AN ASSESSMENT OF REEF RESTORATION POTENTIAL IN SAGINAW BAY, LAKE HURON

by

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TABLE OF CONTENTS

LIST OF TABLES v
LIST OF FIGURES vi
ABSTRACT ix
CHAPTER 1. INTRODUCTION 1
CHAPTER 2. BIOLOGICAL ASSESSMENT OF REEF RESTORATION POTENTIAL 7
2.1 Introduction 7
2.2 Methods 12
2.2.1 Study Site Descriptions 12
2.2.2 Reproductive Utilization 14
2.2.3 Habitat Suitability 14
2.2.4 Data Analysis 15
2.3 Results 17
2.3.1 Reproductive Utilization 17
2.3.2 Habitat Suitability 18
2.4 Discussion 20
2.4.1 Reproductive Utilization 20
2.4.2 Habitat Suitability 24
2.4.3 Implications for Habitat Restoration 27
CHAPTER 3. OVERWINTER HYPOXIA LIMITS SPAWNING OF GREAT LAKES FISH 40
3.1 Introduction 40
3.2 Methods 43
3.3 Results 46
3.4 Discussion 49
3.4.1 Summary and Conclusions 53
REFERENCES 65
APPENDIX 74

LIST OF TABLES

Table 2.1. Study site characteristics. Range of dissolved oxygen represents whole water column Measurements 29

Table 2.2. Catch per net set for overnight, multifilament gillnets, mean ± SE. Catch is divided by sampling season (fall spring 2014-2016), site (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef), and species 30

Table 2.3. Catch per hour of net set for micro-mesh gillnets, mean ± SE. Catch is divided by sampling season (fall and spring 2014-2016), site (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef), and species 32

Appendix Table A1. Underwater video captured by MDNR in June 2015 at all study locations. Videos show best available rock substrate and mixed substrate for remnant reef sites, and typical substrate for proposed restoration sites 74

LIST OF FIGURES

Figure 2.1. Locations of study sites within Saginaw Bay. Duck Reef (DR) and North Island Reef (NR) are remnant reef sites, while Saginaw River Mouth Reef (SR) and Coreyon Reef (CR) are proposed reef restoration sites....34

Figure 2.2. Catch per gillnet set by site of target individuals (Lake Whitefish, Walleye) across all sampling seasons (fall and spring 2014-2016) and sites (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef). Closed points represent males, open points represent females....35

Figure 2.3. Catch per gillnet set of target individuals (Lake Whitefish, Walleye) in spawning condition across all seasons (fall and spring 2014-2016) and sites (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef)....36

Figure 2.4. Relative rates of egg deposition (eggs m^{-2} d^{-1}) by site (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef) across all sampling seasons (fall and spring 2014-2016), ± SE....37

Figure 2.5. Time series of water temperature data by site (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef) across all seasons (fall and spring 2014-2016). Rectangular overlays indicate literature spawning ranges for Lake Whitefish (fall spawners) and Walleye (spring spawners)....38

Figure 2.6. Egg predation results for both fall and spring seasons, pooled by season across all sampling years (2014-2016). For each species, frequency of occurrence of target eggs (Lake Whitefish in fall, Walleye in Spring) in diets, as well as mean number of eggs consumed in a diet, are reported. Mean egg consumption values for each species are calculated from only those diets that contained target eggs....39

Figure 3.1. Locations of study sites within Saginaw Bay. Duck Reef (DR) and North Island Reef (NR) are remnant reef sites, while Saginaw River Mouth (SR) and Coreyon Reef (CR) are proposed restoration sites 55

Figure 3.2. Characteristics of Duck Reef. Three-dimensional representations of A) bathymetry and B) relative hardness from side-scan sonar data. Underwater camera shows C) best reef structure and D) typical reef structure observed 56

Figure 3.3. Characteristics of North Island Reef. Three-dimensional representations of A) bathymetry and B) relative hardness from side-scan sonar data. Underwater camera shows C) best reef structure and D) typical reef structure observed 57

Figure 3.4. Characteristics of Coreyon Reef. Three-dimensional representations of A) bathymetry and B) relative hardness from side-scan sonar data. Underwater camera shows C) typical habitat observed 58

Figure 3.5. Characteristics of Saginaw River Mouth. Three-dimensional representations of A) bathymetry and B) relative hardness from side-scan sonar data. Underwater camera shows C) typical habitat observed 59

Figure 3.6. Relative hardness for each study site in Saginaw Bay, by percent of area covered. Hardness scales are only relative within a site, not across sites. Duck Reef displayed the widest range in hardness values, while Saginaw River Mouth was most consistent. Coreyon Reef showed a mix of harder and softer substrates, while North Island Reef had a large range of softer values. Coefficients of variation are also shown for relative hardness values within each study location. Proposed restoration sites displayed smaller CVs than remnant reef sites 60

Figure 3.7. Relative sedimentation (g m^{-2} d^{-1}) for all sites during Fall 2015, overwinter 2015 2016, and Spring 2016. Due to poor recovery following overwinter sampling, no data were collected from CR during overwinter and spring seasons, and only one trap was deployed at both DR and NR 61

Figure 3.8. Time series of dissolved oxygen data by site across all fall and spring sampling seasons. Points indicate means of three water column measurements (0.5 m increments from 0-2 m) for a given site and date 62

Figure 3.9. Moving average of dissolved oxygen readings, overwinter 2015-2016. No logger was placed at NR. Dissolved oxygen data were capped at 15 mg L^{-1} to adjust for erroneous readings above 100% saturation 63

Figure 3.10. Moving average of dissolved oxygen readings, overwinter 2016-2017. Only one logger was placed at NR, and no loggers were recovered from DR. Dissolved oxygen data were capped at 15 mg L^{-1} to adjust for erroneous readings above 100% saturation.........................64

ABSTRACT

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Historically, Saginaw Bay, Lake Huron had a complex of rocky reefs that functioned as preferred spawning habitat for various fish species, including Walleye (*Sander vitreus*) and Lake Whitefish (*Coregonus clupeaformis*). This reef system likely acted as a source of protection from egg predation, as well as of increased spawning diversity. Shifts in land use from forest to primarily agriculture and industry resulted in elevated runoff and sedimentation, leading to the loss of nearly all reef structure in Saginaw Bay. Coupled with overfishing and additional habitat degradation, these shifts precipitated dramatic declines of many fish species in the bay, including Walleye. Until recently, stocking was necessary to maintain Walleye in Saginaw Bay. Today, Walleye abundance is high, but the majority of production comes from Walleye spawning in tributaries, with limited production in the bay itself. Lake Whitefish production may also remain impacted by degraded spawning habitat in the bay. In recent years, improved land use and potential decreased sedimentation, has led to momentum towards reef restoration in Saginaw Bay. The purpose of this study was to analyze spawning patterns of two key Great Lakes fish species, Walleye and Lake Whitefish, to determine whether current reproductive usage indicates potential for successful reef restoration. Additionally, we sought to analyze physical conditions in Saginaw Bay and their potential impact on restoration efforts. We evaluated four sites with varying levels of reef degradation; two sites contained remnant reef habitat, while two sites contained little to no rocky structure, but served as potential restoration locations. We analyzed water quality, substrate, sedimentation, reproductive usage, and egg deposition and predation. After completion of a two-year study, we have documented actively spawning Walleye and Lake Whitefish and egg deposition and predation at multiple sites. However, densities of spawners and deposited eggs were low, suggesting that target species are not utilizing study sites as major spawning locations. Additionally, predation of both Walleye and Lake Whitefish eggs was documented for multiple fish species. Larger-bodied fish species, such as Channel Catfish (*Ictalurus punctatus*), in particular were able to consume large numbers of deposited eggs. Water temperatures and dissolved oxygen concentration appeared appropriate during spawning seasons to allow for successful spawning, but low overwinter dissolved oxygen was documented at multiple sites. Sedimentation analyses also suggested high amounts of suspended sediment at study locations, and a need for further understanding of sedimentation dynamics. Overall, we suggest that there is potential for successful restoration from a biological standpoint, but that more information is needed before full-scale reef restoration can occur. Reefs may be able to attract additional fish to spawn and provide protection from egg predators, but it remains unclear how sedimentation and overwinter dissolved oxygen may affect quality of restored spawning habitat.

CHAPTER 1. INTRODUCTION

Degradation and loss of habitat represent some of the most important threats to fisheries worldwide (e.g., Munday 2004; Jelks et al. 2008). The Laurentian Great Lakes are no exception, with several fish stocks severely reduced at least partially due to anthropogenic impacts on habitat (e.g., Christie 1974; Keller et al. 1987; Ivan et al. 2014). Sedimentation, alteration of benthic structure, high chemical inputs, and bottom hypoxia represent only some of the consequences that can result from habitat mismanagement (Schneider and Leach 1977; Henley et al. 2000; Soulsby et al. 2001; Diaz and Rosenberg 2008). These consequences may be especially severe if habitat degradation occurs on spawning grounds and limits future recruitment. In recent decades, management goals in the Laurentian Great Lakes have increasingly begun to focus on restoration of degraded habitat (Great Lakes Fishery Commission 1987, 2001; McLean et al. 2015). Across the United States, 27 zones in the Great Lakes have specifically been designated as Areas of Concern by the US Environmental Protection Agency. These heavily impacted regions were identified high priority areas for environmental restoration. One such area of concern includes Saginaw Bay, Lake Huron.

Saginaw Bay is a shallow and productive embayment of Lake Huron that serves as important nursery habitat for many fish species. The bay has historically supported strong fisheries for many economically and recreationally important species, such as Walleye (*Sander vitreus*) and Lake Whitefish (*Coregonus clupeaformis*). In the first part of the 20th century, the bay accounted for the second largest Walleye fishery in the entire Great Lakes, second only to the western basin of Lake Erie (Hile 1954). However, decades of overfishing, poor land management, and industrial pollution led to crahes of fish populations across Saginaw Bay (Keller et al. 1987; Fielder and

Baker 2004). Walleye in particular were so heavily impacted that by the late 1940s, the population in the bay could no longer be sustained through natural reproduction alone (Fielder 2002). Along with overfishing, loss of spawning habitat was likely a major contributor to the Walleye crash (Schneider 1977; Schneider and Leach 1977). Historically, an extensive network of rocky reef structure covered much of Inner Saginaw Bay (Fielder 2002). This structure represented important spawning grounds for Walleye, along with lithophilic spawners such as catostomids, Lake Whitefish, and other coregonid species. As the land surrounding Saginaw Bay was converted from forest to primarily agriculture and industry, significant sediment runoff began to accumulate in the bay. This sediment filled in and covered much of the historic reef complex in Saginaw Bay; only small patches of reef structure remain today in the inner bay (Fielder 2002). Outer bay reef habitat remains but is thought to warm too late in the spring to prove attractive to spawning fishes (Fielder 2002). The additional influence of high chemical and nutrient loadings resulted in the degradation and loss of important spawning grounds for Walleye, which served to exacerbate existing anthropogenic stressors and precipitate a crash in Walleye numbers across the bay (Schneider 1977; Schneider and Leach 1977). Indeed, it is thought that reef spawning fish may have sustained already dwindling Walleye populations, until severe degradation of reef spawning habitat led to sharp declines in abundance of reef spawning fish (Schneider and Leach 1977).

For decades, Walleye were maintained in Saginaw Bay through supplemental stocking by the Michigan Department of Natural Resources (Fielder and Baker 2004). However, following the crash of Alewife (*Alosa pseudoharengus*) populations in Lake Huron in 2003, natural Walleye recruitment rapidly rebounded (Fielder et al. 2007; Fielder et al. 2013). Early life stages of Walleye were released from predation and competition with Alewife, and a succession of strong year classes allowed stocking of Walleye to cease in 2006; recovery targets set by the MDNR were met soon after in 2009, and natural production continues to sustain Walleye populations in Saginaw Bay (Fielder and Thomas 2014). However, much of this production comes from a limited group of tributaries surrounding the bay (Jude 1992; Fielder 2002). With so few sources of production and a seeming lack of recovery by reef spawning stocks, the overall Walleye population in the bay may still be at risk. Similarly, current Lake Whitefish harvest in the bay is high relative to some historic levels (Mohr and Ebener 2005), but may be constrained by reduced spawning opportunities on degraded reef structure.

Along with a resurgence in some fish populations, Saginaw Bay has also seen improvements in environmental conditions. Land management practices have improved and chemical loadings have declined through nutrient abatement programs (Fielder and Baker 2004). As a result, levels of total phosphorus have decreased (XXX) and sedimentation may have decreased (Limnotech, Inc., personal communication). Both trends would bode well for the long-term stability of Walleye and Lake Whitefish in the bay. Physical restoration of spawning habitat may be an additional avenue to promote stability of fish populations. Although abundance targets may have been met for Walleye, underlying historic processes and mechanisms for sustainability have not been fully restored. To that end, reef restoration has received increased attention in recent years. Successful restoration of rocky spawning habitat in the bay may allow for fish such as Walleye and Lake Whitefish to diversify their spawning locations and timing, providing additional long-term population stability. Through the concept of portfolio effects, populations can buffer against interannual variability by diversifying when, where, or on which structure spawning occurs (Hilborn et al. 2003, Schindler et al. 2015). Essentially, diversity in fish stocks can operate much as a productive stock market portfolio, which weathers market fluctuations through a diverse range of investments. Reef restoration may thus present an opportunity to expand diversity of spawning stocks for both Walleye and Lake Whitefish. For Walleye, spawning may be able to expand from surrounding tributaries to Saginaw Bay itself, as was historically the case. This diversity in sources of production is not unlike that of Lake Erie today, where Walleye successfully reproduce in both tributaries and on reefs (Roseman et al. 2001). It is possible that there may be some remaining Walleye that are genetically predisposed to reef spawning in Inner Saginaw Bay (Jennings et al. 1996; Fielder 2002), but are unable to reproduce in high numbers due to limited rocky reef habitat. For Lake Whitefish, portfolio effects would act on a larger scale. Reef restoration may allow Lake Whitefish to increase successful spawning in Saginaw Bay, thereby diversifying spawning stocks over the entire basin of Lake Huron.

Before restoration can occur, however, it is necessary to establish baseline, pre-restoration conditions. Without baselines, it would be extremely difficult to quantify any potential success of restoration projects. To that end, this study aimed to document current biological and physical conditions at various study sites in Saginaw Bay. By investigating reproductive usage by Walleye and Lake Whitefish (representative spring and fall spawners, respectively) at locations both with some remnant inner bay reef habitat and at proposed restoration sites mostly devoid of rocky structure, we hoped to determine current spawning utilization (or lack thereof) of reef habitat in the bay. Additionally, we assessed physical conditions at all study locations to determine the extent to which current habitat degradation may be impacting reproductive success. With information on both biological and physical conditions at study locations, we aimed to help forecast potential success of any future restoration projects.

Overall, we documented spawning adults at all study sites and egg deposition at nearly all sites for both Walleye and Lake Whitefish. However, catch of adult females in peak spawning condition was low for both species. Additionally, rates of egg deposition were well below values reported in other systems. Both results suggest that some amount of spawning may be occurring at study locations, but that most spawning activity is focused in other areas. While egg predation was fairly sporadic, diet analyses indicate that relative to small-bodied predators, large-bodied predators are currently more likely to consume deposited eggs; eggs were found most frequently and in highest numbers in stomachs of large predators such as Channel Catfish (*Ictalurus punctatus*) and Common Carp (*Cyprinus carpio*). During spring and fall sampling seasons, we found that water temperature and dissolved oxygen were sufficient so as not to negatively impact spawning success. However, overwinter, under-ice hypoxia may be a concern for incubating eggs deposited by fall spawning species. Multiple data loggers at several study sites detected prolonged periods of low bottom oxygen, though exact duration of hypoxic conditions was variable. We also deployed sediment traps, which collected high amounts of suspended sediment floating throughout Saginaw Bay. However, differences in sedimentation across study sites were relatively minor, suggesting that rocky structure at remnant reef locations has been able to persist despite high amounts of suspended sediment.

Given our overall results, we suggest that there is potential for successful reef restoration in Saginaw Bay. Restored spawning habitat may be able to increase reproductive utilization at restoration sites, and may also provide refugia from predation for deposited eggs. Given that large-bodied predators may be the greatest current predation threat, interstitial spaces in rocky structure may be key to protecting eggs. Additionally, reefs may help shield deposited eggs from suspended sediment, and could provide a relatively low-sediment location for egg incubation. While there are some concerns about reduced bottom oxygen overwinter, reef restoration would likely still provide numerous advantages to both spring and fall spawners. Based on current reproductive usage at study locations, there may be potential to increase spawning stock diversity and portfolio effects through restoration of rocky reef habitat.

As this study represents baseline, pre-restoration conditions in Saginaw Bay, continued monitoring is essential, should reef restoration proceed. Information collected during and post-restoration activities would help complete any measure of restoration success. Furthermore, as reef restoration is an increasingly utilized method of spawning enhancement around the Great Lakes (McLean et al. 2015), data collected by this study may help inform future endeavors.

