GENETIC ORIGINS AND MOVEMENT OF LAKE STURGEON *ACIPENSER FULVESCENS* IN THE ST. LOUIS RIVER AND WESTERN LAKE SUPERIOR.

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ABSTRACT

Lake Sturgeon *Acipenser fulvescens* were extirpated from the St. Louis River (SLR) by the early 1900's due to overfishing and habitat degradation. With the passing of the Clean Water Act and improvements to water quality, a stocking program was initiated in 1983 by the Minnesota Department of Natural Resources, Wisconsin Department of Natural Resources, and Fond Du Lac Band of Lake Superior Chippewa to reintroduce Lake Sturgeon to the SLR. Most stocked Lake Sturgeon were obtained from the Wolf River (Lake Winnebago) genetic stock and some (much fewer than the Wolf River) were obtained from the Sturgeon River (Lake Superior) genetic stock. Stocking continued almost yearly until 2000. Recently, spawning and natural recruitment has been documented near the Fond Du Lac Dam, the upstream limit for Lake Sturgeon migrating from Lake Superior. However, it was unknown if the Lake Sturgeon spawning in the SLR were from stocking events or strays from other areas of Lake Superior. Additionally, it is unknown if Lake Sturgeon in the SLR represent a resident population or if they exhibit a migratory life history; movements of Lake Sturgeon in and out of the SLR is unknown and represents a knowledge gap hindering effective management of this population. My objectives were to determine (1) the genetic origins of Lake Sturgeon Spawning in the SLR, (2) if the timing, frequency, and magnitude of Lake Sturgeon migrations between the SLR and Lake Superior were related to genetic strain, physical characteristics (sex, size) or environmental conditions (temperature, discharge) and (3) if spawning locations were influenced by genetic stock, individual demographic characteristics, environmental conditions, and restored habitats. Most Lake Sturgeon captured (79%) genetically assigned to the Wolf River genetic stock (Lake Winnebago) with greater than 80% probability. Other genetic stocks present included the Pic River and Goulais River. The SLR Sturgeon population was found to be an open population with fish exhibiting both migratory and resident life histories. Over the course of the study 78 of 137 acoustically tagged Lake Sturgeon emigrated from the SLR to Lake Superior and nearly half of these fish were detected on U.S. Fish and Wildlife acoustic receivers between Bark Point and Chequamegon Bay, WI. Emigration peaked in June of each year but was not related to genetic strain or physical characteristics. Water temperature was a significant predictor of emigration and it is possible SLR Lake Sturgeon use Lake Superior for thermal refuge. Egg mats set in 2018 captured no Lake Sturgeon eggs and Sturgeon were only observed spawning immediately below the Fond Du Lac Dam. Spawning area does not appear to be limited in the SLR. Furthermore, the restoration stocking effort of Lake Sturgeon into the SLR appears to have been successful. The stocking of Wolf River strain Sturgeon appears to have been successful, and it is possible that the stocking of Sturgeon River fish was also successful although none of the genotyped samples genetically assigned to the Sturgeon River population. The presence of Lake Sturgeon strays coupled with the open population of the SLR and observed movement of SLR Sturgeon to other areas of Lake Superior highlights the importance of interjurisdictional management of Lake Superior Lake Sturgeon populations. My results indicate that the Lake Sturgeon fishery in the Wisconsin waters of Lake Superior is likely a mixed stock fishery. However, harvest of Lake Sturgeon in these waters is likely counter-productive to the restoration of the female-limited SLR population, especially if minimum length limits increased as proposed. Within the SLR, sampling of the population during the spring spawning period should continue at the current level of effort to allow for estimation of abundance and better knowledge of population dynamics and demographics. The acoustic array should be maintained through 2028 to inform spawning periodicity and examine the various life history strategies of SLR Lake Sturgeon. Genetic assessment of the spawning population should continue as the genetic composition of the

spawning population may change as more stocked fish become sexually mature and due to the spawning periodicity exhibited by Lake Sturgeon. The stocking of the SLR is potentially scheduled to recommence in 2019 and should be viewed as an important opportunity to learn more about the juvenile life stage of Lake Sturgeon in the SLR as well as other life history and population attributes (e.g., age and growth). Overall, the SLR Sturgeon population appears to be headed towards recovery. Adaptive management practices currently being employed and should be continued to help guide the further recovery of this population.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: GENERAL INTRODUCTION

