patterns. However, observed diet patterns of both larval and later-stage age-0 walleye were roughly consistent with diets observed in other systems. Of note, we found that relatively-recent invasive species (*Bythotrephes* and round goby) were important diet components for young walleye. Moreover, we found that yellow perch constituted a relatively unimportant diet component for age-0 walleye.

As adults (age-1 and older), walleye fed almost exclusively on fish (primarily round goby, yellow perch, shiners, and rainbow smelt; Figure 4.6). In contrast to age-0 walleye, young yellow perch were a more important prey for age-1+ walleye, particularly during the summer when young perch represented 60% (by number) of fish prey in walleye diets. During other seasons, yellow perch were less common in walleye diets and in both spring and fall, round goby was the most common prey in age-1+ walleye diets (41% and 60%, respectively). The importance of round goby as walleye prey is noteworthy as this relatively-recent invader has become a key forage species, seemingly supporting the walleye population in a manner similar to alewife before their crash.

Yellow perch: During both 2009 and 2010, we initially collected larval yellow perch in far inner Saginaw Bay (a relatively warm area near the mouth of the Saginaw River). Subsequently, we collected recently hatched larval yellow perch (2

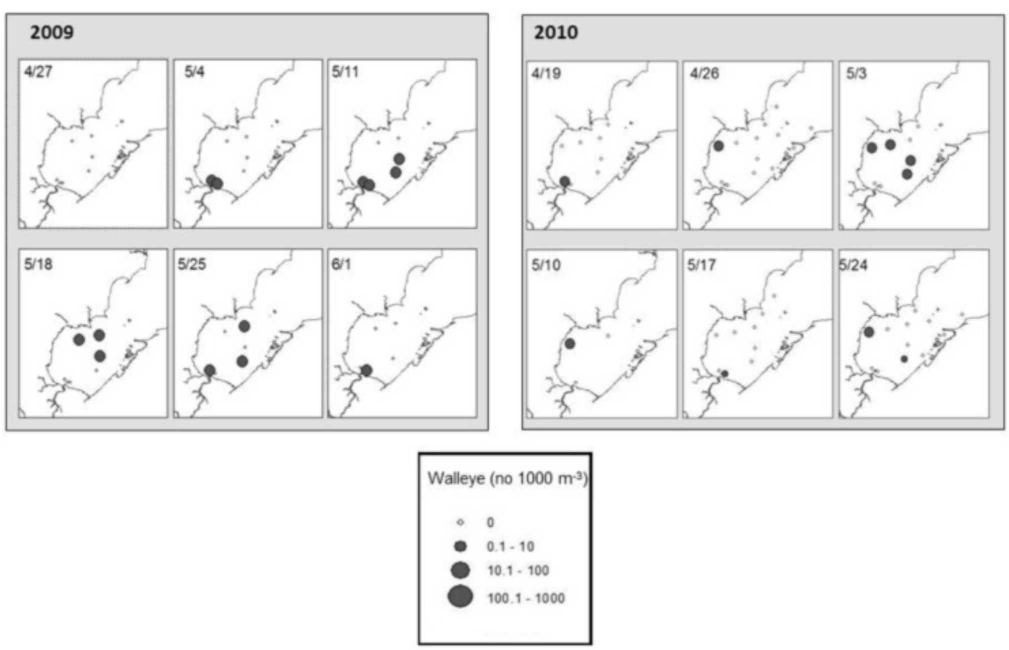


Figure 4.3 - CPUE (number 1000 m^{-3}) of larval walleye caught in bongo tows by week for 2009 and 2010. In 2009 and 2010, larvae first appeared near the mouth of the Saginaw River before distributing throughout the Bay. Spring 2010 was warmer than 2009, and in turn, walleye larvae emerged. During both years, young larvae less than two days old were caught far from the Saginaw River.