CHAPTER 2. BIOLOGICAL ASSESSMENT OF REEF RESTORATION POTENTIAL

2.1 Introduction

Adequate quality and quantity of reproductive habitat has long been recognized as one of the most important factors affecting production of fishes (Gibson 1994; Hayes et al. 1996). Within the Laurentian Great Lakes, much of the historic rocky spawning habitat for fishes has been altered through a variety of anthropogenic-related mechanisms, including nutrient and sediment runoff resulting from land use shifts towards timber harvest, agriculture and industry (Kelso et al. 1996). In recent decades, habitat restoration has been a fisheries management priority in the Great Lakes (Great Lakes Fisheries Commission 1987, 2001). Diverse management goals such as native species restoration, improved fishery stability, and achieving maximum sustainable yields all require reproductive habitat in high quantity and quality. Before habitat restoration can occur, however, it is necessary that managers have a baseline for pre-restoration conditions (Kondolf and Micheli 1995). Without such information, it is difficult to determine relative success of habitat restoration efforts. Furthermore, detailed assessments of existing conditions can help managers determine whether habitat restoration is a cost-effective and worthwhile endeavor.

The dynamic nature of ecosystems can confound interpretation of habitat restoration efforts and fish stocks which rely upon them. Inter-annual variation and long-term shifting environmental conditions present additional complications for fisheries management. The goal should be to manage individual fish stocks or ecosystem functions over time, capable of sustainability in spite of varying environmental conditions, rather than for a single point in time (Hilborn et al. 2003). The concept of portfolio effects has gained traction in recent years as a method to achieve this management goal (Figge 2004; Hook et al. 2008; Schindler et al. 2010). These effects, analogous to diversification in a stock market portfolio, are based on the idea that a range of biological conditions available to different members of a population will allow the overall population to experience less volatility (Schindler et al. 2015). An example is stocks of Lake Erie Walleye (*Sander vitreus*), each with a unique early life habitat (DuFour et al. 2015). Though each stock may respond differently to changing environmental conditions, the overall complex of stocks and the fishing which depends on may remain relatively stable due to the diversification of spawning conditions. For many fishes, this reproductive diversification can be manifest in numerous ways, including variation in timing and location of spawning, and ultimately the reduction of interannual variation in year-class success (Beletsky et al. 2007; Höök et al. 2008). In systems with a history of changing conditions, reducing temporal variation through spawning diversification may be especially important.

Saginaw Bay, Lake Huron (Figure 2.1), is a warm, shallow, productive embayment that serves as key nursery habitat for a variety of fish species. This includes many recreationally and commercially important species, such as Walleye and Lake Whitefish (*Coregonus clupeaformis*). Saginaw Bay historically contained the second-largest Walleye fishery in the Great Lakes until a succession of year-class failures in the 1940s led to a population crash (Hile 1954; Keller et al. 1987; Fielder and Baker 2004). This crash was precipitated by a variety of anthropogenic stressors, but degradation of rocky reef spawning habitat in the bay was likely one of the final factors that led to complete collapse of Walleye populations (Schneider 1977; Schneider and Leach 1977). The majority of inner bay reef spawning habitat in Saginaw Bay was lost to increased runoff and sedimentation, with only isolated patches of degraded reef remaining (Fielder 2002). Though rocky habitat remains in the outer bay, warming likely occurs too late in the spring to be attractive to spawning fishes (Fielder 2002). With the implementation of nutrient abatement programs in the

1970s and adoption of improved land-use practices, habitat conditions in the inner bay began to improve, and focused recovery efforts targeting Walleye reintroduction began (Fielder and Baker 2004). The Michigan Department of Natural Resources (MDNR) began stocking Walleye fingerlings in the early 1980s. Though a strong recreational fishery developed, natural reproduction was limited, and the Walleye population remained dependent on stocking until the early 2000s (Fielder 2002). With the crash of Alewife (*Alosa pseudoharengus*) populations in Lake Huron, early life stages of Walleye were released from the effects of a potentially important competitor and predator, and Walleye numbers in Saginaw Bay rapidly increased (Schneider and Leach 1977; Fielder and Baker 2004; Fielder et al. 2007). Stocking ceased in 2006, and MDNR recovery targets for Walleye in Saginaw Bay were met in 2009 (Fielder and Thomas 2014). While the Walleye population is now fully sustained by natural reproduction in the Saginaw Bay system (Fielder and Thomas 2006; Fielder et al. 2007), this production is likely primarily supported by the tributaries to the bay (Fielder 2002). The Tittabawassee River, a major tributary of the Saginaw River, is particularly well documented as a primary source of Walleye production (Jude 1992; Fielder 2014; Brenden et al. 2015). This dependency on a limited range of reproductive habitats presents an unstable foundation for the Saginaw Bay Walleye population. Unpredictable environmental conditions (particularly as concerns about climate change intensify) and year-to-year shifts in the system could have profound effects on such a specialized spawning population, leading to high interannual variability in recruitment. This may be particularly true for Walleye in Saginaw Bay, given that there is no evidence of a large-scale recovery of reef spawning fish and a continued lack of quality reef habitat (Fielder 2002). Saginaw Bay Walleye have in fact experienced high interannual variability in recruitment in recent years (Ivan et al. 2011).

It is likely that additional spawning habitat in the bay would have marked benefits for many fish species beyond Walleye. Many catostomid and coregonid species also spawn on rocky structure, and Cisco (*Coregonus artedi*) and Lake Whitefish may be able to utilize restored habitat to increase diversity of spawning grounds. In the same way that Walleye could benefit from portfolio effects, Lake Whitefish in particular may be able to utilize restored reef habitat in Saginaw Bay to decrease variability of abundances . Although current commercial harvest of Lake Whitefish in central Lake Huron is high relative to some historical levels, food web shifts coincident with invasion of dreissenid mussels have resulted in decreased growth and size-at-age for Lake Whitefish (Mohr and Ebener 2005; Pothoven and Madenjian 2007). Portfolio effects for Lake Whitefish would likely operate at a broader spatial scale than for Walleye; increased spawning opportunities in Saginaw Bay might provide spawning diversity and stability for the larger complex of Lake Whitefish populations distributed throughout Lake Huron.

In the last few decades, shifting environmental conditions in Saginaw Bay have led to increased hope for the establishment of a more stable fish community with reductions in the scale of interannual variability in recruitment of individual species. Recent sediment modeling as part of the 2008-2013 National Oceanic and Atmospheric Administration's (NOAA) Saginaw Bay Multiple Stressors project suggests that the high, anthropogenically-driven sedimentation regime found in Saginaw Bay for decades has shifted to a lower, more natural pattern in some nearshore areas, reflective of overall reductions in sedimentation across the Great Lakes (Great Lakes Commission 2010). This would bode well for the long-term viability of existing or potential restored spawning habitat in Saginaw Bay. Long-term loadings of total phosphorus and resulting primary production (indexed by chlorophyll *a* concentration) have also declined in Saginaw Bay (Cha et al. 2010; Ivan et al. 2014). As a consequence, fish community structure in Saginaw Bay has shifted to include higher numbers of species that are intolerant to eutrophication, such as Lake Whitefish (Ivan et al. 2014). Together with sedimentation, high nutrient loadings loadings represent some of the most important threats to reef habitat across the entire Great Lakes region (McLean et al. 2015). Biofouling and algal accumulation, both potential results of high phosphorus loadings, have been shown to have significant negative impacts on deposition and survival of fish eggs on reef structure (Marsden and Chotkowski 2001). Continued reductions of phosphorus loads may contribute to decreased densities of biofoulers, such as dreissenid mussels and benthic algae, and thereby reduce their effects on deposited eggs.

Given the above changes to Saginaw Bay, restoration of rocky reef habitat may be an effective way to expand diversity in spawning habitat and potentially contribute to stabilizing interannual recruitment for fish species such as Walleye and Lake Whitefish (Beletsky et al. 2007; Sesterhenn et al. 2014). Saginaw Bay expresses a high degree of thermal variation across both spatial and temporal dimensions, which has been shown to influence hatch timing of larvae and later recruitment success (Johnson 1961; Schupp 2002; Sesterhenn et al. 2014). Presently, hydrological conditions of Inner Saginaw Bay may make it preferable to the outer bay for reef habitat restoration. Inner Saginaw Bay is a warmer, more productive environment than Outer Saginaw Bay, which is more similar to the main basin of Lake Huron (Beeton et al. 1967). Along with warming earlier and more quickly than the outer bay (Great Lakes Coastal Forecasting System, NOAA; www..noaa.gov/res/glcfs), the more sheltered location of the inner bay may promote larval fish survival. Specifically, recent models have suggested that eggs and planktonic larvae are more likely to be retained in warm, productive waters when deposited towards the most southern part of Inner Saginaw Bay (Sesterhenn et al. 2014). In contrast, variable wind-driven currents may rapidly advect larvae from the outer bay to the less productive waters of the main of basin Lake Huron. Restored reef habitat in the more inner part of the bay may therefore encourage spawning in locations that are beneficial for larval survival.

The goal of this study was to assess whether restoration of rocky reef habitat in Saginaw Bay could provide suitable spawning habitat for species such as Walleye and Lake Whitefish. Our objectives were two-fold. First, we wanted to evaluate potential reproductive utilization of restored reef habitat by both Walleye and Lake Whitefish (representative spring and fall spawners, respectively) in Saginaw Bay. Current utilization patterns may help predict the likelihood of successful reef restoration. To this end, we surveyed current reproductive usage of two remnant spawning reef habitat sites and potential restoration sites. Second, we wanted to determine habitat suitability of potential reef restoration sites in Saginaw Bay. This included assessment of substrate, water quality, and potential for egg predation. Knowledge of current habitat conditions, coupled with evaluation of reproductive utilization, could provide further insights into characteristics necessary to restore functional reef habitat.

2.2 Methods

2.2.1 Study Site Descriptions

Four study sites were chosen in Inner Saginaw Bay (Figure 2.1). Two sites contained remnant reef habitat: Duck Reef (DR) and North Island Reef (NR). These sites were located on the northeast side of Inner Saginaw Bay, not far from the connection with the outer bay. Sampling areas at both DR and NR were about 120 ha each, centered around 43.840704^{o}, -83.476539^{o} and 43.871130^{o}, -83.429092^{o}, respectively. Based upon habitat mapping using side-scan sonar, DR and NR contain small, shallow areas of rocky structure. Two additional sites contained very limited rocky structure, and served as proposed restoration sites: Coreyon Reef (CR; historically part of a large spawning reef; Fielder 2002) and Saginaw River Mouth Reef (SR). These sites were located within the inner bay, farther from the outer bay than the remnant reef sites, and were chosen partially as locations likely to contain optimal conditions for developing eggs and larvae, including potentially warmer waters and a higher chance of retention in the inner bay (Sesterhenn et al. 2014). Additional rationale for selection of proposed restoration sites also stemmed from a contrast between chosen sites, as CR represented a more open-water site and SR served as a more shoreline location. Sampling areas for proposed restoration locations were about 50 ha each, and centered around 43.871130º, -83.429092º (CR) and 43.672953º, -83.853729º (SR). Habitat mapping at these locations revealed almost no rocky structure at CR, and only sporadic rocks at SR. Depth varied across sites, with remnant reef sites having lower minimum depths in large part due to extant reef structure (Table 1).

Sampling during Fall 2014 and Fall 2015 occurred across all sites and targeted the Lake Whitefish spawn, while Spring 2015 and Spring 2016 targeted the Walleye spawn at all sites. During each season, all study locations were sampled approximately once per week for six weeks (Fall: November through mid-December; Spring: April through mid-May), with some discrepancies due mainly to weather. Fall 2014 in particular suffered from an early and hard freeze, greatly reducing sampling during that season. Remnant reef sites were only sampled once in Fall 2014. Sampling dates were chosen based on water temperatures. We aimed to begin sampling prior to water temperatures reaching reported spawning ranges for each target species, and continue until the spawn was completed. Lake Whitefish begin spawning in mean water temperatures of about 7°C and below (Hart 1931; Sigurdson 2011), while Walleye spawn in temperatures between roughly 5.5-11°C (Collette et al. 1977).

2.2.2 Reproductive Utilization

We quantified reproductive usage of study sites by both Walleye and Lake Whitefish in two ways. First, we set two multi-mesh, microfilament gillnets (50 m length; 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, and 35 cm mesh sizes; Memphis Net and Twine Co., Inc.) overnight approximately once per week (weather dependent) at all sites to target spawning Walleye and Lake Whitefish adults. Numbers of individuals captured by species and reproductive condition (immature, mature, spawning) were recorded for all target species. Fish were determined to be in spawning condition through the presence of loose, flowing eggs (females) or flowing milt (males). All fish captured regardless of species were flash frozen on dry ice and subsequently transferred to -20°C for long-term storage before diet analyses (see below). Second, we used benthic egg mats (see Nichols et al. 2003) to capture eggs deposited by spawning fish. Mats consisted of a 50.8x76.2x2.54 cm furnace filter wrapped around a steel frame, anchored on benthic substrate in gangs of three spaced 3 m apart. Egg mats were checked weekly, and eggs captured during each approximately weeklong set were removed, counted, and identified to species. Egg species were identified both in the field using diameter (mm), oil content, and coloration, as well as through confirmation of a subset of eggs via later hatching at the USGS Great Lakes Science Center in Ann Arbor, MI. Both metrics of reproductive usage allowed us to determine relative amounts of spawning activity at each study location.

2.2.3 Habitat Suitability

We assessed suitability of habitat for reef restoration through collection of water temperature and dissolved oxygen, as well as analysis of egg predation potential. A sonde (YSI Model 85, YSI, Inc.) was used to collect data on water temperature and dissolved oxygen during sampling. Both temperature and dissolved oxygen measurements were collected for the whole water column at three random locations within each site, in increments of 0.5 m from water surface to substrate.

Potential for egg predation was assessed through diet analyses of fish collected using two methods of gillnet sampling. First, two hour sets of micro-mesh gillnets (28.5 m length; 1.25 cm, 2 cm, and 2.5 cm mesh sizes; Memphis Net and Twine Co., Inc.) were used to capture potential small-bodied egg predators at study locations. Specifically, two micro-mesh gillnets were set at each site approximately once per week during daylight hours, concurrent with multifilament gillnet sets. To minimize digestion after capture, fish were immediately flash-frozen using dry ice and were then transferred to -20°C for long-term storage. Second, diet analyses were also performed on all fish captured in multifilament gillnets during assessment of reproductive usage, so that all individuals captured, regardless of species, were subject to diet analysis.

Depending on species, diet contents in the anterior third of the digestive tract or anterior to the pyloric caecum were analyzed for all fish. All items were counted, photographed, and identified to at least order, with the exception of non-dreissenid mollusks. All non-dreissenid mollusks were identified only as members of phylum Mollusca. Fish eggs found in diet analyses were identified based on day of year caught, size, and oil content, then counted and photographed. For all diet items, ImageJ (Rasband, US National Institutes of Health) was used to measure lengths of photographed items.

2.2.4 Data Analysis

All data analyses were carried out in Program R (R Core Team 2016, Version 3.3.1), including R package lme4 (Bates et al. 2015). Analysis of variance (ANOVA) was used to statistically compare catches of target species in spawning condition (separate analyses for Walleye and Lake Whitefish) across sites, sampling date (day of year) and year; interactions were not included due to lack of significance in models. ANOVA assumptions were checked for both Lake Whitefish and Walleye data; Lake Whitefish data did not violate assumptions, but Walleye data were square-root transformed to more closely approximate parametric distributions. Post hoc analyses (Tukey's HSD) were used to investigate differences in any significant explanatory variables.

Relative differences in egg deposition (eggs d^{-1} m^{-2}) across sites were compared separately for Walleye and Lake Whitefish. Specifically, nested ANOVAs (individual egg mat served as a subsample for each gang of three mats) were used to compare egg deposition across three factors: site, sampling date, and year; interaction effects were included as well, for both Lake Whitefish and Walleye models. Egg counts were square-root transformed to more closely approximate parametric distributions for both Lake Whitefish and Walleye data. Due to a lack of data, however, Lake Whitefish egg deposition was only considered as a function of site, sampling date, and the interaction between those two factors. Tukey's HSD was again used for post hoc analyses.

ANOVA was also used to investigate differences in number of eggs found in predator diets, with separate analyses performed for both fall and spring seasons. Explanatory factors included site, sampling date, year, and predator species. Interaction effects were included for the Lake Whitefish model, but not the Walleye model due to a lack of significant effects. Predators considered included only those species that were found to consume eggs in diet analyses. Egg counts in predator diets for both Lake Whitefish and Walleye data were square-root transformed to more closely approximate parametric distributions. Specific differences between levels of factors were determined using Tukey's HSD.