Twenty-four species of Sturgeon (Acipenseridae) occur throughout the World, with all species inhabiting the northern hemisphere; nine of these species inhabit North America. All Sturgeon species Worldwide have experienced declines over the last 150-200 years (Rochard et al. 1990; Haxton et al. 2016). Sturgeon declines have been attributed to overharvest, habitat loss, reductions in water quality, and fragmentation via dams and impoundment, as well as challenging inter-jurisdictional management (Haxton et al. 2016).

Lake Sturgeon *Acipenser fulvescens* are an ecologically important benthivore that have cultural importance to indigenous peoples within the Great Lakes region (FDLBLSC 2008). Lake Sturgeon are long-lived (capable of reaching an age of ≥ 150 years; Scott and Crossman 1973) and large bodied, with most adult Lake Sturgeon measuring between 100-215 cm and weighing 11-100 kg (Peterson et al. 2007). The largest documented Lake Sturgeon measured 241 cm and weighed 141 kg and was taken from Lake Michigan in 1941 (Van Oosten 1956). Age at maturation for males typically occurs between 12-15 years, while females do not typically mature until they reach 18-27 years of age (Peterson et al. 2007). Lake Sturgeon also exhibit spawning periodicity; females typically spawn every 3-5 years while males may spawn every 1-3 years (Roussow 1957; Forsythe et al. 2011).

Similar to other Sturgeon species, Lake Sturgeon have suffered declines throughout their native range. For example, the Lake Sturgeon population in and around Lake Michigan is thought to be approximately 1% of its historical size (Hay-Chmielewski and Whelan 1997). These basin-wide declines have resulted in Lake Sturgeon being designated as endangered, threatened, or a species of “special concern” in many waters throughout the Great Lakes Basin (Auer 1996; Peterson et al. 2007; Schloesser and Quinlan 2010). Lake Sturgeon life history characteristics (delayed maturation and spawning periodicity), coupled with over-exploitation, habitat degradation, and diminishing water quality have led to basin-wide declines of Lake Sturgeon in the Great Lakes region during the last 200 years (Auer 1996; Schram et al. 1999; Auer 2003; Peterson et al. 2007).

The St. Louis River (SLR), the largest U.S. tributary to Lake Superior, historically supported Lake Sturgeon. However, by the early 1900’s Lake Sturgeon were extirpated from the SLR and greatly reduced in Lake Superior due the combined effects of over-fishing, and habitat alterations including dredging, sedimentation and wetland filling, and degradation of water quality (Schram et al. 1999; Auer 2003). However, following the passage of the clean water act in 1972, water quality and habitat improved. After these improvements in water quality and habitat, coupled with restrictive fishing regulations nearly eliminating exploitation, a joint effort was made by the Minnesota and Wisconsin Departments of Natural Resources to re-establish Lake Sturgeon in the SLR. Lake Sturgeon may have been successful in recolonizing the SLR naturally from adjacent tributaries (e.g., Bad River); however, re-population of the SLR may have taken centuries due to Lake Sturgeon’s intermittent spawning cycle and late age at maturity (Schram et al. 1999). These life history characteristics led to the management decision to stock juvenile Lake Sturgeon into the SLR. Lake Sturgeon were stocked during most years from 1983-2000 from Lake Michigan and Lake Superior brood sources (see chapter 2 for further details).