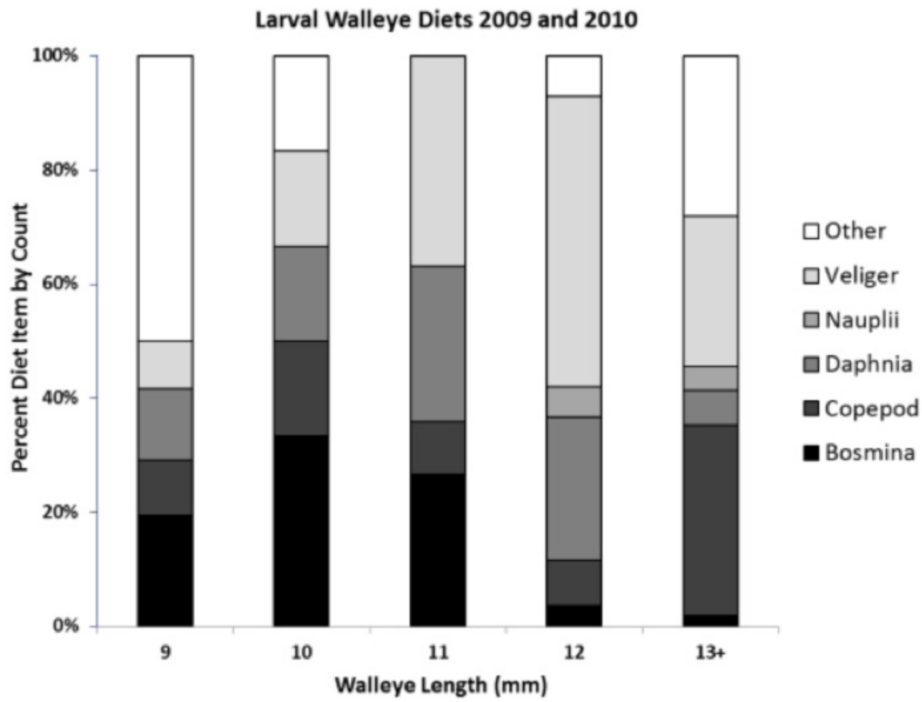


Figure 4.4 - Diets of larval walleye in Saginaw Bay, 2009 and 2010. Larvae began exogenous feeding at approximately 9 mm and fed on a diversity of taxa through the larval stage.

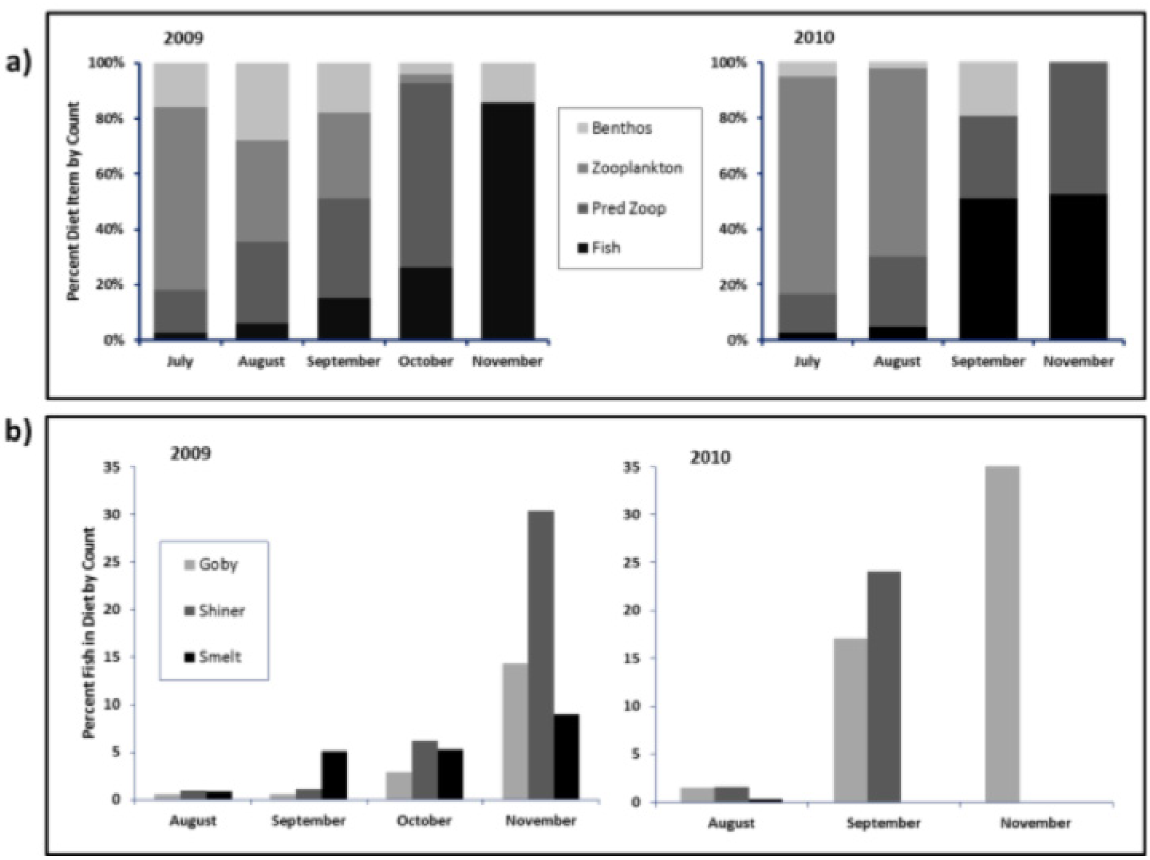


Figure 4.5 - Diets of young of year (YOY) walleye in Saginaw Bay 2009 and 2010.

a. YOY walleye diet composition for all taxa by counts. Predatory zooplankton, primarily non-native *Bythotrephes*, and fishes became important as walleye transitioned from herbaceous zooplankton. Walleye shifted to piscivory in early fall as fish dominated diets by September in terms of biomass.

b. Composition of fishes in YOY diets by counts. Young walleye relied on various fish prey, including non-native gobies.