2.3 Results

2.3.1 Reproductive Utilization

Target species, Lake Whitefish and Walleye, were captured in multifilament gillnets at all sites during fall and spring spawning seasons, respectively (Table 2; Figure 2.2). Beyond target species, a variety of other species were captured in multifilament gillnets. For example, Common Carp (*Cyprinus carpio*), Channel Catfish (*Ictalurus punctatus*), and White Sucker (*Catostomus commersonii*) were captured frequently, but were not as consistently represented across all sites and seasons as target species. Walleye were also captured frequently in fall, non-spawning seasons. Though catch of target species was fairly consistent within sites, sex ratio of captured target individuals in spawning condition was skewed (Figure 2.3). Males in spawning condition were consistently caught in higher numbers (n=148 for both species, across all seasons) than females (n=12). This uneven sex ratio was particularly apparent for Walleye in Spring 2016, when no females in spawning condition were caught (n=42 for males in spawning condition). Analyses of catches of Lake Whitefish in spawning condition showed no differences across site ($F=1.66_{3,10}$, p=0.238) or year ($F=0.30_{1,10}$, p=0.599), but did show a significant effect of sampling week ($F=4.21_{5,10}$, p=0.026) on number of individuals captured in spawning condition. Specifically, catches of Lake Whitefish in spawning condition increased until the fourth sampling week and subsequently declined until the end of the spawn. Catches of Walleye in spawning condition were significantly affected by sampling year ($F=16.16_{1,3}$, p=0.028) but not site ($F=2.10_{3,3}$, p=0.279) or sampling week ($F=2.85_{3,3}$, p=0.206). More individuals in spawning condition were captured in 2016 than 2015.

Rates of relative egg deposition across all sites and seasons were consistently low (range 0-31.73 eggs d^{-1} m^{-2}; Figure 2.4). No data are available for remnant reef sites (DR, NR) during

Fall 2014 due to weather affecting sampling. Eggs of target species were captured on mats at all sites during all seasons sampled, with the exception of Walleye eggs at NR during both spring sampling seasons. Statistical analyses of egg deposition for fall seasons showed that site ($F=17.55_{3,66}$, $p<0.001$) and sampling week ($F=3.53_{6,66}$, $p=0.004$) had significant effects on the number of Lake Whitefish eggs captured. Interaction between site and sampling week was also significant ($F=2.29_{11,66}$, $p=0.019$). Post-hoc tests indicated that egg mats at DR captured more Lake Whitefish eggs than mats at SR, though significance of this difference was marginal ($p=0.056$). Analyses of egg deposition for spring seasons showed that site ($F=22.74_{3,107}$, $p<0.001$), sampling date ($F=10.75_{5,107}$, $p<0.001$), and year ($F=38.50_{1,107}$, $p<0.001$) all significantly affected number of Walleye eggs captured. Specifically, CR egg mats captured more eggs than all other sites, second and third weeks of sampling captured the most eggs, and more Walleye eggs were captured in 2015 than 2016 across all sites. Interaction effects were all significant as well, including between site and sampling date ($2.79_{15,107}$, $p=0.001$); site and year ($F=11.16_{3,107}$, $p<0.001$); sampling date and year ($F=6.71_{3,107}$, $p<0.001$); and site, sampling date, and year ($F=3.07_{9,107}$, $p=0.003$).

2.3.2 Habitat Suitability

Temperature profiles for all sites during all seasons indicated that there were relatively small differences across sites (Figure 2.5). For all seasons, sampling began prior to water temperatures reaching literature-defined spawning ranges for each species (indicated by rectangular overlays in Figure 2.5), and continued until the end of the spawn. All sites displayed similar thermal patterns throughout sampling seasons, with no discernable differences between remnant reef sites and proposed restoration sites. Oxygen concentrations during sampling periods were consistently above a minimum of 7 mg L^{-1} at all sites.

For both fall and spring seasons, a variety of small-bodied potential egg predators were captured in micro-mesh gillnets (Table 3). Several potential egg predators were captured including: Round Goby (*Neogobius melanostomus*), White Perch (*Morone americana*), and Yellow Perch (*Perca flavescens*). The number of individual fish and total number of species captured in micro-mesh gillnets were greater during spring sampling, as compared to fall sampling. During both fall and spring seasons a variety of potential egg predators, including Common Carp, Channel Catfish, White Sucker, and White Perch were also captured in multifilament gillnets (Table 2).

In total, we examined diet contents of 1,247 individual fish across 23 different species. During fall sampling, Lake Whitefish eggs were found in stomachs of five species across both multifilament and micro-mesh gillnets: Lake Whitefish, Common Carp, Channel Catfish, White Sucker, and White Perch. During spring sampling, Walleye eggs were found in diets of four species: Walleye, Common Carp, Channel Catfish, and Yellow Perch. However, the frequencies of occurrence of eggs in stomachs of these species were low during both fall and spring (Figure 2.6). Eggs were never found in more than 22% of diets for any species. Moreover, mean number of eggs found in diets of those individuals that did consume eggs were fairly low during both seasons (Figure 2.6). Means for all species were below 200 eggs per stomach, with the exception of Channel Catfish in fall seasons.

During fall seasons, site ($F=35.93_{3,4}$, $p=0.002$), sampling date ($F=7.50_{3,4}$, $p=0.040$) and predator species ($F=146.06_{4,4}$, $p<0.001$) had a significant effect on number of Lake Whitefish eggs found in diets; year had no effect ($F=0.02_{1,4}$, $p=0.926$). Specifically, SR displayed a significantly higher amount of egg predation than all other sites and the third sampling week had more egg predation than the second week. Channel Catfish had a much higher mean Lake Whitefish egg count than all other species, driven primarily by one individual that had 1,508 eggs in its stomach;

Lake Whitefish also showed more egg predation than Common Carp. Interaction between site and sampling date was also significant ($F=117.64_{1,4}$, $p<0.001$). For spring seasons, site ($F=11.14_{3,28}$, $p<0.001$), sampling date ($F=7.25_{5,28}$, $p<0.001$), and predator species ($F=2.26_{4,28}$, $p=0.02$) all had significant effects on numbers of Walleye eggs found in predator diets, while sampling year ($F=2.68_{1,28}$, $p=0.113$) and predator species ($F=2.26_{4,28}$, $p=0.088$) had no effect. Predators captured at DR contained significantly more Walleye eggs than all other sites, and the sixth and final spring sampling week across both years resulted in more Walleye eggs found in predator diets than during all other weeks. Paired post-hoc tests of predator effects were inconclusive, but Channel Catfish again displayed highest mean eggs per predator species.

2.4 Discussion

Overall, we were able to capture spawning individuals of both target species across all sites and seasons. However, catch of spawning females was consistently low. Similarly, while some amount of eggs of both species were deposited at nearly all study sites, catches of eggs were very low. Though perhaps influenced by the small amount of eggs in the study environment, egg predation was also limited. When eggs were found in diet analyses, larger bodied fish predators seemed to represent a greater current threat to deposited eggs than smaller fish predators.

2.4.1 Reproductive Utilization

Both Lake Whitefish and Walleye were present in multifilament gillnet catches at all sites across both of their respective spawning seasons, but CPUE for both species was consistently low at all sites. Additionally, catch was highly variable throughout the spawning season for both species and in both sampling years. The variability in catch rates of individuals in spawning condition suggests that study sites may not currently represent important spawning grounds for either study species. A distinct lack of time periods with consistently high CPUE indicates that fish may be passing through study sites, but are not congregating to spawn at these locations in large numbers. For many fish species, including Walleye, females may only remain on spawning grounds long enough to deposit eggs (Colby et al. 1979). Low catches of females in spawning condition throughout the entire spawning season therefore suggest that very few female fish are moving into study sites to spawn; instead, most spawning may be taking place elsewhere. In the case of Walleye, it is likely that most spawning in the Saginaw Bay system is taking place in surrounding tributaries such as the Tittabawassee River, as indicated in past studies (Fielder 2002, Fielder 2014). As fish pass study sites on the way to tributary spawning locations, there may be a lack of ideal physical structure at study locations to encourage large-scale reproductive usage. Diversification of spawning habitats to include rocky reefs may be contingent on attraction of spawners through habitat restoration.

It is also important to note that both Lake Whitefish and Walleye often display strong site fidelity for spawning locations (Todd and Haas 2003; Ebener et al. 2009). Given that most recent spawning of Walleye has likely taken place in tributaries surrounding Saginaw Bay, rather than the bay itself, it is perhaps unsurprising that most fish would seek to return to these alternative locations to spawn. However, as some individuals of both target species were caught in spawning condition, there may be some small amount of adult spawners that are predisposed to spawn at locations within the bay itself. For Walleye in particular, presence of adults in spawning condition may suggest a remnant population of reef spawning fish. There is evidence that site fidelity is a heritable genetic trait for Walleye (Jennings et al. 1996), and that stocks can be separated based on genetic characteristics (Strange and Stepien 2007). If a reef spawning strain of Walleye could be confirmed, it would increase confidence that fish would preferentially choose restored reef habitat for spawning grounds. For Lake Whitefish, that same confidence can be gained from the fact that site fidelity is often related to substrate type, and that new sites displaying preferred physical structure are often colonized (Anras et al. 1999).

Egg deposition data show similar patterns as catch of adult spawners. For both Lake Whitefish and Walleye, eggs were collected at all sampled sites during respective spawning seasons, with the exception of Walleye eggs at NR. However, the low rates of egg deposition observed stand out dramatically when compared to past studies. For Lake Whitefish, egg densities of over 1,000 eggs m^{-2} have been observed on spawning reefs in Thunder Bay, Lake Huron (Adams et al. 2012, USFWS project report template). On large spawning reefs in Lake Erie, Walleye eggs have been observed at peak densities of nearly 900 eggs m^{-2} during a single sampling event (calculated from Roseman et al. 1996). In both cases, observed densities in previous studies far outweigh egg densities at study sites in Saginaw Bay, even if maximum catch of eggs m^{-2} d^{-1} was extrapolated over the entire sampling season. Additionally, these literature sources for egg densities represent observations on established and functional spawning reef habitat. As with catch of adult fish for both target species, it may be likely that current physical structure at study sites precludes a large degree of targeted spawning at these locations. However, given site fidelity for both Lake Whitefish and Walleye (Todd and Haas 2003; Ebener et al. 2009), the fact that some eggs were observed on egg mats for both species provides additional evidence that some small amount of individuals are potentially targeting spawning habitat in Saginaw Bay. Reef habitat restoration may allow for those individuals to experience increased spawning success, and for reef spawners to represent a higher proportion of egg deposition at study sites for both species.

Despite low rates of egg deposition overall, egg deposition rates for both Lake Whitefish and Walleye varied across sites, suggesting that locations differed in their relative attractiveness as spawning habitat. Greater densities of Lake Whitefish eggs were found at DR than SR (though post-hoc significance was marginal). This suggests that at least some amount of remnant reef structure may have proven more attractive to spawning Lake Whitefish than habitat at proposed restoration sites. As Lake Whitefish only spend time in Inner Saginaw Bay during the spawn, there is potential for greater suitability for the more outer remnant reef sites due simply to their location. In contrast, a large proportion of Walleye that spawn around Saginaw Bay remain in the bay system (Fielder and Thomas 2006), suggesting that these fish may be able to utilize proposed restoration sites for spawning. In fact, Walleye egg deposition rates were greater at degraded CR than all other sites. It is possible that any remaining reef spawning Walleye may recognize CR as a central location in the historic reef complex that once existed in the inner bay, even if very limited structure presently persists near CR. Unlike Lake Whitefish, it seems that Walleye did not attempt to utilize remnant structure at DR in any appreciable numbers.

For both Walleye and Lake Whitefish, egg deposition was highest at intermediate dates during the sampling season. This seems consistent with a typical pattern of fish densities observed during a spawning season, as fish move in and subsequently vacate spawning grounds. Finally, spring egg deposition was also significantly affected by sampling year, with greater densities of Walleye eggs in Spring 2015 than Spring 2016. Lower egg catches in 2016 were consistent with the lack of female Walleye in spawning condition captured in Spring 2016. Underlying reasons for the disparity in spawning females and egg deposition between years is currently unclear; however, past studies have suggested that interannual variation in Walleye egg deposition may not be an uncommon occurrence regardless of numbers of spawning adults (Roseman et al. 1996).

It should also be noted that all interactions between site, sampling date, and year were significant for eggs deposited in spring seasons. Site and sampling date also significantly interacted in fall seasons, suggesting that the specific date a site was visited could potentially affect its yield of eggs. These interactions may confound some interpretation of the relative strength of each factor affecting rates of egg deposition, and all conclusions should be considered with interactions in mind. Still, it is clear that factors included in models are playing important roles in site selection by spawning fish of both target species.

2.4.2 Habitat Suitability

Seasonal variation of water temperatures was consistent across sites. During fall seasons, the full duration of the spawn (as determined by water temperatures) was sampled. Study sites were never more than about 3°C apart during any given sampling week. For spring seasons, we saw similar patterns, despite any potential influence of water from Outer Saginaw Bay on nearby remnant reef sites. It is possible, however, that our sampling seasons did not coincide with influxes of main basin Lake Huron water into Saginaw Bay, which has been shown to be a frequent occurrence (Beeton et al. 1967). Such influxes may still have disproportionate cooling effects on remnant reef sites due to their location closer to the outer bay. Additionally, water currents at remnant reef sites may be more likely to transport eggs and developing larvae into the outer bay versus proposed restoration locations (Sesterhenn et al. 2014). Overall, no sites showed temperature patterns that should negatively impact spawning for either target species; however, proposed restoration sites may still be more conducive to restoration due to the potential influence of water currents.

Catch of small-bodied potential egg predators was highly variable, with higher rates of capture in spring sampling seasons. More small-bodied fish seemed to be present and active as waters warmed in spring seasons, with nearly five times the small-bodied individuals caught in spring as compared to fall. Despite this activity, most documented egg predation seemed driven by large-bodied egg predators captured in multifilament gillnets. For both fall and spring sampling seasons, eggs were infrequently found in diet analyses. Additionally, the range of species that consumed eggs was quite limited, with only five unique species consuming eggs in fall seasons, and four species in spring seasons (only one of which was not observed during fall seasons). Research on spawning reefs in western Lake Erie, however, has shown that a wider range of Great Lakes fish species has been documented as egg predators (Roseman et al. 2006). Thus, documented egg predation in this study likely does not represent the full suite of potential predators. In fall seasons, SR had significantly higher egg predation than all other sites. The lack of cover for deposited eggs may have helped account for differences between predation at SR and remnant reef locations, while the proximity of SR to the Saginaw River may help attract more predators than at an open water site such as CR. Additionally, predation of Walleye eggs was highest at DR, which possesses the most concentrated and central remnant reef structure across all sites. Though Walleye egg deposition at DR was not greater than at proposed restoration locations, diet analyses suggest that higher numbers of eggs may still be found at DR. This may provide some evidence for reef spawning fish utilizing remnant rocky structure. In contrast, although CR possessed greatest rates of Walleye egg deposition, lack of attractive rocky structure may have precluded predators from taking full advantage of eggs as a diet item. Restoration of reef habitat may remove a barrier preventing use of degraded sites such as CR, and allow for increased diversification of spawning locations.

When eggs were present in diets, mean number of eggs consumed was quite low for almost all species. A noteworthy exception was Channel Catfish, which proved capable of consuming very large numbers of eggs from target species when eggs were available. To a lesser extent, Common Carp and Walleye also proved opportunistic in feeding upon target eggs. Overall, the low occurrence of eggs in fish diets implies that eggs are only infrequently found, consumed, or targeted by predators at study sites; however, large-bodied egg predators, particularly Channel Catfish, are capable of consuming eggs in significant quantities when available. In contrast, smaller-bodied species such as Yellow Perch did not seem as likely or able to consume large numbers of target eggs. This stands in contrast to previous work on spawning reefs in Lake Erie, which implicated Yellow Perch as important predators of Walleye eggs (Wolfert et al. 1975; Roseman et al. 2006). Additionally, eggs were not found in higher frequency in small-bodied fish as compared to large-bodied fish, so cumulative effect of egg predation by small-bodied fish was still low. This occurred despite the fact that less digestion would be expected during a two-hour, micromesh net set versus an overnight gillnet set. Interestingly, we documented no egg predation in any season from known invasive egg predators such as Round Goby and White Perch (Roseman et al. 2006). It is possible that egg predation from these species, particularly Round Goby, was underestimated. Round Gobies are highly abundant in Saginaw Bay (Fielder and Thomas 2014; Foley et al. 2017), which was not fully reflected in catch rates for this study. Still, given the overall disparity in mean eggs consumed between large- and small-bodied predators, it may be that large-bodied egg predators represent more of a current threat to egg survival in Saginaw Bay.

As with egg deposition data, it should also be noted that analysis of egg predation during fall seasons did have one significant interaction between factors. Site and date were related to each other during the collection period for potential Lake Whitefish egg predators. Although we attempted to sample all sites during each weekly sampling event, it is possible that the exact visit date could play some role in the egg predation documented at a given site.

2.4.3 Implications for Habitat Restoration

Overall, we documented low numbers of individuals in spawning condition for both Lake Whitefish and Walleye, as well as low rates of egg deposition for both target species. Despite low catch rates, we still captured individuals in spawning condition and eggs at all sites for both species, apart from Walleye eggs at NR. The low amount of spawning activity at study sites for both target species suggests that neither Walleye nor Lake Whitefish are using study locations as major spawning grounds, but some small amount of spawning may be taking place at these locations. Given that site fidelity is frequently displayed by both species, it is possible that any small amount of spawning at study sites may represent remnant strains of reef spawning fish. We suggest that restoration of rocky reef structure may encourage increased reproductive utilization of such sites by fish in Saginaw Bay, and result in added population stability through portfolio effects. Furthermore, restored reef structure would likely provide improved protection of eggs from predation. Large-bodied predators appear to be a primary threat to deposited eggs, and interstitial spaces within reefs would likely provide a refuge from predation by such fishes.