Concurrently with the stocking program being implemented, the SLR and estuary was designated as an Area of Concern (AOC) by the Minnesota Pollution Control Agency in 1987 (US EPA 2015). This designation, coupled with the passing of the clean water act in 1972, led to many habitat and water quality improvement projects within the SLR and estuary (US EPA 2013). The most important project for Sturgeon rehabilitation within the SLR may have been the creation and improvement of spawning habitat directly below Fond Du Lac dam in 2009 (Figure 1.1). This habitat improvement project was coordinated by The Nature Conservancy and funded by the MNDNR and EPA, included the creation of several rock weirs immediately below the Fond Du Lac Dam to provide better spawning habitat for SLR Lake Sturgeon (MPCA 2013). Following completion of this project in 2011, the Fond du Lac Band of Lake Superior Chippewas (FDLBLSC) observed naturally reproduced larval Lake Sturgeon during their annual larval drift net sampling in the newly improved spawning area (Brian Borkholder, Fond du Lac Resource Management, unpublished data). Additionally, the AOC board funded another spawning habitat improvement project near Chambers Grove Park in Fond Du Lac, MN which was completed in 2016. However, the use of this area for Lake Sturgeon spawning is currently unknown. So, despite a perceived successful stocking program, habitat improvements, and documented natural reproduction of Lake Sturgeon in the SLR, many questions still remain unanswered regarding whether this population is truly “rehabilitated.”

The Lake Sturgeon Subcommittee for Lake Superior has adopted specific fish community objectives that defined rehabilitation of Lake Sturgeon, including maintaining self-sustaining Sturgeon populations, as a priority. To reach this objective the Lake Sturgeon Subcommittee set the goal of having at least 1,500 adults, representing 20 year classes, spawning in each of the 17 tributaries that were known to have once supported spawning populations of Lake Sturgeon (Auer 2003). Additionally, adult fish from these populations should produce yearly evidence of reproduction measured by collecting viable eggs and juvenile Lake Sturgeon (ages 0-5) in tributaries (Horns et al. 2003). The SLR and estuary are listed as a critical management area for the overall health and recovery of the Lake Superior Lake Sturgeon population (Auer 2003). However, management agencies know little about Lake Sturgeon in the SLR and Western Lake

Superior. For example, little is known regarding the genetic composition of the Lake Sturgeon population in the St. Louis River (SLR). Understanding the genetic composition of the SLR Lake Sturgeon population is also essential to address the objectives outlined in the Lake Sturgeon Rehabilitation Plan (Auer 2003). Namely, working to identify the genetic variability with populations in Lake Superior, determining the efficacy of stocking, as well as the vulnerability of the SLR Lake Sturgeon population to genetic hazards such as outbreeding depression due to strays from other Lake Superior tributaries. Additionally, little is known about movement of SLR Sturgeon within the river, between the river and Lake Superior, and among Lake Superior tributaries. Information about movement is critical in guiding management of this population to meet the objectives of the Lake Superior Lake Sturgeon rehabilitation plan. Knowledge of movements will lead to more informed decision making by fisheries managers, especially with regards to harvest regulations and stocking efforts. Specifically, movement data will lead to a better understanding of population dynamics, including the proportion of the recovering SLR Lake Sturgeon population that may be susceptible to harvest. Currently, there is no harvest of Lake Sturgeon allowed in the SLR, but there is a catch and release fishing season (Wisconsin Department of Natural Resources Bureau of Fisheries Management 2018). However, one Lake Sturgeon over 50” may be harvested annually from Wisconsin Waters of Lake Superior near the SLR. Recently, there has been social pressure to open a season for harvest of Sturgeon in the SLR, however, current data are insufficient to determine the probable effects of a harvest season (Paul Piszczek, Wisconsin Department of Natural Resources, Dan Wilfond, Minnesota Department of Natural Resources, personal communication).

The information on population genetics and movements obtained and during this study of the SLR Lake Sturgeon population will help to guide the management of this important native species. Genetic information will help to guide future decisions regarding stocking efforts in the SLR and Lake Superior. Understanding movements of this population will also help to guide the management of this population, including identifying areas for restoration, further conservation, and understanding the vulnerability of this recovering population to harvest. Finally, data collected during this research will help biologists and managers understand the role that the SLR Lake Sturgeon population plays with respect to Sturgeon recovery in the entire Great Lakes basin.