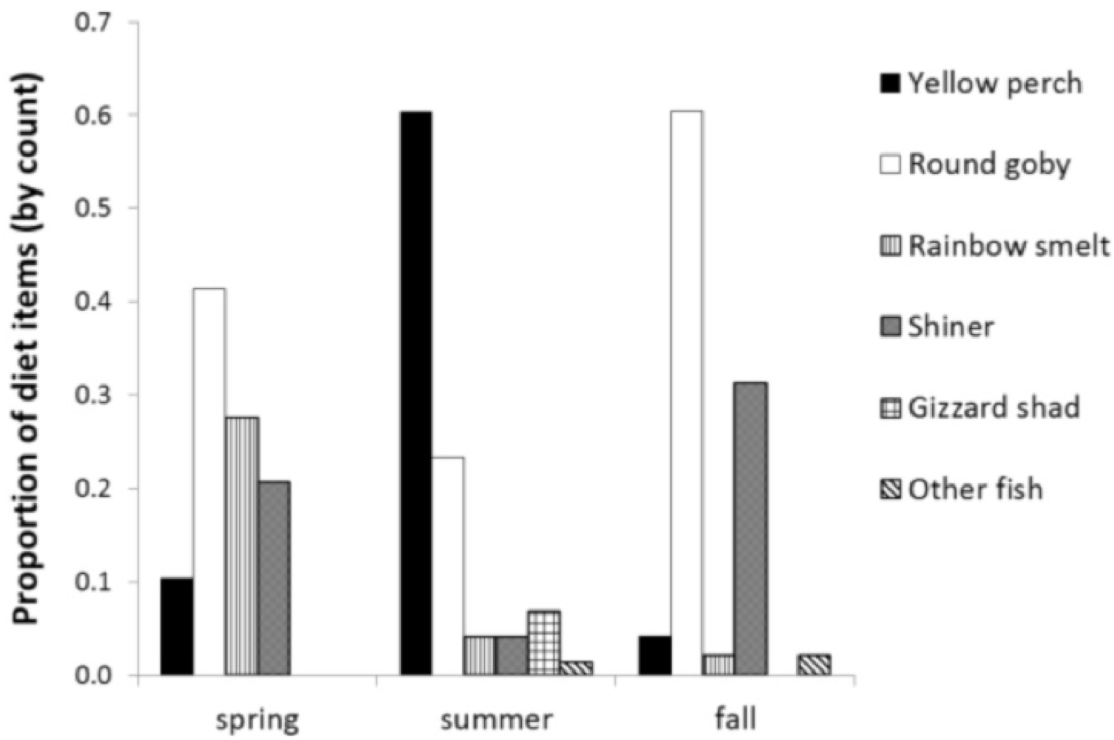


Figure 4.6 - Diets of age-1 and older walleye in Saginaw Bay 2009 and 2010.

days or less post-hatch based on otolith increment counts) from throughout inner Saginaw Bay. The emergence of yellow perch was rather prolonged during both years (Figure 4.7). Larval yellow perch ate a fairly diverse diet of small-bodied zooplankton, with cyclopoid copepods, calanoid copepods, and nauplii all serving as important prey (Figure 4.8). Most larval yellow perch diets we examined had some prey in their digestive tract (in contrast to some systems where empty larval digestive tracts are relatively common). In turn, larval yellow perch grew at a relatively fast rate (~0.3 mm d^{-1} from hatch to 20 days post-hatch; Figure 4.9).

Later-stage age-0 yellow perch (collected via trawling from July-November) expanded their diet to include more diverse prey, including larger bodied zooplankton and benthic invertebrates. Based on diet biomass, *Daphnia* represented the most common zooplankton prey, followed by calanoid copepods and *Bythotrephes*, while Chironomidae larvae represented the most common benthic prey, followed by *Chydoridae*. Surprisingly, we did not find evidence of strong ontogenetic niche shifts from zooplankton to larger-bodied benthic prey (as has been documented in other sytsems). Instead, zooplankton constituted the main prey for age-0 yellow perch from July-November during both study years. We did, however, find evidence of strong spatial differences, with site SB-10 primarily supporting benthic-feeding age-0 yellow perch and site SB-5 supporting primarily zooplanktivores (Figure 4.10).

Similar to larval yellow perch, older age-0 yellow perch maintained fairly rapid growth during early summer (July-August). Their growth then slowed in late summer and fall (Figure 4.9). This seasonal decline was evident for both growth in biomass and growth in total body energy. Moreover, the decline in growth appeared to occur before seasonal drops in water temperatures in inner Saginaw Bay. On the one hand, this suggests that declining growth may reflect feeding habits of young yellow perch; perhaps continued consumption of small-bodied zooplankton prey leads to seasonally slow growth. On the other hand, slower growth later in life may simply reflect the allometry of consumption and metabolism, whereby the potential for growth may decline precipitously as young yellow perch increase in size.