Based on the collected data, we suggest that there is potential for successful reef restoration in Saginaw Bay from a biological standpoint, though some concerns remain. With informed reef design and location, it may be possible to promote diversity of spawning locations for Lake Whitefish, Walleye, and a variety of other species. Added stability in these key fish populations can only benefit fisheries in Lake Huron, and provide confidence for managers under uncertain future environmental conditions. However, increased utilization of reef structure may depend in part on a viable, remnant population of genetic reef spawning fish; past research suggests that successful spawning habitat enhancement for Walleye is highly dependent on the presence of an existing, reproducing adult population (Geiling et al. 1996). In Saginaw Bay, existence of such a population remains unclear. Ongoing analysis of genetic samples collected during this assessment may help shed light on the degree to which genetic reef spawners may remain.

Additional uncertainties surround the success of spawning habitat restoration within Saginaw Bay. To date, reef restoration has only been implemented in the outer bay, which may not be comparable to inner bay reef habitat (Foster and Kennedy 1995; Fielder and Baker 2004). A pilot study assessing resulting physical conditions of a restored, small reef in the inner bay may be one method of predicting long-term reef dynamics. Furthermore, reef restoration in other areas of the Great Lakes has shown promise as a method to increase adult abundance and egg production on spawning sites, but has not directly provided evidence for strong year classes of target species (McLean et al. 2015). If reef construction were to proceed, continued monitoring during and post-construction would be necessary to determine success in reef restoration efforts. This study represents baseline conditions pre-restoration, and should serve as a comparison for such future endeavors.

Table 2.1. Study site characteristics. Range of dissolved oxygen represents whole water column measurements.

Site	*Range Sampled Depth (m)*	*Range Spring Dissolved Oxygen (mg/l)*	*Range Fall Dissolved Oxygen (mg/L)*	*Substrate Type*
Saginaw River Mouth (SR)	2.2-3.9	6.68-11.48	6.38-13.59	Sand, isolated rock
Coreyon Reef (CR)	4.4-5.0	8.24-11.55	7.0-12.24	Sand, minimal rock
Duck Reef (DR)	0.9-3.4	8.02-12.2	7.17-11.35	Mixed gravel, cobble, sand
North Island reef (NR)	1.4-3.1	8.03-12.2	7.38-11.42	Mixed gravel, cobble, sand

Table 2.2. Catch per net set for overnight, multifilament gillnets, mean ± SE. Catch is divided by sampling season (fall spring 2014-2016), site (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef), and species.

	Fall 2014				*Fall 2015*			
	SR	*CR*	*DR*	*NR*	*SR*	*CR*	*DR*	*NR*
Walleye	1.6±1	3.5±0.35	7	2	1.83±1.47	1.4±0.93	2.0±0.89	1.0±0.48
Lake Whitefish	2.2±1	2.5±0.35	2	6	4.67±1.63	3±2.07	5.2±2.44	5±2.1
Common Carp	4.4±2.22	--	--	--	4.67±2.0	1±0.55	1.8±0.97	4.6±2.11
Channel Catfish	0.6±0.22	--	2	--	0.67±0.33	0.2±0.2	0.2±0.2	0.2±0.2
White Sucker	1±0.44	2±0.71	--	--	0.67±0.33	0.2±0.2	--	0.2±0.2
Gizzard Shad	0.8±0.72	--	--	--	--	--	--	--
White Perch	0.2±0.18	0.5±0.35	--	--	--	0.2±0.2	--	--
Yellow Perch	--	--	--	--	0.17±0.17	0.2±0.2	--	0.4±0.24
	Spring 2015				*Spring 2016*			
	SR	*CR*	*DR*	*NR*	*SR*	*CR*	*DR*	*NR*
Walleye	2.5±1.23	0.8±0.37	0.8±0.58	0.5±0.29	1.75±0.48	8.25±6.69	2.5±2.18	0.5±0.29
Common Carp	3.33±1.98	0.2±0.2	0.4±0.24	3.5±1.19	1.25±0.48	--	0.5±0.5	2.25±1.44
Channel Catfish	5.5±1.54	--	0.8±0.37	0.5±0.5	4.5±2.22	--	0.25±0.25	2.25±0.85
White Sucker	0.17±0.17	1.2±0.97	--	--	0.25±0.25	2.25±1.44	0.25±0.25	--
Gizzard Shad	0.17±0.17	--	--	--	--	--	--	--
White Perch	0.17±0.17	1.2±0.73	--	--	--	--	0.25±0.25	--
Yellow Perch	0.33±0.21	0.2±0.25	--	--	--	--	--	0.25±0.25
Northern Hog Sucker	--	0.6±0.24	--	--	--	--	--	--
Greater Redhorse	--	0.4±0.4	--	--	--	--	--	--
White Bass	0.33±0.21	--	--	--	0.5±0.5	--	--	--

Table 2.2. Continued

Freshwater Drum	0.67±0.33	--	--	--	3±0.58	0.5±0.5	--	0.5±0.29
Longnose Gar	0.5±0.5	--	--	2.25±1.65	--	--	--	--
Goldfish	0.17±0.17	--	--	--	--	--	--	--
Muskellunge	0.17±0.17	--	--	--	--	--	--	--
Quillback	0.17±0.17	--	1±1	0.25±0.25	--	--	0.5±0.5	0.25±0.25
Smallmouth Bass	--	--	--	0.25±0.25	--	--	--	--
Northern Pike	--	0.2±0.2	--	--	0.25±0.25	0.25±0.25	--	--
Golden Redhorse	--	--	--	--	--	--	--	0.25±0.25
Steelhead	--	--	--	--	--	--	--	0.25±0.25

Table 2.3. Catch per hour of net set for micro-mesh gillnets, mean ± SE. Catch is divided by sampling season (fall and spring 2014-2016), site (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef), and species.

	Fall 2014				*Fall 2015*			
	SR	*CR*	*DR*	*NR*	*SR*	*CR*	*DR*	*NR*
Round Goby	0.65±1.07	--	--	0.86	0.18±0.4	--	--	0.1±0.2
Yellow Perch	0.11±0.18	--	--	0.86	--	0.13±0.25	0.77±1.36	0.51±0.77
White Perch	0.22±0.22	--	--	1.71	--	--	0.38±0.58	0.1±0.2
Spottail Shiner	--	--	--	2.57	0.18±0.24	--	0.19±0.25	0.1±0.2
Logperch	0.33±0.54	0.16±0.27	--	--	--	--	0.1±0.2	0.1±0.2
Trout-perch	--	0.16±0.27	--	--	--	--	--	--
Emerald Shiner	--	--	--	--	--	--	0.19±0.25	6.9±11.5
Gizzard Shad	--	--	--	--	--	--	--	0.21+0.25
	Spring 2015				*Spring 2016*			
	SR	*CR*	*DR*	*NR*	*SR*	*CR*	*DR*	*NR*
Round Goby	0.79±0.56	0.16±0.33	2.5±3.33	1.02±1.56	0.45±0.63	--	0.48±0.63	0.59±0.73
Yellow Perch	5.53±7.36	3.73±6.89	1.37±1.4	2.19±2.52	3.16±5.65	--	3±4.18	2.55±2.4
White Perch	--	0.08±0.17	--	--	--	--	--	--
Spottail Shiner	0.18±0.33	0.16±0.33	--	1.68±3.73	0.23±0.34	--	--	1.08±1.71
Logperch	--	--	0.48±0.63	0.29±0.5	0.08±0.17	--	--	--
Trout-perch	0.44±0.83	0.97±1.41	0.08±0.33	0.22±0.34	0.6±0.42	0.21±0.34	1.64±3.4	--
Rainbow Smelt	--	0.08±0.17	--	0.22±0.22	0.83±1.14	0.07±0.17	0.1±0.2	1.18±1.91
Walleye	0.09±0.17	0.16±0.33	--	--	0.08±0.17	0.08±0.17	--	--
Emerald Shiner	0.09±0.17	1.46±3	--	0.58±0.83	2.63±3.83	--	0.39±0.49	0.39±7.62
Freshwater Drum	--	--	0.08±0.17	--		--	--	--

Table 2.3. Continued

Longnose Gar	--	--	--	0.07±0.17	--	--	--
Smallmouth Bass	--	--	0.08±0.17	--	--	--	--
Unknown Shiner Spp.	--	--	0.08±0.17	--	--	--	--

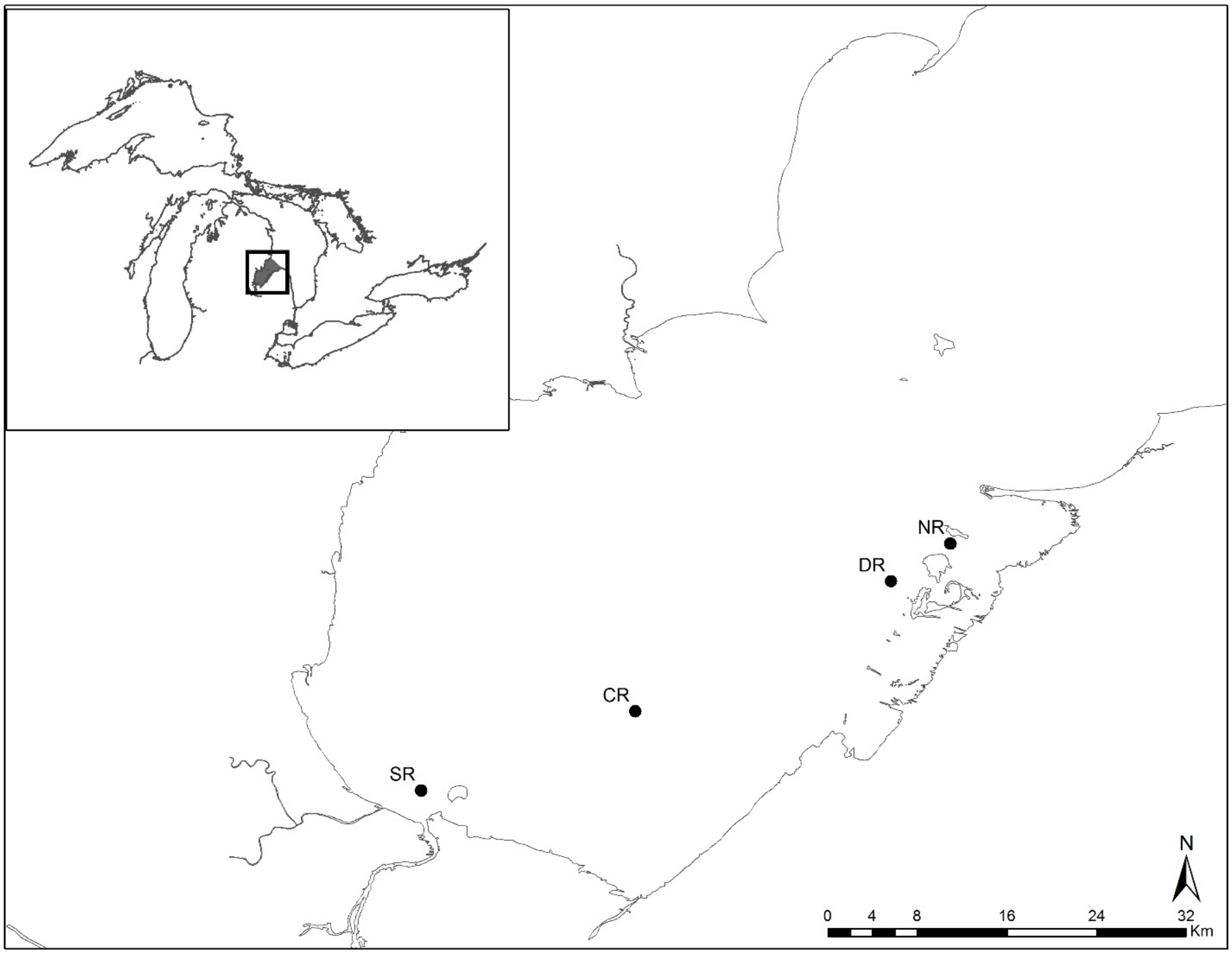

Figure 2.1. Locations of study sites within Saginaw Bay. Duck Reef (DR) and North Island Reef (NR) are remnant reef sites, while Saginaw River Mouth Reef (SR) and Coreyon Reef (CR) are proposed reef restoration sites.

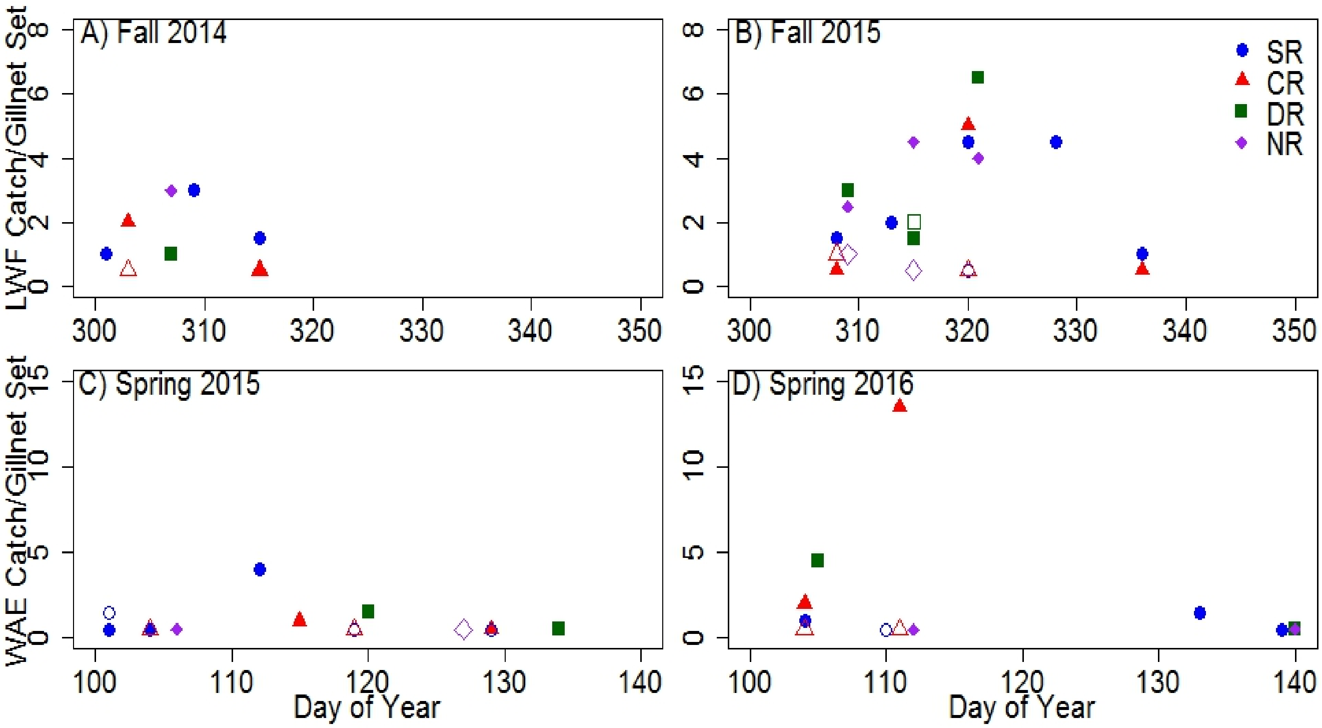

Figure 2.2. Catch per gillnet set by site of target individuals (Lake Whitefish, Walleye) across all sampling seasons (fall and spring 2014-2016) and sites (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef). Closed points represent males, open points represent females.

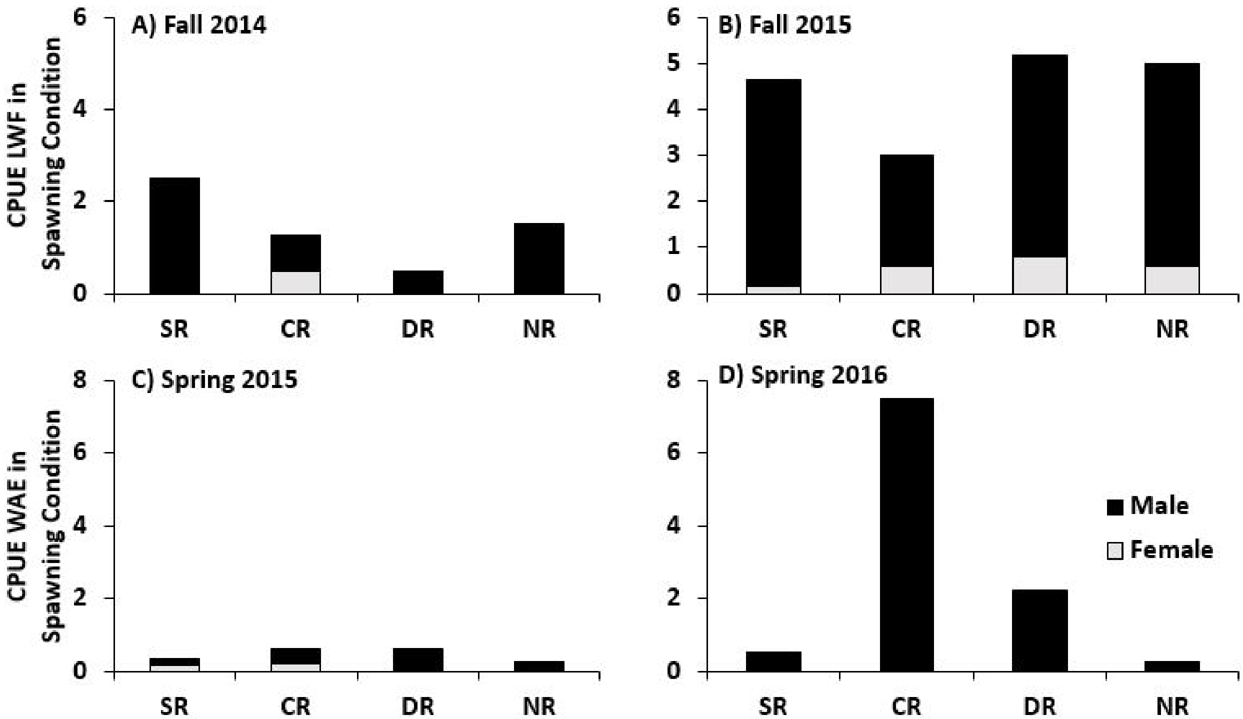

Figure 2.3. Catch per gillnet set of target individuals (Lake Whitefish, Walleye) in spawning condition across all seasons (fall and spring 2014-2016) and sites (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef).