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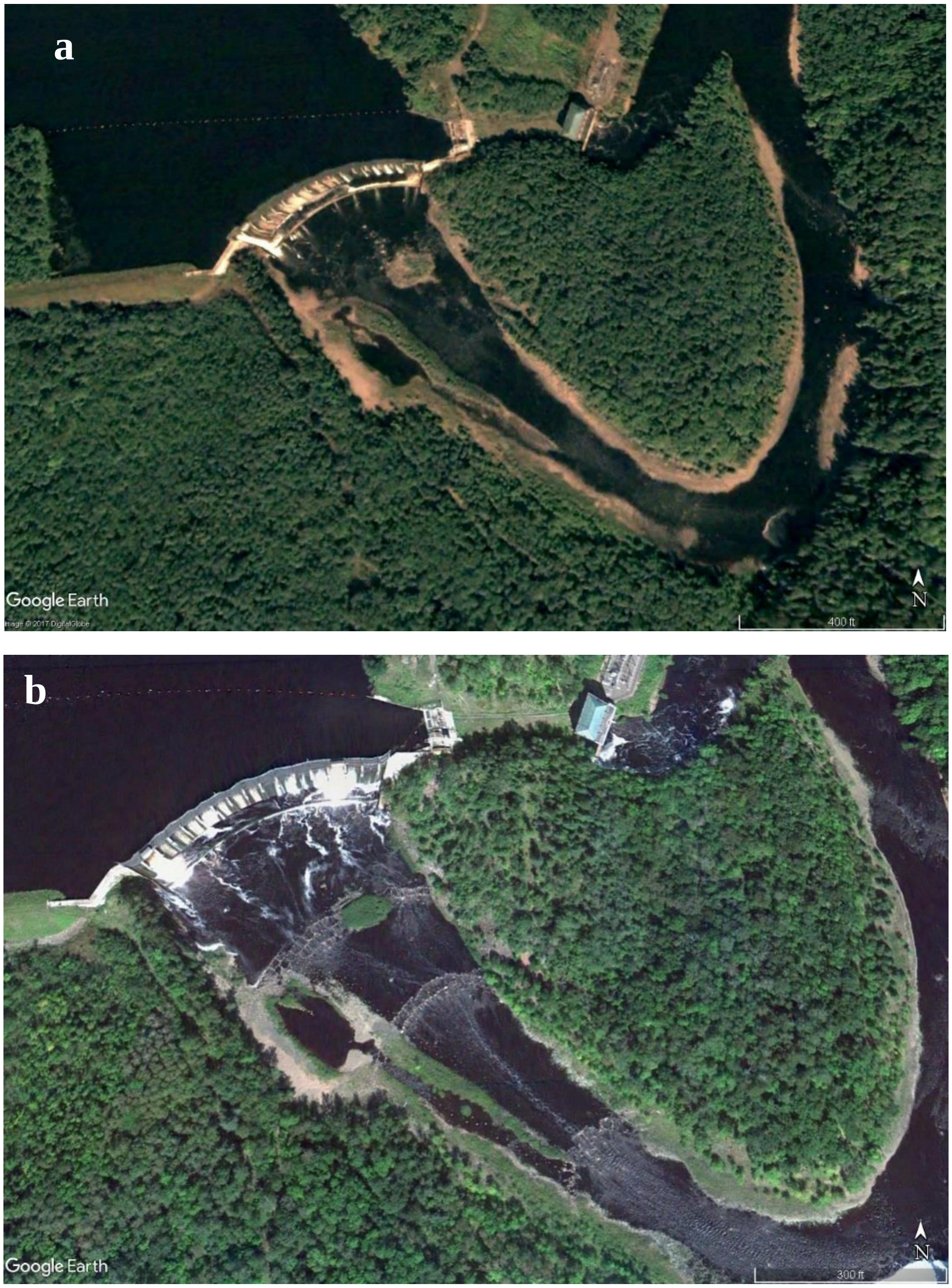

Figure 1.1. Aerial photographs of Fond Du Lac Dam on the St. Louis River pre-restoration (a) and post-restoration (b) of Lake Sturgeon Spawning habitat. Several rock weirs consisting of boulders added in 2009 to increase the area of suitable spawning habitat.

CHAPTER 2: GENETIC ORIGINS OF LAKE STURGEON IN THE ST. LOUIS RIVER

INTRODUCTION

Lake Sturgeon (*Acipenser fulvescens*) have experienced significant declines in abundance throughout their range over the last 200 years (Peterson et al. 2007). The decline of Lake Sturgeon in the Laurentian Great Lakes has been attributed to habitat degradation, loss of water quality, overfishing, and construction of dams (Harkness and Dymond 1961). In some locations populations of Lake Sturgeon were even extirpated (Auer 1996; Schram et al. 1999).