While it is not entirely clear why growth of young yellow perch slowed down in late summer and early fall, it is clear that smaller yellow perch are more susceptible to mortality, and hence slow growth could contribute to poor survival. We found that the mean lengths of young yellow perch in the environment (collected via trawling) were consistently lower than the mean lengths of young yellow perch found in the stomachs of piscivorous walleye; suggesting that the smallest

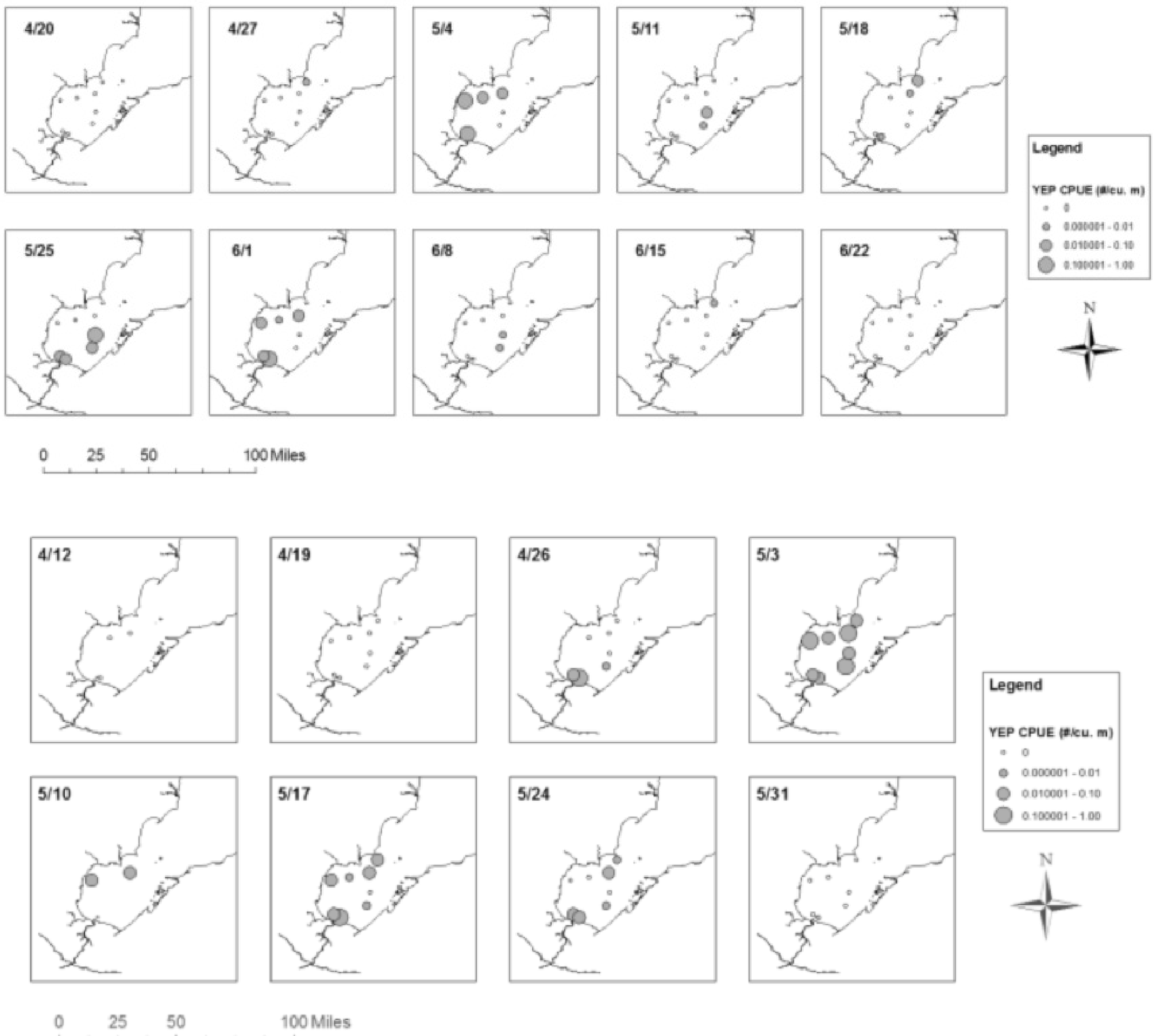
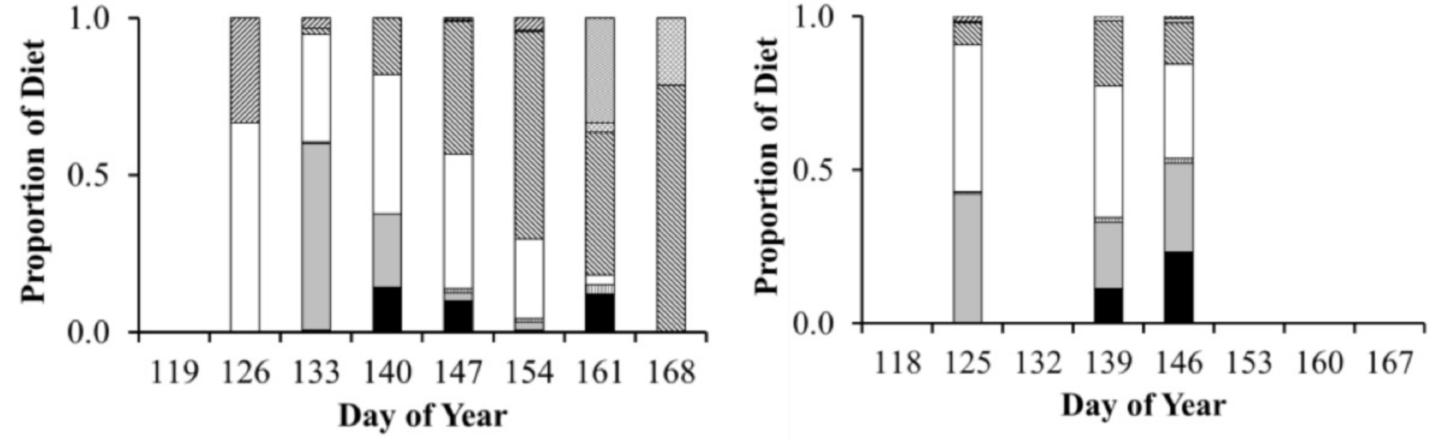