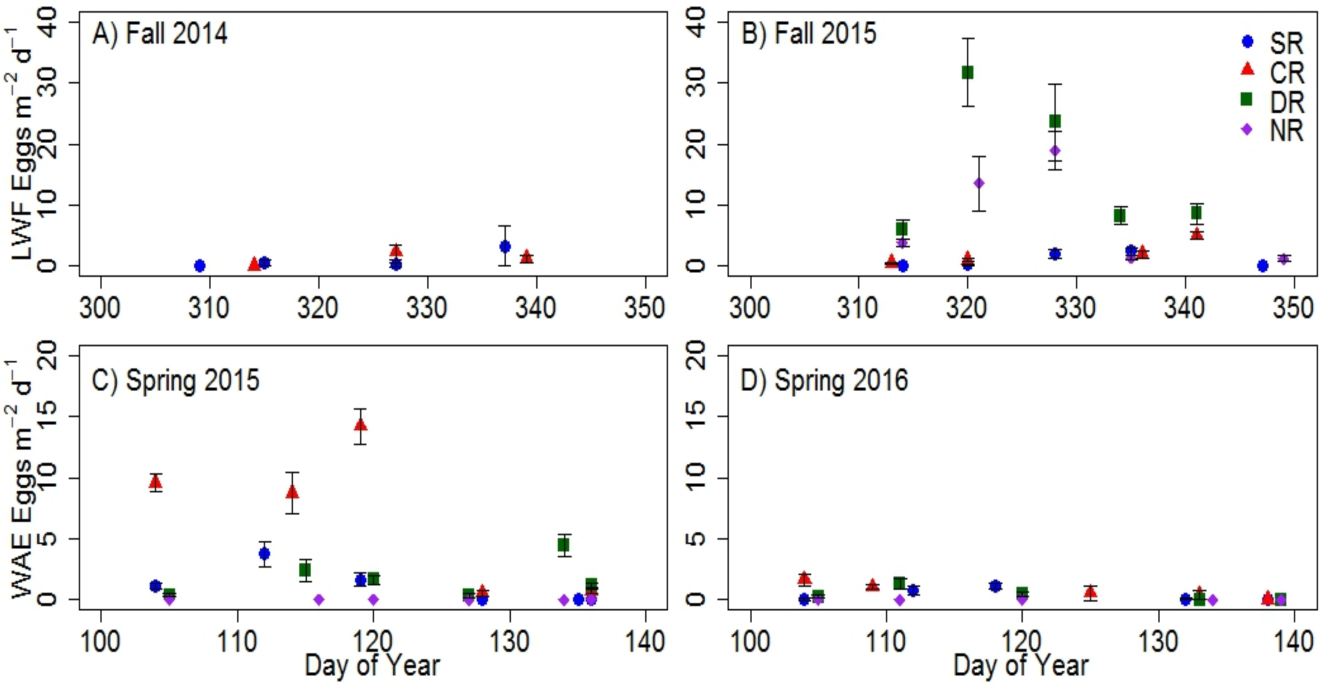

Figure 2.4. Relative rates of egg deposition (eggs m^{-2} d^{-1}) by site (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef) across all sampling seasons (fall and spring 2014-2016), ± SE.

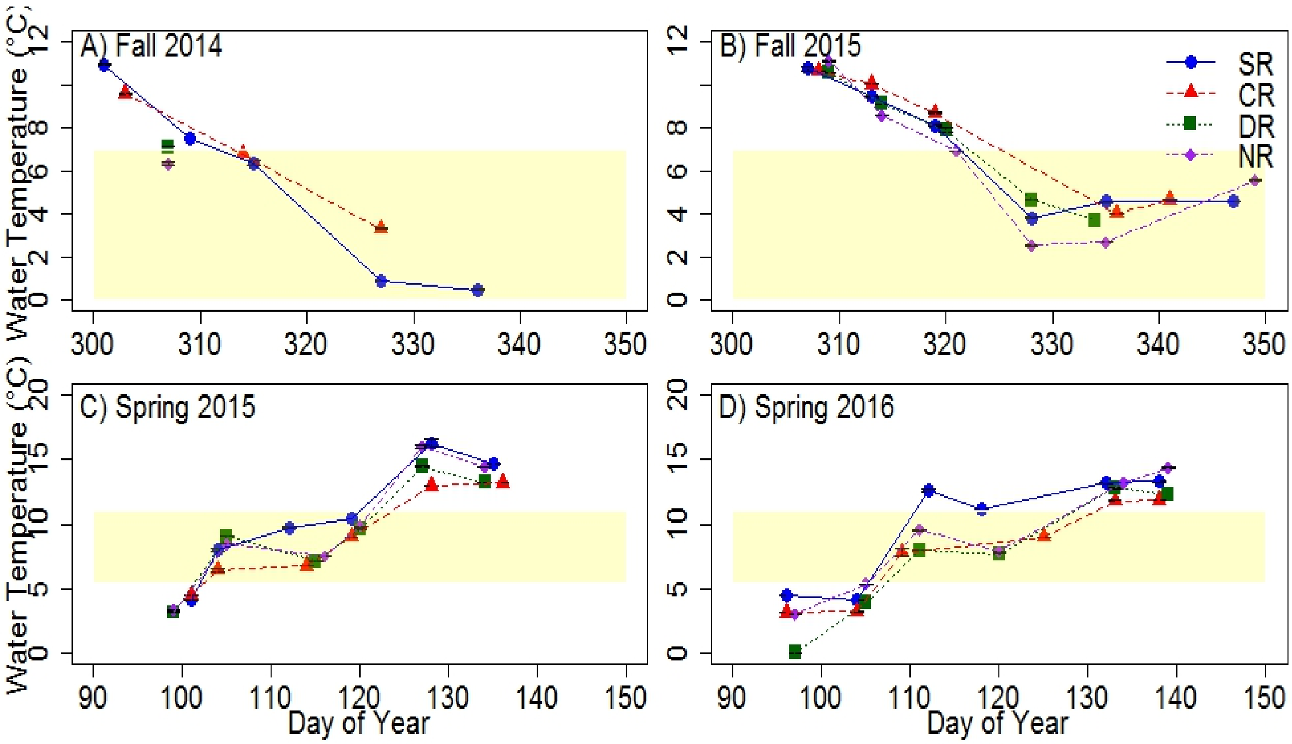

Figure 2.5. Time series of water temperature data by site (Saginaw River Mouth Reef, Coreyon Reef, Duck Reef, North Island Reef) across all seasons (fall and spring 2014-2016). Rectangular overlays indicate literature spawning ranges for Lake Whitefish (fall spawners) and Walleye (spring spawners).

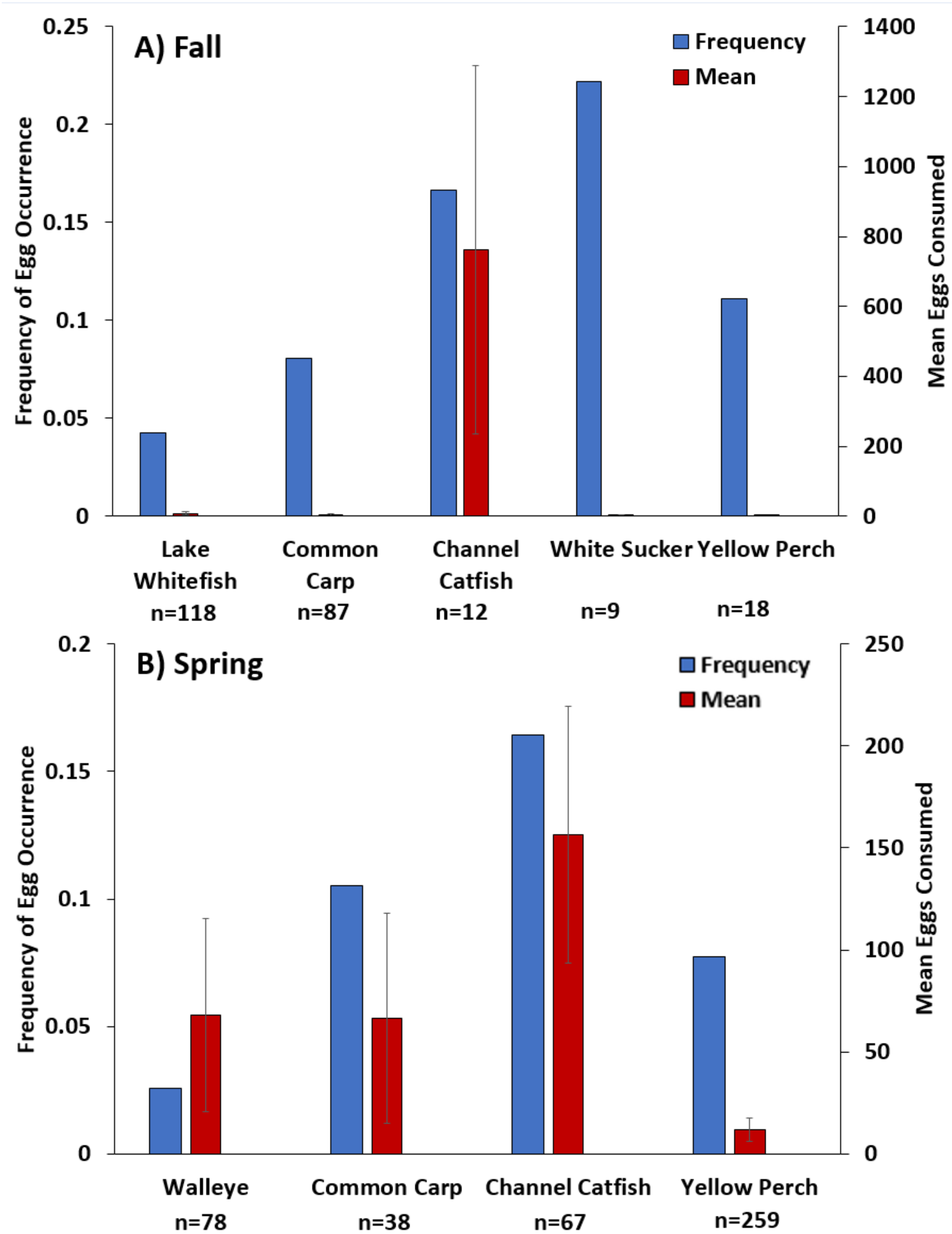

Figure 2.6. Egg predation results for both fall and spring seasons, pooled by season across all sampling years (2014-2016). For each species, frequency of occurrence of target eggs (Lake Whitefish in fall, Walleye in Spring) in diets, as well as mean number of eggs consumed in a diet, are reported. Mean egg consumption values for each species are calculated from only those diets that contained target eggs.

CHAPTER 3. OVERWINTER HYPOXIA LIMITS SPAWNING OF GREAT LAKES FISH

3.1 Introduction

Successful reproduction of demersal spawning fishes is highly dependent on the quality of spawning and incubation habitat for eggs (Manny et al. 1989; Magee et al. 1996). Declines in populations of a variety of native fish species have been attributed at least in part to degradation of physical, chemical, and biological condition of benthic spawning habitat (Schneider 1977; Keller et al. 1987; Evans et al. 1996; Jones et al. 2003). In particular, anthropogenic activities on land and in water can affect spawning habitat by contributing to factors such as sedimentation, degradation of spawning structure, and bottom hypoxia (Schneider and Leach 1977; Henley et al. 2000; Soulsby et al. 2001; Diaz and Rosenberg 2008).

Excessive sedimentation can have adverse impacts on spawning success in multiple ways. Over time, sediment can cover important bottom structure used for spawning. Interstices that provide refugia from predation for eggs become filled in by sediment, and thereby rocky areas may no longer provide advantageous conditions for incubating eggs. Additionally, high levels of suspended sediments can settle on incubating eggs and severely limit gas exchange, thereby suffocating deposited eggs. Lithophilic spawners such as Walleye (*Sander vitreus*), Lake Whitefish (*Coregonus clupeaformis*), Cisco (*Coregonus artedi*), and Sucker species (*Catostomidae*) deposit eggs in rocky areas that may be highly affected by sedimentation. Coregonid eggs also overwinter before hatching, resulting in a long period (up to nearly five months; Price 1940; John and Hasler 1956) of susceptibility to excessive sediment deposition. Sediment has been a major historical concern across the Laurentian Great Lakes (Beeton 1965; Kemp et al. 1974). Shallow aquatic systems which drain land with high sediment loss (e.g., clearcut forests and intensive agricultural lands), such as the western basin of Lake Erie and Saginaw Bay, Lake Huron may be particularly vulnerable to sedimentation. Due to their shallow depths and high productivity, these areas are also important nursery habitats for developing fish.

Along with high rates of sedimentation, spawning structure can also be degraded by biofouling. Accumulation of benthic algae, such as Cladophora, can limit the amount of eggs and larval fish found on spawning habitat (Johnson et al. 2006). Invasive dreissenid mussels can have similar effects, by limiting egg deposition through occupation of spawning spaces and increasing damage to deposited eggs (Marsden and Chotkowski 2001). A recent analysis of reef restoration in the Great Lakes concluded that together, sedimentation and biofouling represent some of the most important threats to the success of reefs as spawning habitat (McLean et al. 2015).

Hypoxia, generally defined as oxygen levels below 2.0 mg/L, is a worldwide concern in freshwater and marine systems (Diaz 2001), and several recent studies have documented and evaluated causes and consequences of summer bottom hypoxia in Great Lakes systems (e.g. Hawley et al. 2006; Arend et al. 2011; Zhou et al. 2013). Though the proliferation of mid-summer hypoxia is a major ecological concern, it is unlikely to severely affect egg incubation success of most Great Lakes fishes, which primarily spawn during the spring or fall. In contrast, hypoxia that occurs over winter and under ice cover can have direct impacts on fall-spawning species. Ice and snow cover limits light penetration, which in turn reduces the effective production of oxygen by photosynthetic organisms (Olson 1932; Greenbank 1945). Additionally, diffusion of oxygen across the air-water interface is greatly reduced during ice cover (Magnuson et al. 1985). As respiration occurs under the ice, oxygen is depleted and hypoxic conditions can develop (Greenbank 1945; Magnuson et al. 1985). For fall spawners with eggs that incubate under the ice over winter, winter hypoxia can have pronounced negative effects on egg survival. Exact duration of incubation is temperature dependent, but lasts for a minimum of two months for fall spawning species such as coregonids and Lake Trout (*Salvelinus namaycush*) (John and Hasler 1956; Martin 1957; Thome et al. 2016). Due to the length of incubation, fall spawned eggs are susceptible to reduced levels of oxygen occurring essentially any time during winter. Shallow, productive areas such as Green Bay, Lake Michigan, and Saginaw Bay may be especially susceptible to the formation of over winter hypoxia (Epstein et al. 1974; Freedman 1974).

Saginaw Bay is a large (2,947 km^2), historically productive embayment of the Lake Huron that has experienced degradation of physical conditions through high rates of sedimentation, reduction in quality of spawning structure, and high demand for biochemical oxygen (Freedman 1974). During the early part of the 20th century, the Saginaw Bay watershed experienced a shift from forested to agricultural land use. Clear-cutting and intensive land management likely contributed to an increase in nutrient and sediment run off (Schneider and Leach 1977), while industrial growth in the watershed brought about increased loading of various chemicals (Freedman 1974; Schneider and Leach 1977). A net result of these anthropogenic influences was the loss of spawning habitat in Saginaw Bay. In particular, most of an extensive rocky reef complex that once spanned nearly the entire length of the inner bay was covered by sediment and severely degraded (Schneider 1977; Fielder 2002). These reefs historically supported many productive fisheries in Saginaw Bay, including Walleye (Hile 1954). With the loss of reef spawning structure, many fish populations experienced sharp declines; Walleye in particular were severely impacted (Keller et al. 1987; Fielder and Baker 2004). Remaining reef spawning habitat was further exposed to biofouling by dreissenid mussels, adding to degradation from high rates of sedimentation. Additionally, most remnant reef habitat is subject to water currents that may advect eggs and larvae out of the nursery environment of the inner bay (Sesterhenn et al. 2014). During winter, high rates of nutrient inputs and ice cover on the inner bay from roughly December through March (Keller et al. 1987) also make Saginaw Bay highly susceptible to hypoxia. Together, these sources of degradation represent significant impairments to spawning habitat in Saginaw Bay.