Several methods can be employed to facilitate the recovery or restoration of diminished or extirpated fish populations. Where natural recolonization or recovery is likely, often decreased or carefully targeted exploitation along with supplemental stocking will help to enhance the population (Beamesderfer and Farr 1997; Hubert and Quist 2010). Where natural recolonization is unlikely to occur, resource managers often use restoration stocking to enhance the recovery of a diminished or extirpated species (Hubert and Quist 2010).

The St. Louis River (SLR) Lake Sturgeon population was considered extirpated by the early 1900's due to the effects of overfishing, habitat degradation, and poor water quality (Auer 1996, Schram et al. 1999). Restoration stocking of Lake Sturgeon in the SLR became possible following improvements in water quality and habitat in the SLR after the passage of the Clean Water Act in 1972. The SLR Lake Sturgeon may have eventually recovered on its own due to re-colonization by Sturgeon straying from other tributaries. However, recovery from natural recolonization of the SLR likely would have taken centuries. Therefore, a restoration stocking program was initiated by the Wisconsin Department of Natural Resources (WDNR), Minnesota Department of Natural Resources (MNDNR), and Fond Du Lac Band of Lake Superior Chippewa in 1983 to enhance the recovery efforts of Lake Sturgeon in the SLR (Schram et al.

1999). Lake Sturgeon from the Bad River, Wisconsin (Lake Superior origin) were originally chosen to be the gamete source for reestablishing the SLR population. However, the adult population size in the Bad River was unknown and logistics for obtaining gametes proved too difficult. Instead, Lake Sturgeon from the Wolf River of the Winnebago system (Lake Michigan origin) were spawned and the subsequent progeny were stocked in the SLR from 1983-1994 (Schram et al. 1999). The WDNR released fry (13-35 mm) during May of each year from 1983-1994. Additionally, during August or September of these years, WDNR released fingerling Lake Sturgeon (105-152 mm; Table 2.1). During this same time period, the MNDNR obtained and reared Lake Sturgeon progeny from the WDNR. The MNDNR then stocked Lake Sturgeon fry in May, and fingerlings in September and October (Schram et al. 1999). Lake Sturgeon from other Lake Superior sources (Sturgeon River, Michigan) were also stocked from 1998 until 2000. Stocking ceased due to concerns about introducing strains that are not native to Lake Superior, and efforts were redirected to focus on habitat improvements and enhancing natural reproduction (John Lindgren, MNDNR, personal communication 2017).

While stocking can be a very useful management tool to develop or augment a wild fish population, anytime hatchery fish are used there are several potential genetic hazards. Four main genetic hazards are associated with using propagated fish including: demographic extinction (excessive removal from donor source), domestication selection, loss of within-population diversity (inappropriate numbers of broodstock or mating scheme), and loss of between-population diversity (inappropriate broodsource; Miller and Kapuscinski 2003). The first genetic hazard is not believed to be an issue for the Lake Sturgeon stocked into the SLR, as the Wolf River and Sturgeon River broodstocks have adequate population sizes. For example, the Wolf River stock of Lake Sturgeon is believed to be one of the largest stocks in North America (Bruch