Figure 4.7 - CPUE (number m-3) of larval yellow perch caught in bongo tows during sampling weeks in 2009 and 2010.

indivdiuals were most likely to be consumed by predators (Figure 4.9). In addition, when comparing length distributions and total body energies of young yellow perch just prior to winter (October-November) versus after winter (age-1 yellow perch in April-early June), we documented an increase in mean size of yellow perch and a 20% drop in length-specific total body energy (Figure 4.11). Thus, young yellow perch lose a great deal of energy over winter, which could contribute to size-dependent mortality. That is, smaller yellow perch may be more likely to die over winter due to lower energy stores and higher mass-specific metabolism, leading to starvation and/or necessitating risky feeding behavior.

4.3 Knowledge/Data Gaps – Research Needs

Collapse of alewife in Lake Huron appears to have released young walleye in Saginaw Bay from predatory and competitive control. In turn, young walleye now appear to survive well during early life and are entirely supported by



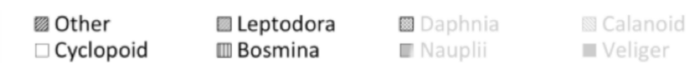


Figure 4.8 - Diets of larval yellow perch in Saginaw Bay by sampling week in 2009 and 2010.

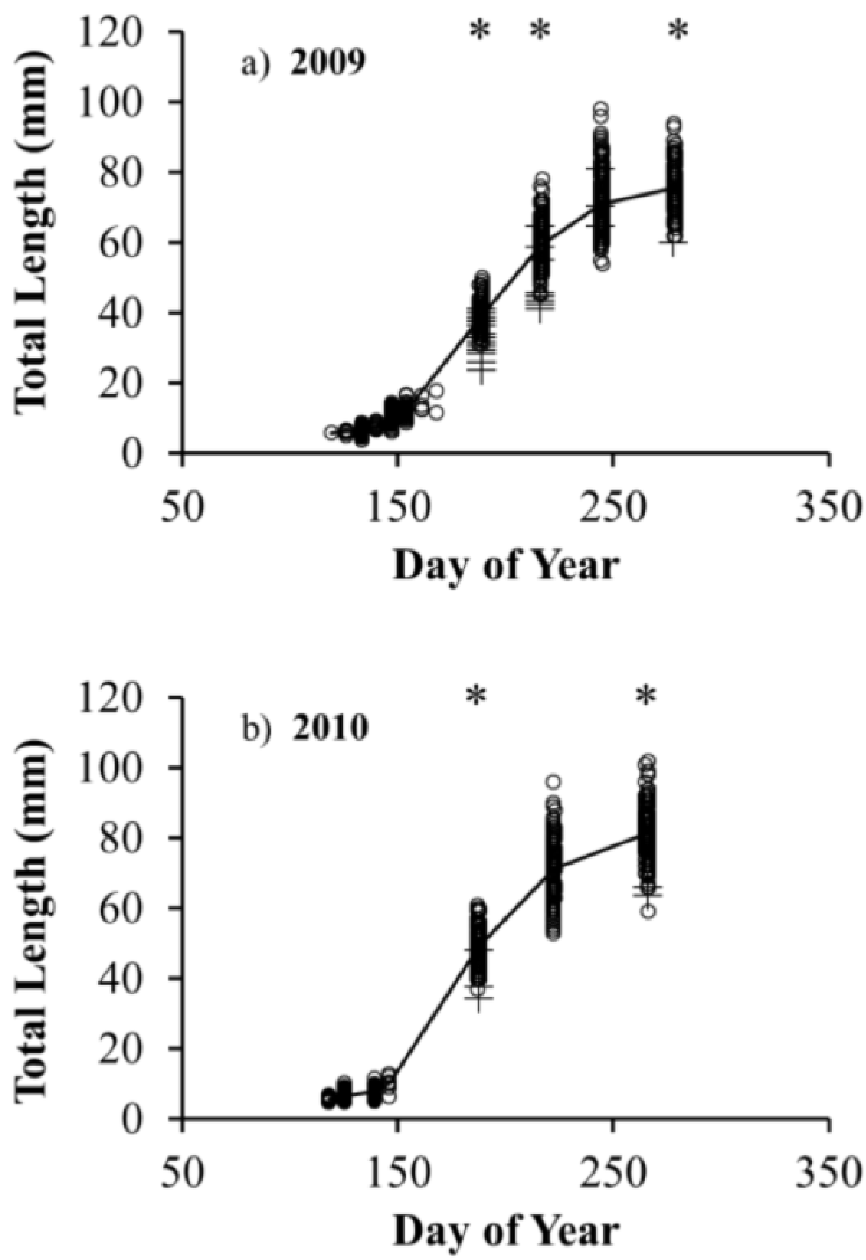