In recent years, efforts have focused on the possibility of restoring rocky reef habitat in Saginaw Bay. Evidence of reduced sedimentation patterns, along with the need to diversify spawning habitat for species such as Walleye and Lake Whitefish, have prompted investigation into the feasibility of reef habitat restoration. The goal of this study was to assess whether physical conditions at remnant reefs and potential restoration sites were conducive to successful spawning for species such as Walleye and Lake Whitefish (representative spring and fall spawners, respectively). Our objectives were three-fold. First, we aimed to evaluate current bottom structure at study locations. Depth, structural relief, and relative hardness data for all sites could help determine suitability of study locations for spawning habitat restoration. Second, through the use of sediment traps we assessed the current state of sedimentation at study sites. Finally, we wanted to determine if dissolved oxygen concentrations could be a limiting factor for spawning, both during the fall and spring spawning seasons and over winter. Sub-surface dissolved oxygen loggers placed during spawning seasons and over winter allowed for a season-long assessment of potential hypoxia in Saginaw Bay.

3.2 Methods

Four study locations were chosen in Inner Saginaw Bay, two of which contained remnant reef habitat and two that served as proposed restoration sites (Figure 3.1). Remnant reef sites contained some amount of historic rocky reef structure (Duck Reef, DR; North Island Reef, NR) while proposed restoration sites were much more limited in benthic structure (Saginaw River

Mouth, SR; Coreyon Reef, CR). Total area of remnant reef sites was also larger than proposed restoration sites, at about 120 ha each, versus about 50 ha each for proposed restoration sites. Proposed restoration sites were identified based on a variety of favorable factors, including potentially warmer water temperatures, proximity to river spawning Walleye who may be able to utilize restored reef habitat, and increased likelihood of retention of eggs and larvae in the inner bay (Sesterhenn et al. 2014). CR was also chosen for its historical inclusion in the reef habitat that once spanned Inner Saginaw Bay (Fielder 2002). Total range of the sampling period was between Fall 2014 and Spring 2017, with targeted sampling during the Lake Whitefish spawn (fall seasons), the Walleye spawn (spring seasons) and during summer 2015.

Bathymetric and relative hardness measurements were obtained and processed by the Michigan Department of Natural Resources (MDNR) in June 2015 at all sites. Hardness measurements were relative within each site, allowing for examination of range of substrate hardness at each location. A coefficient of variation (CV) was also calculated using hardness data for each site, allowing for some comparisons between sites. Exact site coordinates were chosen based primarily on past literature (Schneider 1977; Fielder 2002). Parallel transects (80 m) of side-scan sonar readings, coupled with GPS, were conducted in a grid pattern at each site. Transects were spaced 40m apart, with port and starboard side-scan ranges of 26m. Sonar data were measured using Hummingbird acoustic technology (model 998c), with a down-looking beam frequency of 200kHz and image frequency of 455kHz. Data were processed and interpolated using DrDepthPC software (version 7.510). Underwater video was also captured at all sites for visual inspection. Additionally, dissolved oxygen measurements were taken concurrent with side-scan sonar readings (meter from YSI, Inc.).

Sediment traps were used to assess relative amounts of sedimentation across sites. Traps consisted of four 35.56 cm lengths of vertical PVC tubing (10.16 cm diameter), closed on the lower end and anchored in a plastic crate on benthic substrate. Traps were set surrounding best available spawning habitat, as determined by visual inspection, for the duration of the Fall 2015 and Spring 2016 seasons, as well as overwinter 2015-2016. Four traps were set at all sites in Fall 2015, while two traps were set at SR and one trap was set at both DR and NR for overwinter 2015-2016 and Spring 2016 seasons. At the end of each season, traps were pulled, sediment was removed, and traps were replaced in the bay. Collected sediment was then dried for three days at 70°C and weighed to the nearest milligram. Sediment from individual PVC tubes was pooled within each trap, and traps were statistically compared across sites. ANOVA was used to determine differences in relative amounts of dry sediment across sites, with separate ANOVAs performed for Fall 2015, overwinter 2015-2016, and Spring 2016 seasons (R Core Team 2016, Version 3.3.1). Tukey's HSD post-hoc tests were used to determine exact differences between sites, when applicable.

A handheld dissolved oxygen meter (YSI Model 85; YSI, Inc.) was used at all sites during both spring and fall data collection, with readings taken approximately once per week in 0.5m increments from water surface to substrate at three random locations per site. Additionally, dissolved oxygen dataloggers (HOBO U26 Dissolved Oxygen Datalogger, Onset Computer Corporation) were set overwinter 2015-2016 and 2016-2017. One logger each was placed at SR, CR, and DR sites from mid-December 2015 to early April 2016. Loggers were attached to cinder blocks, placed close on top of the substrate to approximate ambient conditions experienced by deposited eggs, and set surrounding best available spawning habitat at each site. Loggers were placed adjacent to, rather than on top of, best available habitat due to potential damage from ice floes at shallowest depths. Each logger recorded dissolved oxygen levels every six hours. Informed by overwinter 2015-2016 results, additional loggers were deployed the following year. From late October 2016 to early April 2017, loggers were deployed in pairs, with one logger just off the substrate and one approximately 0.5m off the bottom on a steel frame. One near-sediment/elevated pair was set at both SR and CR, two low/high pairs were deployed at DR, and one logger was placed at NR in the high position. Upon logger retrieval, data were downloaded and analyzed using HOBOware software (Onset Computer Corporation, Version 3.7.8). To minimize influence of occasionally erroneous readings, data were considered as moving averages of dissolved oxygen across the duration of logger deployment.

3.3 Results

Based on side-scan sonar readings, remnant reef sites displayed a much wider range of bathymetric structure than proposed restoration sites. In particular, DR featured a consistent, fairly linear distribution of shallow structure, with minimum depths reaching less than 1m (Figure 3.2A). Visual observations from underwater video confirmed that shallow locations at DR consisted of a mix of gravel and cobble, with sand substrate beginning at greater depths along the periphery of rocky structure (Supplementary Material, Table 1 [S1]). Additionally, rock substrate was generally devoid of dreissenid fouling. A relative hardness profile of DR confirmed visual observations except at shallowest depths, where side-scan sonar suggested extremely soft substrate (Figure 3.2B). This discrepancy with visual observations is likely due to poor sonar signal reflection in very shallow water. Structure at NR was much more diffuse, but again displayed minimum depths of less than 1m (Figure 3.3A). As with DR, most of this shallow structure consisted of rock substrate, with sand in between shoals (S1). Relative hardness data again generally followed visual interpretation, except at some of the very shallow, rocky areas of NR (Figure 3.3B). Shallow areas again showed extremely soft substrate, which was not the case upon visual inspection.

Proposed restoration sites contained much lower amounts of rocky structure. CR in particular possessed a fairly homogenous, sandy bottom in both sonar readings and visual inspection (Figure 3.4; Appendix Table A1). Relative hardness data showed some differences across CR, perhaps indicative of the underlying historic reef structure below deposited sediment. SR bathymetry showed more variation than CR, with a slight grade to the site and some shallow peaks indicative of isolated rocks (Figure 3.5). Visual inspection also indicated that many of the rocks present at SR were fouled by dreissenids (Appendix Table A1). However, relative hardness at SR was fairly consistent.

Across all sites, there were marked differences in distribution of relative hardness values (Figure 3.6). SR displayed the smallest range of relative hardness values for any site. CR showed a more bimodal hardness distribution, suggesting the presence of some historic reef structure below the sand substrate. Remnant reef sites also differed from each other, with DR possessing a fairly normal distribution of hardness values, and NR displaying a mix of diffuse rocky structure and softer stretches between shoals. Coefficients of variation for relative hardness values within each study location help add some degree of comparability for across sites. Proposed restoration sites both had comparable CVs to each other (SR=5.93%, CR=7.60%), but smaller CVs versus hardness sites (DR=12.45%, NR=12.64%).

Overall, relative rates of sediment accumulation were comparable across all sites and seasons, with only minor differences occurring (Figure 3.7). Sample sizes for latter seasons were very low due to limited trap recovery, primarily after overwinter 2015-2016. After Fall 2015 sampling, only one trap at CR was lost. However, no traps were recovered from CR, two traps were recovered from SR, and only one trap was found at both DR and NR following the overwinter 2015-2016 season. Due to immediate redeployment after overwinter recovery, no additional traps were added for Spring 2016 sampling. All traps deployed for Spring 2016 were recovered at the end of the season. ANOVA results show that sites had different rates of relative sedimentation during Fall 2015 only (Fall 2015: $F=24.82_{3,11}$, $p<0.001$; overwinter 2015-2016: $F=11.01_{2,1}$, $p=0.208$; Spring 2016: $F=38.64_{2,1}$, $p=0.113$). During this season, CR, DR, and NR all had higher rates of sediment accumulation than SR. CR accumulation rate was also higher than NR. Low trap recovery during overwinter 2015-2016 and Spring 2016 seasons prevented statistical analyses of any differences across sites.

During spring (early April to mid-May) and fall (early November to mid-December) sampling seasons, oxygen was high and consistent across all sites (Figure 3.8). Dissolved oxygen measurements collected in June 2015 along with side-scan sonar readings showed that oxygen was above hypoxic levels across all sites during the summer as well. DR had a mean dissolved oxygen reading of 9.77 mg L^{-1} (9.57-9.96 mg L^{-1}, 95% confidence interval) while NR had a mean of 10.15 mg L^{-1} (9.92-10.38 mg L^{-1}, 95% confidence interval). Dissolved oxygen at CR was comparable to remnant reef sites, with a mean of 9.55 mg L^{-1} (9.48-9.62 mg L^{-1}, 95% confidence interval). However, SR possessed lower mean dissolved oxygen levels than all other sites with mean dissolved oxygen of 5.40 mg L^{-1} (5.10-5.71 mg L^{-1}, 95% confidence interval).

In contrast to spring and fall oxygen levels, overwinter oxygen loggers displayed periods of hypoxic conditions during both years. During overwinter 2015-2016, near-sediment oxygen concentrations at DR experienced a nearly two month stretch of dissolved oxygen levels below 2 mg L^{-1} (Figure 3.9). CR also displayed some rapid fluctuations in near-sediment oxygen below 2 mg L^{-1}, but for only a short time. While oxygen concentrations were variable, SR did not experience any periods of near-sediment low dissolved oxygen.

Expanded placement of oxygen loggers during overwinter 2016-2017 yielded similar patterns of low oxygen levels at some study sites (Figure 3.10). Despite two pairs of loggers being placed at DR, no loggers were recovered from that location. However, all other loggers were recovered from other study sites. The single logger at NR, in the elevated position 0.5 m off the bottom, did not record any periods of low dissolved oxygen. In contrast, near-sediment loggers recovered from SR and CR showed long stretches of oxygen at essentially 0 mg L^{-1}. The elevated logger at CR also displayed some short declines in oxygen, including reaching hypoxic conditions later in the sampling period. Similarly, the elevated logger at SR showed a general downward trend in dissolved oxygen over the sampling period; however, minimum oxygen readings for the elevated logger at SR were not as low as at CR, and did not approach hypoxic levels.

3.4 Discussion

Our documentation of near-bottom oxygen concentrations in the hypoxic range during two winters suggests potential for overwinter conditions to limit successful spawning. Study locations are all relatively shallow and fully mixed by wind and wave action from spring through fall, which can account for high levels of oxygen even during productive times of year. However, ice coverage during winter months can interrupt this mixing and oxygenation, and appears to have influenced dissolved oxygen loggers placed overwinter. During both early 2016 and 2017, Inner Saginaw Bay experienced greater than 95% ice coverage for nearly all of January and February (Great Lakes Environmental Research Laboratory, NOAA). Within this same period, multiple loggers from both winter sampling periods recorded drops in oxygen that reached hypoxic conditions (<2 mg L^{-1}). It is possible that low oxygen levels could be caused by a lack of mixing across the water column; alternatively, prolonged periods of low oxygen readings may have been caused by sediment covering the dissolved oxygen logger. For example, near-sediment loggers at SR and CR during overwinter 2016-2017 both displayed periods of nearly constant measurements of 0 mg L^{-1}, which is not consistent with the more variable oxygen concentrations expected to be observed in the water column (e.g., Scavia et al. 2014). Loggers 0.5 m off the bottom at those same sites, especially CR, display reductions in oxygen overwinter but only occasional hypoxia. These elevated loggers may be more likely to avoid sediment moving along the lake bed ("bed load," as in van Rijn 1984). However, loggers from overwinter 2015-2016 also demonstrate low oxygen at CR and DR in particular, along with variation in measurements. This variation suggests that these recordings may be less likely to have been influenced solely by constant sedimentation. It is also important to note that even if sedimentation influenced logger measurements in some cases, it is still an avenue through which deposited eggs would be subject to hypoxia. Incubating eggs would still suffer harmful effects whether low oxygen was due to hypoxia in the water column, or due to the suffocating effects of sediment. Additionally, eggs may experience negative impacts at oxygen levels above 2 mg L^{-1}; oxygen levels below 4 mg L^{-1} may prove detrimental to coregonids (Brook and Colby 1980). Finally, there were also some instances when oxygen measurements were impossibly high, beyond 100% saturation for winter water temperatures. This was occasionally seen at SR during overwinter 2015-2016, and particularly at NR during overwinter 2016-2017. For plot visualization purposes, oxygen was capped at 15 mg L^{-1} for all overwinter data, eliminating unrealistic readings. However, it is still worth considering the cause of extremely high oxygen data. These spikes may be artifacts of improper logger recording or calibration, but may also represent times when loggers were exposed to air. The NR logger placed during the second sampling winter was in the elevated position at a fairly shallow study site, and could have briefly been exposed to air by wave action as ice patterns shifted. On an extremely fine spatio-temporal scale, readings could potentially have been influenced by release of oxygen by underwater vegetation, or slight shifts in water temperatures. In any case, it should be noted that extremely high spikes in oxygen readings may not always be accurate, and were accounted for in the data.

Remnant reef locations were confirmed to possess some quality rock substrate, but the proportion of habitat that was potentially suitable for spawning was small at both sites. Nevertheless, shallowest areas of both sites exhibited clean stone, devoid of the periphyton that was visible over much of the remainder of the rocks at both locations. High wave action in the shallowest regions was likely responsible for the clean stone, and may have contributed to the relatively lower densities of dreissenids when compared to proposed restoration locations. Though dreissenids were observed at both remnant reef sites, their densities remained low enough to potentially preserve interstitial spaces between rocks.

In contrast, proposed restoration locations were much more indicative of the degradation and infilling that has plagued much of Inner Saginaw Bay. Smaller CVs for hardness values at proposed restoration sites suggest a minimal range of substrate types versus remnant reef locations. Remnant reef sites display ranges of hardness values consistent with both harder rock structure and surrounding sand substrate. However, hardness readings at CR suggest that the historic reef structure once present at the site can be detected underneath the softer sand that is almost universally representative of the site today. For restoration purposes, this harder underlying layer could potentially help minimize sinking of new rock structure versus a site with a softer bottom. CR is also unique in that it is an open water site, yet is still shallow enough to receive scouring wave action that might maintain clean reef structure. Furthermore, as CR was part of the historic reef complex in Inner Saginaw Bay (Fielder 2002), reef construction there would truly be restoration. SR, though superficially similar to CR in that it was largely covered with sand and free from excessive silt, did possess a few unique traits. Rocks were found more frequently than at CR, and were much more heavily fouled with dreissenids that at all other sites. Additionally, the influence of the Saginaw River was more prevalent than at open water locations such as CR, indicated by lower summer dissolved oxygen levels. Thus, due to lower dreissenid colonization, underlying hard structure, and higher summer oxygen, CR may represent a more attractive restoration site at this time.

Sediment traps showed relatively few differences between remnant reef sites and proposed restoration sites. Differences in relative sedimentation among sites was only observed during Fall 2015; however, limited trap recovery may have precluded detection of significant differences in other seasons. During the fall, SR had lower rates of sedimentation than the other three study sites, despite SR being located close to the mouth of the sediment-rich Saginaw River. CR had highest mean sedimentation rates in Fall 2015, with significantly more sediment deposited at CR than SR and NR. Unfortunately, no traps could be recovered from CR during overwinter 2015-2016 and Spring 2016 seasons, and it remains unclear if CR consistently features some of the highest rates of relative sedimentation across all sites.

Overall, mean rates of sedimentation may seem very high across sites. For example, CR had a mean accumulation rate of nearly 820 g m^{-2} d^{-1} in Fall 2015. If actual rates of sediment accumulation were that high across all Inner Saginaw Bay, the bay would be filled in quickly. What these rates suggest, then, is 1) that sediment traps were highly successful at artificially trapping sediment, and 2) there are large quantities of suspended sediment in Saginaw Bay. Natural structure in the bay, including restored reef habitat, would be regularly flushed clean of sediment in a way that PVC tubing would not. Additionally, interstitial spaces in reef structure would likely protect eggs and larvae from sediment moving around the bay.