2011). The second genetic hazard, domestication selection, is also not likely a concern in the SLR as eggs were taken from a wild population each year and captive broodstocks were not maintained. Further, all the Lake Sturgeon stocked into the SLR were age-0 with many of the fish stocked being fry. The shorter duration that a fish is held in the hatchery, the less chance of domestication selection. However, this population may encounter the final two hazards. Loss of within-population diversity (inappropriate numbers of broodstock or mating scheme) is possible. Then again, because the SLR Lake Sturgeon population was extirpated, any diversity added through stocked fish was “added diversity.” Therefore, the biggest genetic concern with this reintroduction was the potential loss of between-population diversity. Since the reintroduction stocking began with Lake Sturgeon from different waters than Lake Superior (Winnebago/Lake Michigan stock) loss of between-population diversity is possible. The mating of genetically distant individuals (e.g., Lake Michigan and Lake Superior stocks) may lead to a reduction in fitness (i.e., outbreeding depression). For example, site-specific adaptations such as thermal tolerance or body morphology may be lost in subsequent generations due to outbreeding depression (Lynch 1991; Homola et al. 2010). Another concern that could lead to loss of diversity among populations may arise from Lake Sturgeon from other populations, such as the Bad River, straying into the St. Louis River or vice-versa, during spawning migrations (Homola et al. 2010). For example, Lake Sturgeon from the Bad River were captured within the Sturgeon River (Homola et al. 2010) leading to concerns that Lake Sturgeon of Lake Michigan origin which were stocked into the SLR could stray into other Lake Superior tributaries (Welsh et al. 2018). At the time of Homola et al. (2010) it was likely that SLR (Lake Michigan Origin) Lake Sturgeon were not mature and hence were not present in the tributaries surveyed. Lake Sturgeon have been shown to exhibit relatively high straying rates in Lake Michigan (Homola et al. 2012), and therefore it is also possible that other Lake Superior populations (e.g., Bad River) may be using the SLR for spawning. Effective straying among Lake Superior populations could increase the probability of outbreeding depression and a loss of within-population diversity for Sturgeon populations throughout Lake Superior. Welsh et al. (2018) found that individual Lake Sturgeon that genetically assigned to the Wolf River population were found at all known spawning locations in Lake Superior except the Kaministiquia River. Hence, Wolf River fish stocked into the SLR are potentially interbreeding with Sturgeon from other Lake Superior populations creating the potential for outbreeding depression. Outbreeding has been observed in Lake Superior rainbow trout *Oncorhynchus mykiss*. In this instance offspring from wild bred populations of Rainbow Trout (Steelhead) had higher survival in Minnesota tributaries of Lake Superior than offspring from wild and hatchery stock (Kamloop) crosses (Miller et al. 2004). However, unlike Lake Sturgeon, Rainbow Trout are not native to this drainage (MacCrimmon and Gots 1972; Hassinger et al. 1974). There is also no documented evidence for outbreeding depression occurring among Lake Sturgeon stocks and it is uncommon within species from the same hydrologic drainage. But the potential for outbreeding depression has yet to be studied in Lake Sturgeon most likely because of their long generation time and life spans (Welsh et al. 2010). Alternatively, low levels of immigration and outbreeding can result in improved fitness of a population, if the population is suffering from inbreeding depression (Tallmon et al. 2004).

The first objective of this research was to determine the genetic origins of Lake Sturgeon captured during the spawning season in the SLR. The second objective of this research was to determine if genetic diversity metrics differed among Lake Sturgeon from the SLR and other Great Lakes populations. I hypothesized that most Lake Sturgeon captured in the SLR will be of Wolf River (Lake Michigan) origin due to the high stocking rates if Wolf River Sturgeon compared to Sturgeon River Sturgeon (Schram et al. 1999). I also hypothesize that a small percentage will be of Sturgeon River (Lake Superior) origin and migrants from other Lake Superior tributaries due to the relatively high straying rates of other Great Lakes Lake Sturgeon populations (Homola et al. 2012). I hypothesized that genetic diversity would be similar to other Lake Superior Lake Sturgeon populations given the results of Welsh et al. (2018) where the genetic diversity of the SLR was shown to be similar to other Lake Superior populations. The introduction of multiple stocks of Lake Sturgeon to the SLR and the propensity of Lake Sturgeon to stray from natal tributaries necessitates the understanding of the genetic diversity of the Lake Sturgeon within the SLR, as well as other spawning populations in Lake Superior. Understanding the genetic diversity of the SLR population will help aid in future management decisions aimed at the recovery of the Lake Superior Lake Sturgeon, as the SLR is the largest U.S. tributary to Lake Superior and the SLR was stocked with a non-native stock of Sturgeon.