Figure 4.9 - Lengths of larval and juvenile yellow perch collected in bongo nets and trawls (circles) in Saginaw Bay during 2009 and 2010. Lengths of yellow perch found in walleye stomachs are depicted with "+", and asterisks indicate weeks when lengths of yellow perch ion walleye stomachs were significantly lower than trawl-caught yellow perch (2 sample t-test).

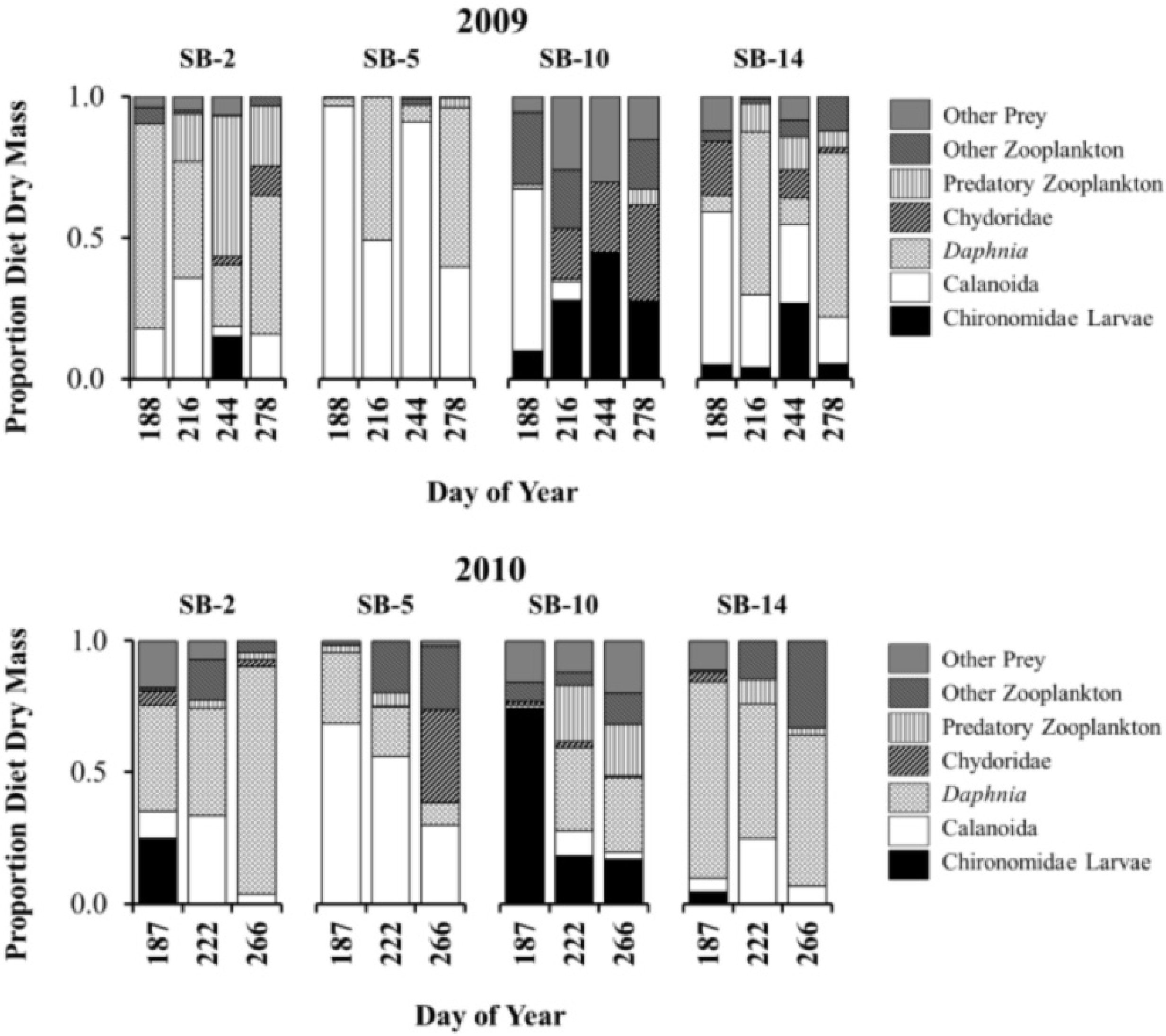


Figure 4.10 - Diets of young-of-year yellow perch by sampling location in Saginaw Bay, 2009 and 2010.

natural reproduction. Nonetheless, under this new regime, there must be limits to walleye production in Saginaw Bay. For example, spawning habitat may now limit walleye production. In the 1990's, most natural production of walleye in Saginaw Bay appeared to come from the Tittabawasee River (a tributary to the Saginaw River; Fielder 2002). Our collections (and studies by other researchers) suggest that walleye larvae are now emerging in other areas, likely including other Saginaw Bay river systems. Historically, walleye likely also spawned on reefs in Saginaw Bay; however, it is an open question if reefs are important contributors of larval walleye in the new regime. We suggest that future studies should evaluate the contributions of walleye from different habitats in Saginaw Bay.