Given the high amount of suspended sediment, it is important to note that there were no consistent differences in sedimentation between remnant reef sites and proposed restoration sites. CR sedimentation rate was similar to DR in Fall 2015, and neither remnant reef site showed different relative sedimentation when compared to SR in the overwinter 2015-2016 and Spring 2016 seasons. This suggests that remnant reef locations have been able to persist in Saginaw Bay in the current sedimentation regime, despite experiencing similar sedimentation patterns to areas devoid of rocky structure. Restored reef structure would therefore be likely to persist as well. Nonetheless, restored reef habitat should be designed to allow flushing of sediment by water currents.

3.4.1 Summary and Conclusions

Overall, physical assessment of current habitat in Saginaw Bay indicates some potential for successful reef restoration at proposed restoration sites, but also cause for concern. Bottom hardness readings at CR in particular show an underlying bed of hard structure that could support restored reef habitat. Though sedimentation analyses suffered from poor trap recovery, relatively small differences across sites coupled with the existence of remnant reef habitat suggests that restored reef structure may be able to persist in Saginaw Bay. Bottom water hypoxia during winter is also a cause for concern. This assessment documented multiple instances of low oxygen across multiple sites, representing a potential threat to incubating eggs. Interstices in reef structure may help shield eggs and larvae from sediment moving around the bay and minimize suffocation of eggs due to lack of gas exchange, but it remains unclear how important these potential benefits may be.

Going forward, it may be important to more properly investigate sedimentation in Saginaw Bay. Understanding spatial and temporal sedimentation patterns may be key to predicting longevity and ultimate success of restored reef structure. Additionally, a more thorough analysis of overwinter dissolved oxygen, especially at sites with low logger recovery, such as DR, could help shed light on the dynamics of overwinter hypoxia. Without reef structure as a refuge from low dissolved oxygen and sedimentation, current physical factors in the bay may limit recruitment. Due to the need for more information on sedimentation and oxygen dynamics on reef structure, coupled with concerns about investment in full-scale restoration, perhaps a trial reef restoration in Inner Saginaw Bay would allow for assessment of feasibility without enormous monetary investment. Pending results of such a pilot reef study, managers may be better equipped to decide on the future of full-scale reef restoration.

This study primarily serves as an analysis of baseline physical conditions at study sites in Saginaw Bay. Should reef restoration proceed, continued and long-term analyses of physical processes around reef structure would also be key to determining success of restored habitat. Overall, there is potential for restored spawning habitat to be successful, but also real concerns about physical conditions. Ultimately, the combination of this assessment and future research will determine if reef restoration is a viable option to promote the continued recovery of fishes in Saginaw Bay.

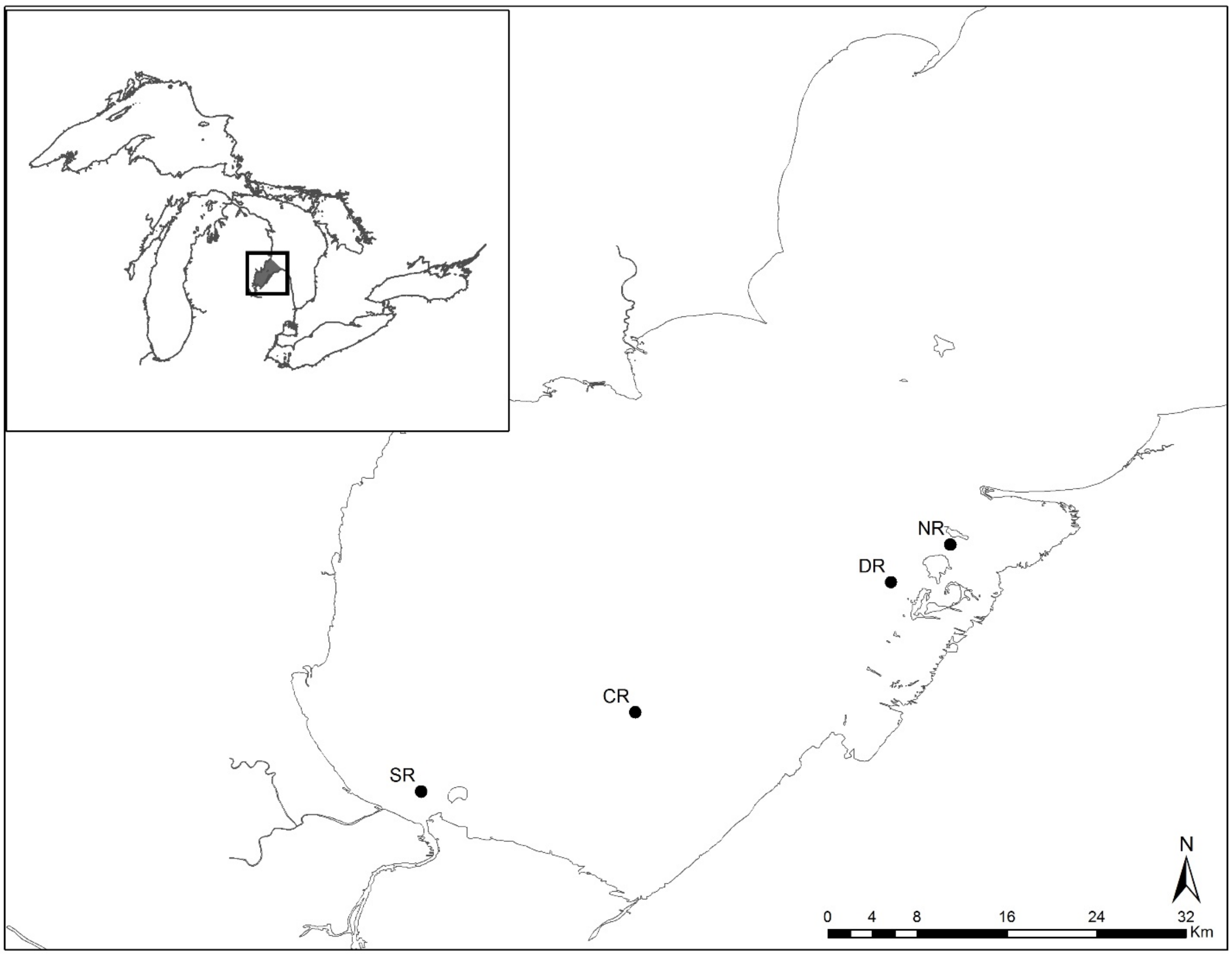

Figure 3.1. Locations of study sites within Saginaw Bay. Duck Reef (DR) and North Island Reef (NR) are remnant reef sites, while Saginaw River Mouth (SR) and Coreyon Reef (CR) are proposed restoration sites.

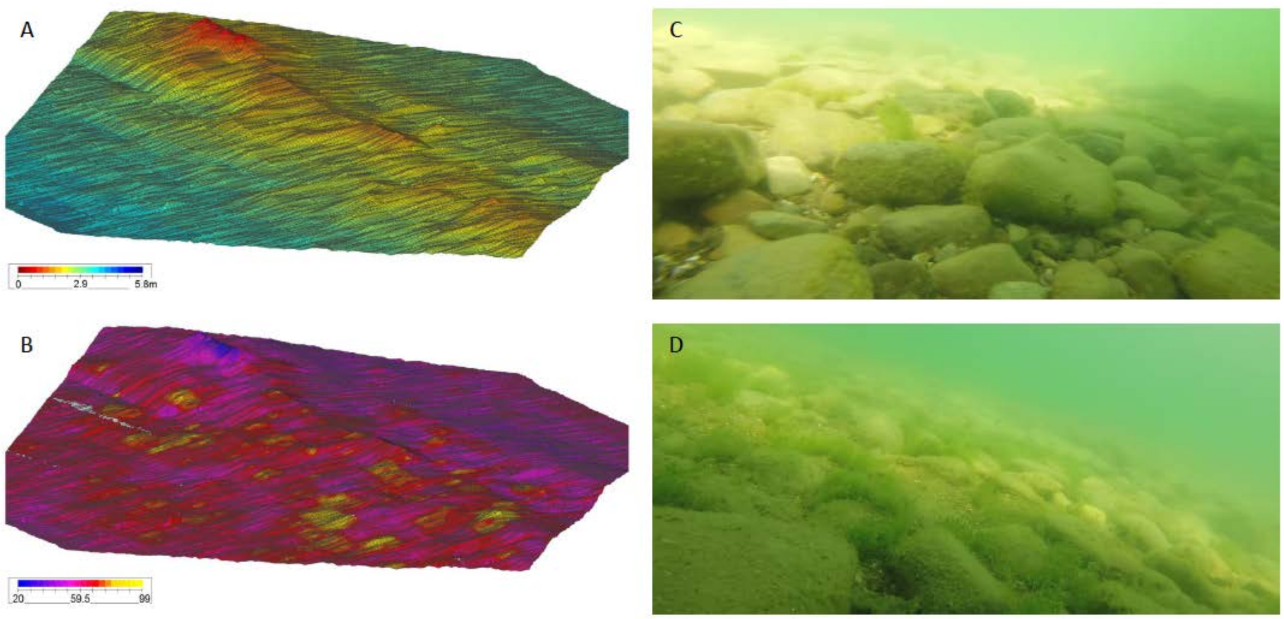

Figure 3.2. Characteristics of Duck Reef. Three dimensional representations of A) bathymetry and B) relative hardness from side-scan sonar data. Underwater camera shows C) best reef structure and D) typical reef structure observed.

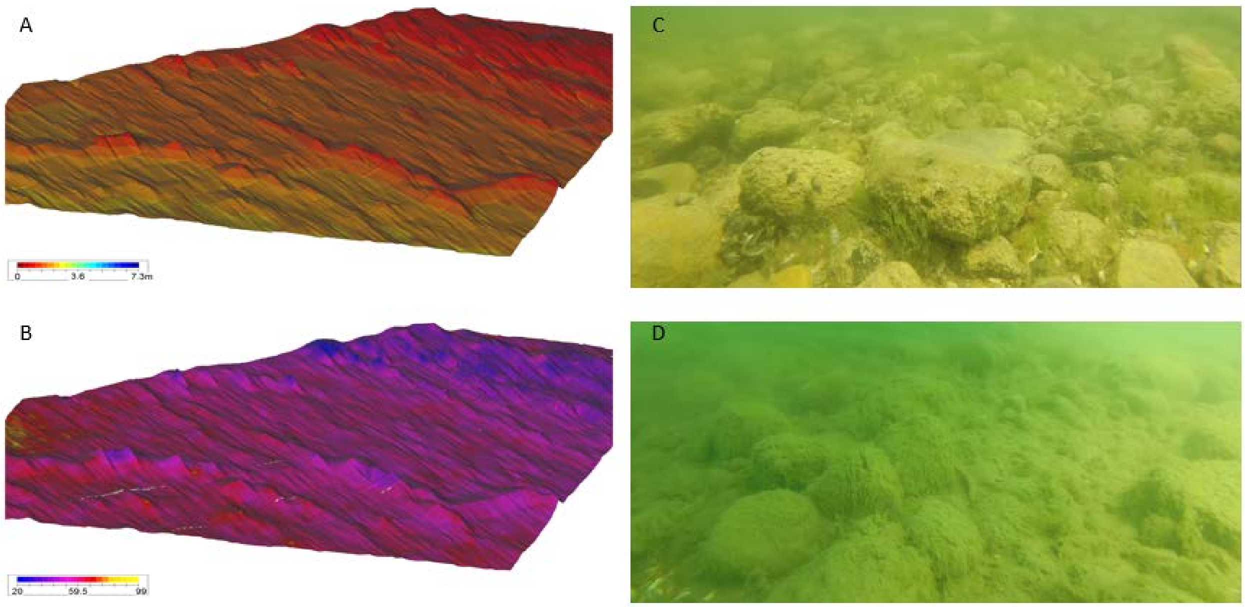

Figure 3.3. Characteristics of North Island Reef. Three dimensional representations of A) bathymetry and B) relative hardness from side-scan sonar data. Underwater camera shows C) best reef structure and D) typical reef structure observed.

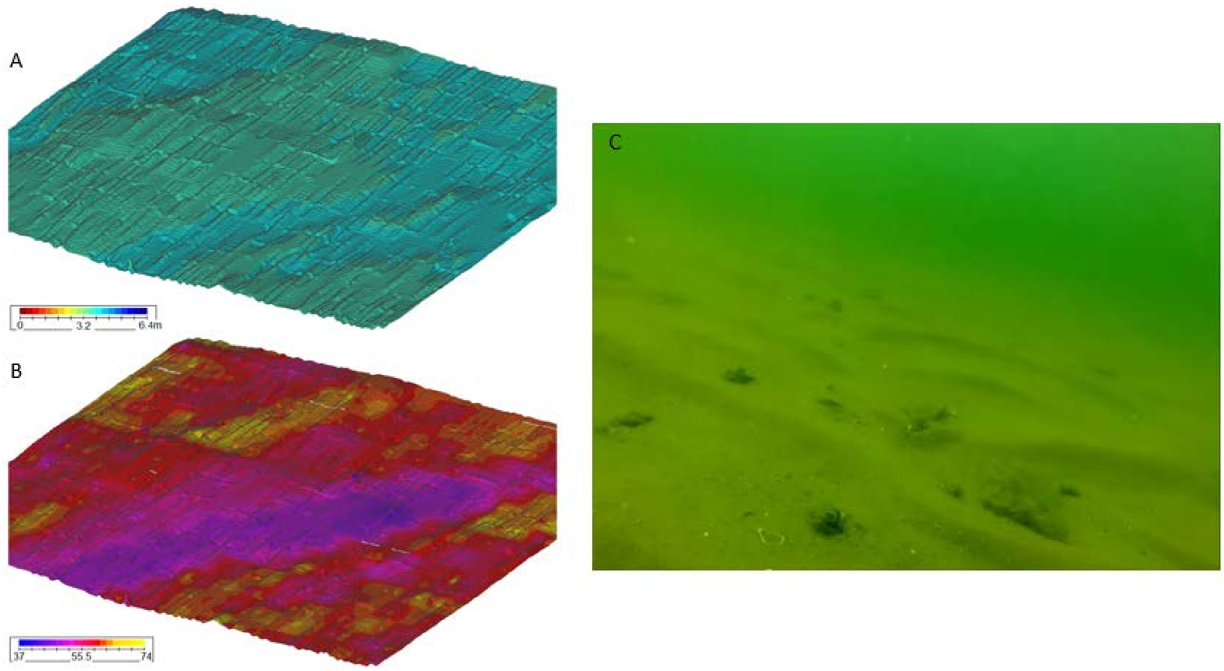

Figure 3.4. Characteristics of Coreyon Reef. Three dimensional representations of A) bathymetry and B) relative hardness from side-scan sonar data. Underwater camera shows C) typical habitat observed.

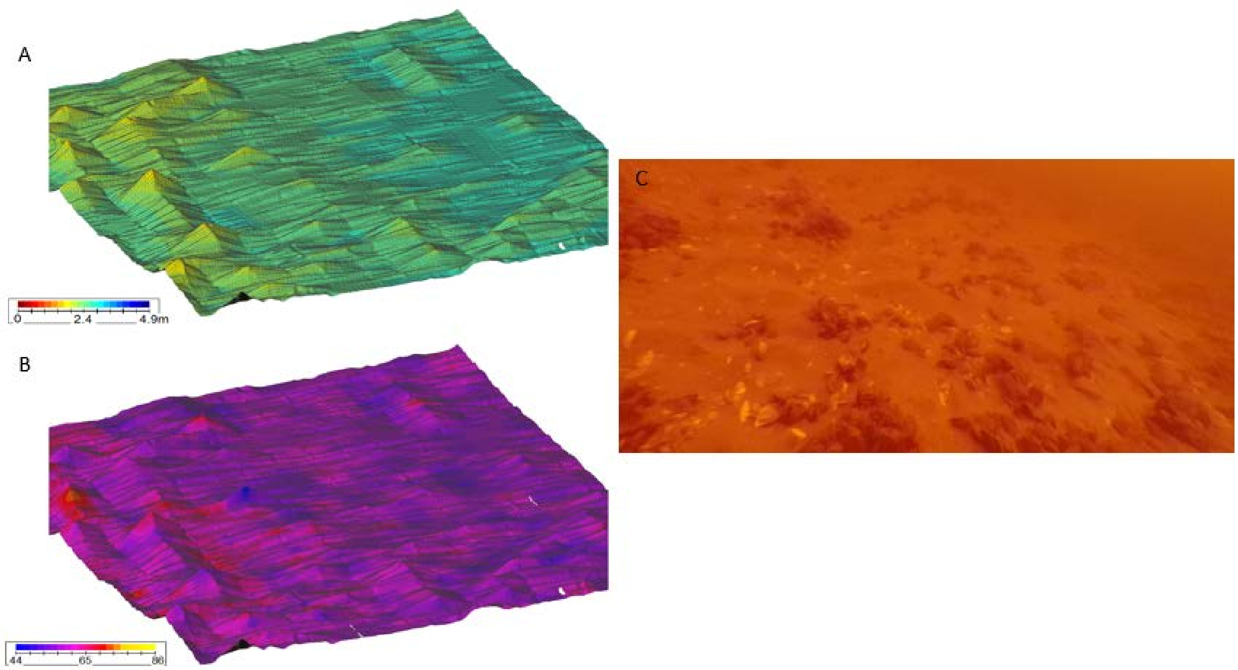

Figure 3.5. Characteristics of Saginaw River Mouth. Three dimensional representations of A) bathymetry and B) relative hardness from side-scan sonar data. Underwater camera shows C) typical habitat observed.