METHODS

Fish Sampling

Lake Sturgeon sampling commenced in the springs of 2016, 2017, and 2018 when water temperatures reached approximately 8-10°C; the temperature when Sturgeon are known to begin spawning or staging for spawning (Auer 1996; McKinley et al. 1998; Bruch and Binkowski 2002). These temperatures were reached in mid-April of 2016 and 2017, and in early May of 2018, due to a later ice-out in 2018. Lake Sturgeon were sampled throughout the majority of the spawning season, mid-April to early-May in 2016 and 2017 and early to mid-May in 2018 to ensure a representative sample of the population (both genetically and demographically) was obtained. Most Lake Sturgeon sampled during 2016 and 2017 were captured via boat electrofishing in the upper most reach of the river primarily between the Fond Du Lac Dam and Highway 23 bridge near Fond Du Lac, MN (Figure 2.1). In 2018, lower river flows allowed for boat electrofishing, dip-netting, and backpack electrofishing below the Fond Du Lac Dam. Angling was also used in the study when boat electrofishing rates declined, and high flows made dip netting below the Fond Du Lac Dam unsafe (see Chapter 3, Figure 3.9). All captured fish were measured for total length (mm), girth (mm), and weighed (kg). Sex was determined visually using manual extrusion of gametes. A small pelvic fin clip (≂15mm) was taken from each captured Lake Sturgeon as the genetic tissue sample. Each tissue sample was placed in an individually labeled vial and preserved in 95% ethanol or placed in a scale envelope and allowed to dry before DNA extraction.

Genetic Analysis

Genetic analysis occurred at the Molecular Conservation Genetics Laboratory at the University of Wisconsin-Stevens Point (UWSP). Genomic DNA was extracted from fin samples using the Promega Wizard® Genomic DNA purification kit (Promega Corp., Madison, WI) with a 96-well modification. DNA was quantified using a Nanodrop® ND-1000 spectrophotometer (Nanodrop Technologies, Wilmington, Delaware) and the concentration was normalized to a standard concentration of 20 ng/µl. All sampled fish were analyzed using the suite of standardized microsatellite markers published for Lake Sturgeon in the Great Lakes (DeHaan et al. 2006; Welsh et al. 2008, 2010). Allele sizes were determined using an internal size standard (GeneFlowTM625, Chimerx Inc., Milwaukee, WI) and GeneMapper® software (Applied Biosystems Inc, Grand Island, NY). Allele calls were also manually confirmed to ensure accuracy. Allele calls from all loci were then combined, resulting in multi-locus genotyping data.

Genetic samples were assessed for Hardy-Weinberg expectations (HWE; Weinberg 1908; Hardy 1908). The Hardy-Weinberg principal has five major assumptions; random mating, no mutation, large population size, no natural selection, and no migration (Allendorf et al. 2013). The null hypothesis for HWE is that expected numbers of each genotype are equal to the observed genotypes (Allendorf et al. 2013). Samples were tested for departure from HWE using chi-square goodness-of-fit tests and linkage disequilibrium using GENEPOP (1,000 dememorization steps, 100 batches, 1,000 iterations per batch) (Rousset 2008). Significance of departures from HWE and linkage disequilibrium were assessed using a sequential Bonferroni correction (Rice 1989).

To describe genetic diversity within the SLR Lake Sturgeon population I calculated observed (H_o) and expected (H_e) heterozygosity, and allelic richness (*Ar*; mean number of alleles per locus) using GenAlEx v6.5 (Peakall and Smouse 2006, 2012) and Microsatellite Toolkit v3.1 (Park 2001). Allelic richness (A_r) and the number of private alleles (*PA*) were also estimated using HP-RARE 1.0 using the rarefaction method (Kalinowski 2005) to facilitate comparison between the SLR population and other Lake Sturgeon populations in the baseline data (Welsh et al. 2010).