Walleye transition through diverse diets as larvae, juvenile, and adults. As larvae and later stage age-0, walleye rely on invertebrates including herbaceous zooplankton, predatory zooplankton (invasive *Bythotrephes*) and, to a lesser extent, benthic invertebrates. However, by the end of their first year of life, walleye have transitioned to an entire piscine diet. While alewives were an important fish prey for walleye in the past, walleye now utilize a diversity of prey (shiners, smelt, round goby, yellow perch), with key diet contributors changing seasonally. Yellow perch were largely absent in diets of age-0 walleye, but they were important diets components for age-1 and older walleye. As a whole, however, soft-rayed fishes including shiners and most importantly, round goby, now constitute the walleye forage base. Nonetheless, we suggest that this forage base may be undergoing transition. Alewife relatively recently collapsed, round goby are fairly recent invaders, high age-0 yellow perch production may not continue indefinitely, and additional forage fish (e.g., lake herring) may be stocked into Saginaw Bay in the future. Moreover, continued species invasions and environmental (e.g.,

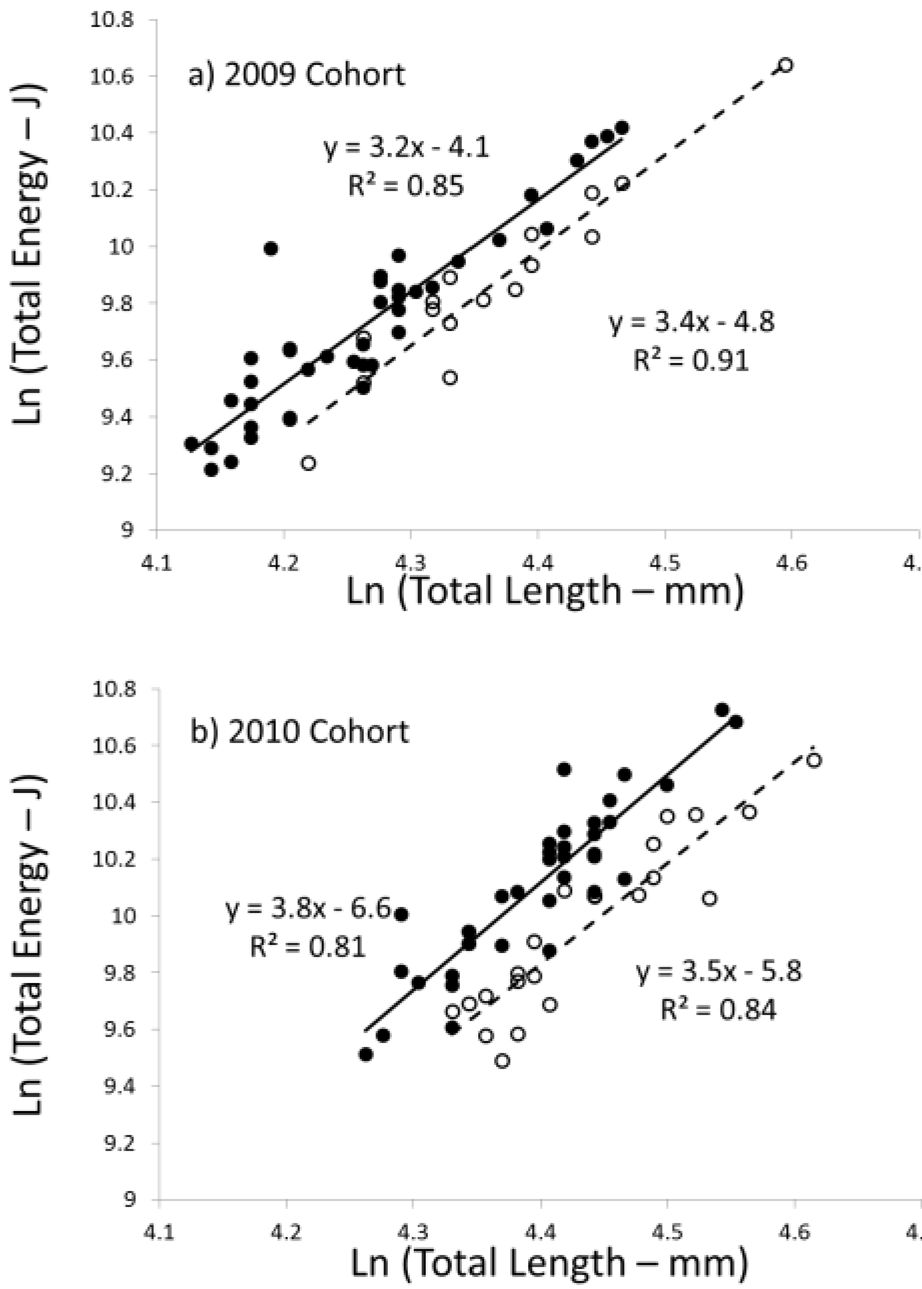


Figure 4.11 - Total length (mm) and total body energy (J) of age-0 yellow perch collected in the fall (filled circles) and age-1 yellow perch the following spring (open circles). Yellow perch lost ~20% of body energy over winter (based on length-specific comparisons).