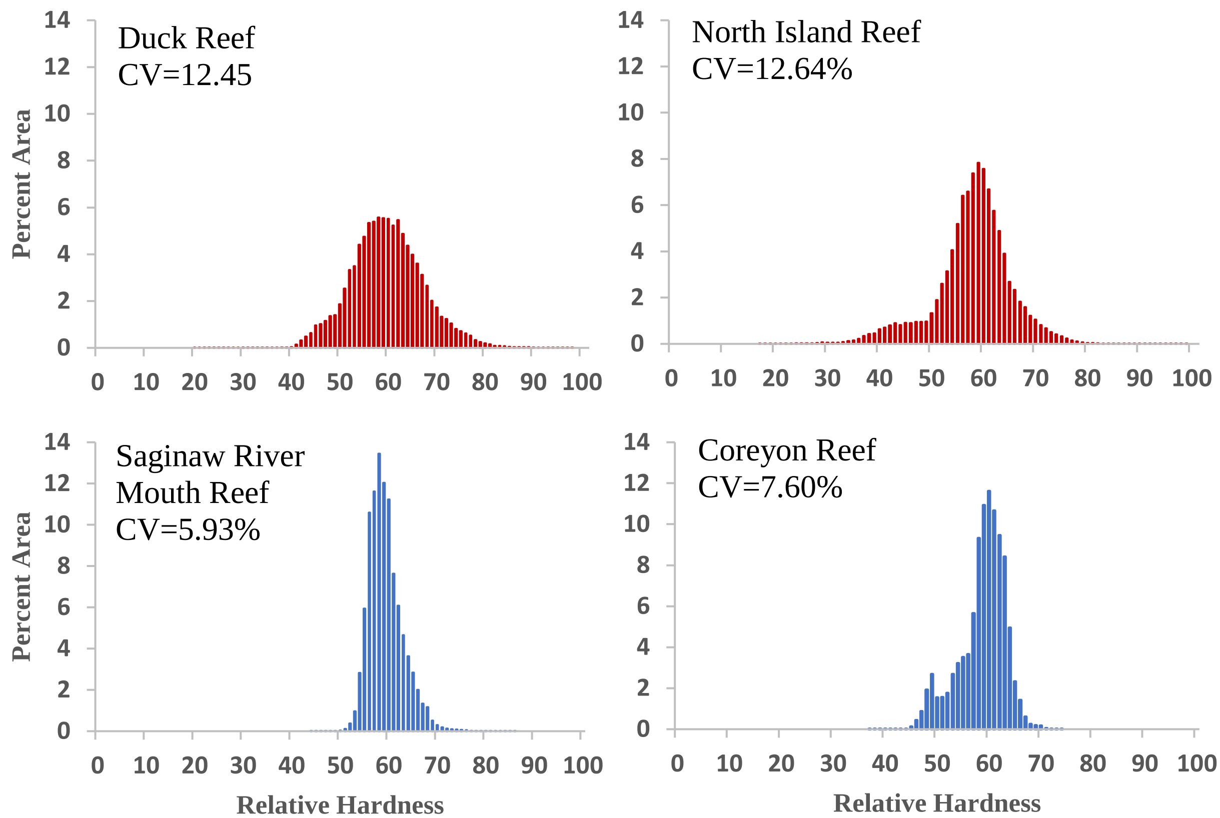

Figure 3.6. Relative hardness for each study site in Saginaw Bay, by percent of area covered. Hardness scales are only relative within a site, not across sites. Duck Reef displayed the widest range in hardness values, while Saginaw River Mouth was most consistent. Coreyon Reef showed a mix of harder and softer substrates, while North Island Reef had a large range of softer values. Coefficients of variation are also shown for relative hardness values within each study location. Proposed restoration sites displayed smaller CVs than remnant reef sites.

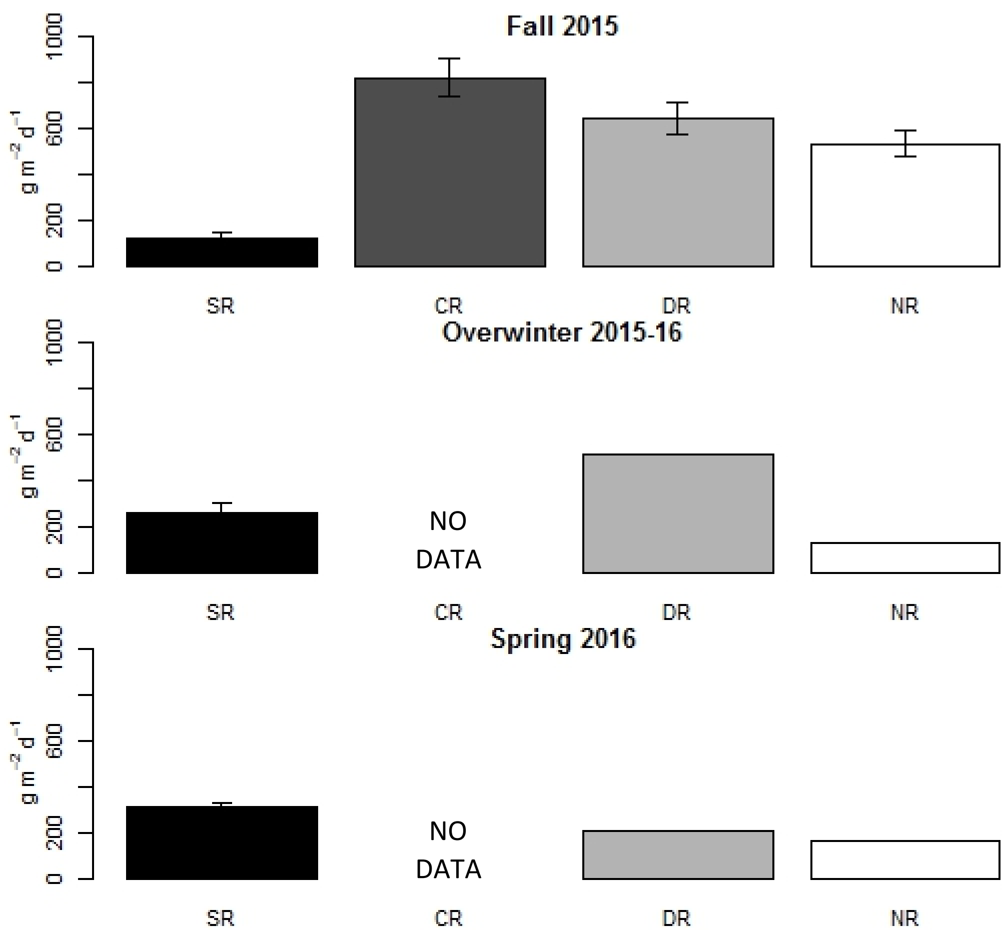

Figure 3.7. Relative sedimentation (g m^{-2} d^{-1}) for all sites during Fall 2015, overwinter 2015-2016, and Spring 2016. Due to poor recovery following overwinter sampling, no data were collected from CR during overwinter and spring seasons, and only one trap was deployed at both DR and NR.

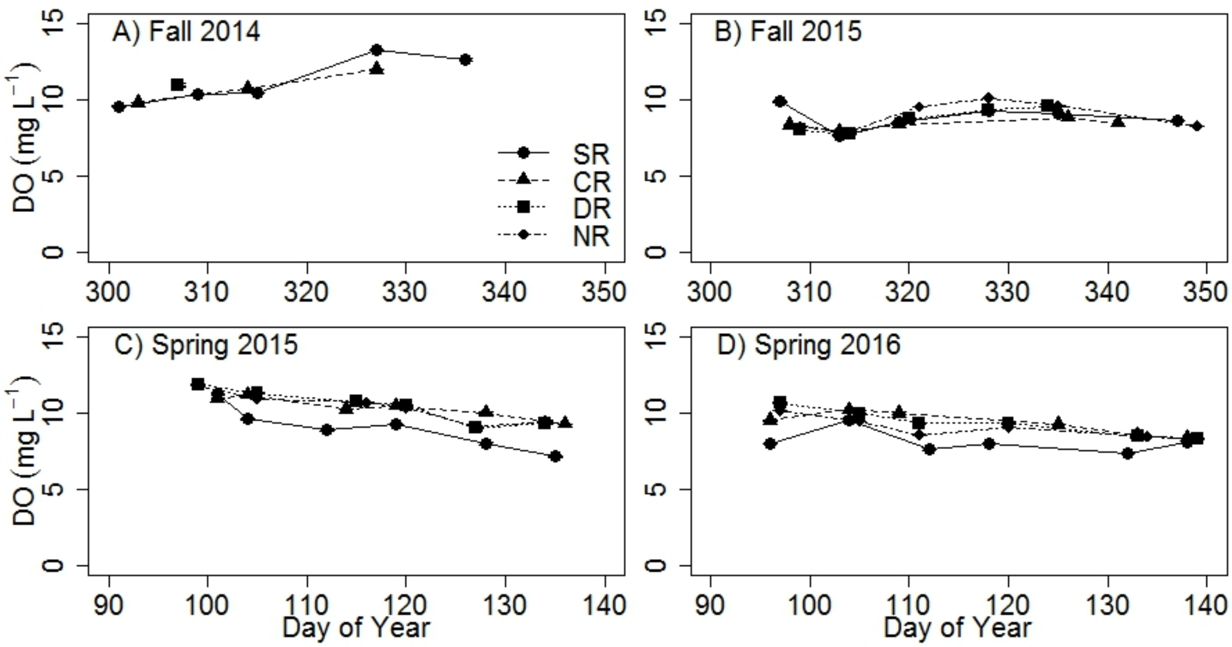

Figure 3.8. Time series of dissolved oxygen data by site across all fall and spring sampling seasons. Points indicate means of three water column measurements (0.5 m increments from 0-2 m) for a given site and date.

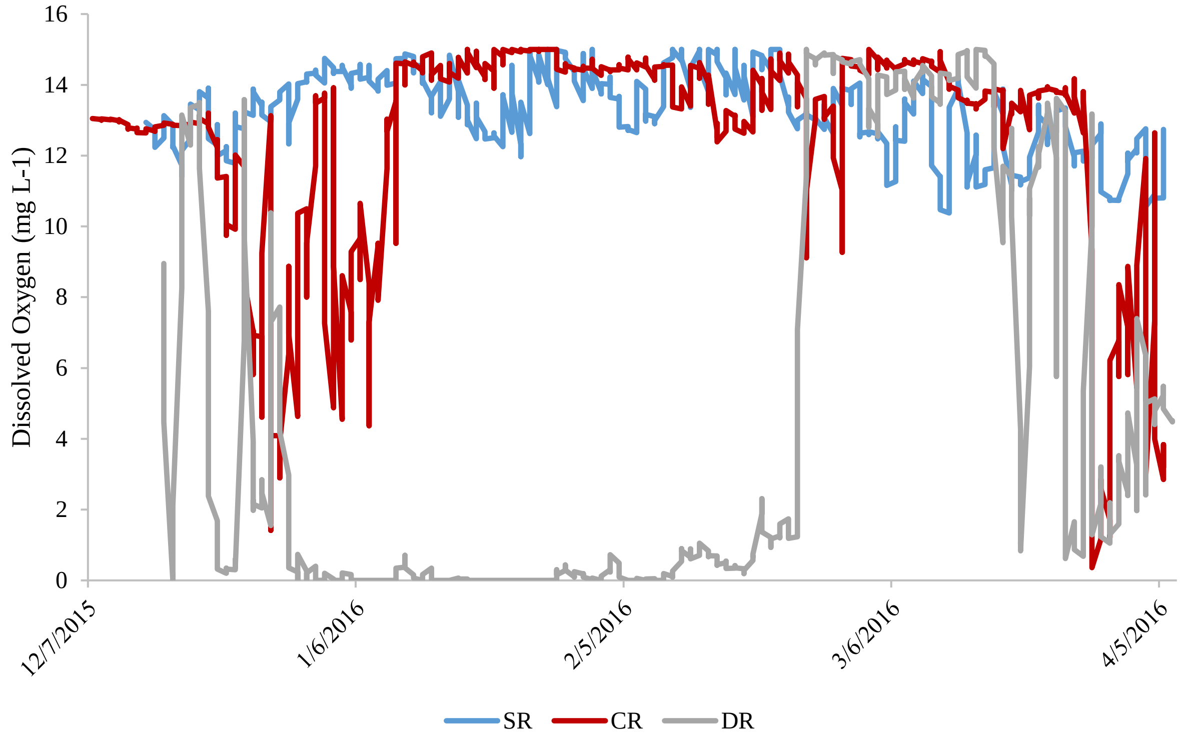

Figure 3.9. Moving average of dissolved oxygen readings, overwinter 2015-2016. No logger was placed at NR. Dissolved oxygen data were capped at 15 mg L^{-1} to adjust for erroneous readings above 100% saturation.

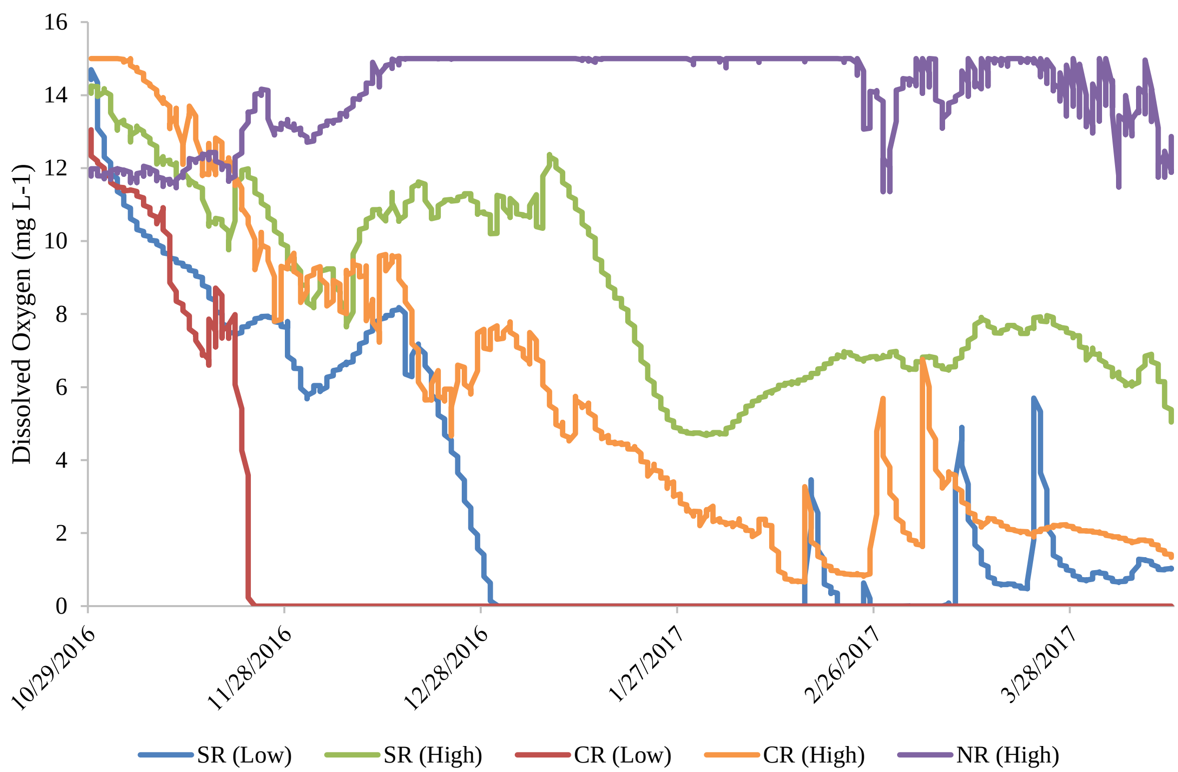

Figure 3.10. Moving average of dissolved oxygen readings, overwinter 2016-2017. Only one logger was placed at NR, and no loggers were recovered from DR. Dissolved oxygen data were capped at 15 mg L^{-1} to adjust for erroneous readings above 100% saturation.

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APPENDIX

SUPPLEMENTARY INFORMATION

Appendix Table A1. Underwater video captured by MDNR in June 2015 at all study locations. Videos show best available rock substrate and mixed substrate for remnant reef sites, and typical substrate for proposed restoration sites.

Location	*Video Description*	*Video URL*
Duck Reef	Best available rock	https://www.youtube.com/watch?v=7PGvIEr6-z0
Duck Reef	Mixed substrate	https://www.youtube.com/watch?v=qNlCNhUOuKo
North Island Reef	Best available rock	https://www.youtube.com/watch?v=INvDnWxql3E
North Island Reef	Mixed substrate	https://www.youtube.com/watch?v=bOif21yd_VA
Coreyon Reef	Typical substrate	https://www.youtube.com/watch?v=jjID24i_eYk
Saginaw River Mouth	Typical substrate	https://www.youtube.com/watch?v=l-jDMCdIbZY