changes in nutrient loading and sedimentation) and physical (e.g., climate change) changes to the Saginaw Bay ecosystem may favor certain types of small-bodied fish species. Potential resulting shifts in the forage base may lead to changes in the type of prey supporting walleye production. In turn, this may have implications for maintenance of the current large Saginaw Bay walleye population and sustainability of small-bodied fish species. Such effects may be difficult to anticipate, and we suggest: (1) a need to continue monitoring of the forage base supporting walleye production in Saginaw Bay throughout the year, and (2) development and application of models to evaluate plausible responses of walleye and forage fish populations to potential future ecosystem changes.

Many potential factors limiting yellow perch recruitment in Saginaw Bay remain unknown. As described above, since 1995, yellow perch production (age-0 abundance) and recruitment (to age-1) in Saginaw Bay appear to be structured differentially than during earlier time periods. In addition, during recent years, spawning stock biomass of yellow perch has remained at the lowest levels during the period of record (since 1970). While, this low spawning stock may be a factor contributing to poor recruitment of yellow perch, high abundances of age-0 yellow perch in recent years suggest that spawning stock size may not be the sole limiting factor. Instead, high predation on age-0 yellow perch by the burgeoning walleye population, coupled with slow growth by later stage age-0 yellow perch (leading to increased susceptibility to predation and overwinter mortality), may also be important factors contributing to poor recruitment. Perhaps, greater overall production of age-0 yellow perch is now necessary to swamp the predation pressure exerted by the walleye population and lead to high numbers of age-1 yellow perch recruits. Future studies should evaluate these balances between walleye predation pressure, young yellow perch growth, density-dependence, and recruitment. Again, we suggest that linked population models should provide a unique mechanism to effectively consider the interactions of these different processes.

4.4 Management Implications

Walleye spawning habitat may now be a limiting factor for production. Moreover, even if there is sufficient spawning habitat, population sustainability may benefit by partitioning spawning among multiple, diverse habitats. That is, walleye recruitment success displays high inter-annual variation, and heterogeneity in spawning may temper such variation by increasing the breadth of environmental conditions experienced by spatially-distinct young walleye during a particular year. In Saginaw Bay, walleye spawning may be diversified by increasing the availability of spawning habitats in rivers and/or reefs. Many Saginaw Rivers are dammed, limiting passage of walleye to potentially suitable upstream spawning habitats. While removal of dams could alleviate such blockages, dam removal may also lead to various deleterious effects (e.g., downstream sediment release, increased contaminant flux, and upstream movement of invasive species [round goby, sea lamprey]). Moreover, walleye in Saginaw Bay are already thought to primarily spawn in rivers, and additional river spawning habitat may not provide environmental conditions fundamentally different from existing spawning environments (and hence, may not temper inter-annual recruitment variation). Instead, we suggest that Saginaw Bay reef restoration represents a particularly worthwhile approach for expanding walleye spawning habitat. Reef spawning habitat could provide a substantially different spawning environment from river habitats (different thermal conditions leading to temporally offset spawning and emergence; dissimilar incubation conditions; and no long-distance, downstream transport). Thus, we suggest that Saginaw Bay management agencies should explore the potential for reef restoration.

Historically, Saginaw Bay likely supported both large walleye and yellow perch populations. However, high predation pressure by walleye may now be a factor contributing to low yellow perch recruitment; potentially coupled with a slow growth of later-stage age-0 yellow perch and a low perch spawning stock biomass. Potential management actions to overcome these bottlenecks could include increased harvest of walleye (thereby decreasing predation pressure on yellow perch), decreased harvest of yellow perch (thereby increasing spawning stock biomass of yellow perch), or establishment of another forage fish population to divert predation pressure from yellow perch. The ultimate effects of any of these actions are unfortunately unknown. Increased harvest rates of walleye have the potential to deleteriously impact the walleye population (especially if recruitment success decreases in the future), and decreased harvest of yellow perch will have social and economic impacts on the commercial and recreational fishers that exploit this population. Introduction of a new, native forage fish (e.g., lake herring) could decrease predation pressure on yellow perch, but to a large extent, round goby are already serving as a predation buffer on yellow perch. Moreover, it is unclear if walleye would select a novel forage fish as prey in favor of yellow perch (e.g., young lake whitefish are present in Saginaw Bay, but were absent from walleye diets). In short, the most suitable management actions are unknown, and we suggest that Saginaw Bay fisheries managers should take an adaptive approach to build the yellow perch population: establish a management action and then monitor responses of populations of interest.

4.5 Section 4 References

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