Genetic Stock Identification

To determine which genetic stock of origin individual Lake Sturgeon sampled in the SLR most likely belonged to, I had to obtain baseline genetic data for genetic stocks from throughout the Lake Superior, Lake Huron, and Lake Michigan (Welsh et al. 2010; Amy Welsh, West Virginia University, Unpublished data; Figure 2.2). Two populations, the Wolf River and the Menominee River were selected to form the baseline for the Lake Michigan genetic stock (Welsh et al. 2008). The Wolf River (WLF) population was selected because this was one of the broodsources for population re-establishment in the SLR. The populations originating from Lake Superior used in the baseline included the Sturgeon River (STG), which was also used as a broodsource for several years of stocking, as well as the Kaministiquia River, Ontario (KAM), Black Sturgeon River, Ontario (BLS), Pic River, Ontario (PIC), Goulais River, Ontario (GOU), White River, Wisconsin (WHT), and Bad River, Wisconsin (BAD). The populations from Lake Huron included populations adjacent to Lake Superior including the Mississagi River (MIS), Spanish River (SPA), Garden River (GRD), and Serpent River (SPR; Figure 2.2). Lake Huron populations were included because recent research has found these fish present in the SLR (Welsh et al. 2018).

Once a baseline data set was established to perform genetic stock assignment, I used a maximum likelihood approach as implemented in the program ONCOR; (Anderson et al. 2008) to determine genetic stock of origin for Lake Sturgeon captured in the SLR. A threshold of 80% assignment probability was used in assigning sampled Lake Sturgeon to their genetic stock of origin (Meek at al. 2016). I chose an assignment probability threshold of 80% to increase confidence in our assignments and decrease bias from poor genotyping and assignment errors (Moran et al. 2014).

RESULTS

A total of 541 Lake Sturgeon samples were genotyped at 10 established microsatellite loci (Schram 2007; Welsh et al. 2008, 2018). Difficulty in genotyping locus SPL120 was encountered during the analysis of most samples for unknown reasons. This difficulty led to 73% missing data at locus SPL120 for the 2018 sample, 79% missing data at locus for the 2017 sample, and 71% missing data for the 2016 sample. This locus was removed from genetic stock assignment testing due to the high occurrence of missing data.

Hardy-Weinberg Equilibrium and Linkage Disequilibrium

For my 2016 sample, 3 of 10 loci were not in HWE following sequential Bonferroni corrections. Additionally, analysis of samples collected in 2017 indicated that 3 of the 10 loci were not in HWE. Similarly, analysis of the samples collected in 2018 indicated that 2 of the 10 loci were not in HWE. When all years were pooled linkage disequilibrium was present in 40% of loci pairs ($P < 0.0017$). In 2016, two of the departures from HWE were attributed to Heterozygote excess and one departure was attributed to Heterozygote deficiency. Heterozygote excess was also responsible for all three departures from HWE in 2017. Similarly, in 2018 both departures form HWE were attributed to Heterozygote excess. The presence of multiple genetic stocks of Sturgeon in the SLR samples likely led to the departures from HWE and elevated levels of linkage disequilibrium. The majority of departures from HWE were due to heterozygote excess; a result that occurs when a population sample contains multiple genetic stocks (Chen et al. 2017).

Genetic Diversity Metrics

For all samples genotyped from 2016-2018, mean H_o ranged from 0.565 to 0.630 and mean H_e ranged from 0.532 to 0.553 (Table 2.2). Across all years, A_r was estimated to be 2.93 (SD = 1.08). Only one private allele was observed in the SLR population (1% frequency across all years) when compared to all other baseline populations. (Table 2.2).

Genetic Stock Identification

A total of 209 of 228 (91.7%) Lake Sturgeon captured in 2016 assigned to Lake Michigan origin (Wolf River). Three samples (1.31%) assigned to the Pic River (Ontario), and two samples (0.78%) assigned to the Goulais River. Thirteen Sturgeon assigned to populations with less than 80% probability and were therefore considered "unknown origin" (Figures 2.2, 2.3).

One-hundred-twelve of 134 (83.6%) Sturgeon genotyped from the 2017 sampling season assigned to Lake Michigan origin (Wolf River), 1 fish assigned to the Pic River (Ontario), and 2 (1.5%) sturgeon assigned to the Goulais River (Ontario). Nineteen Sturgeon assigned to reference populations with less than 80% probability and were considered "unknown origin" (Figure 2.3, 2.4).

During the 2018 sampling season a total of 326 Lake Sturgeon were sampled from the SLR and a subsample of 180 were selected to genotype including all 34 Sturgeon with acoustic tags. The remaining 146 samples were randomly selected according to the proportion of Sturgeon captured each day to ensure I adequately represented any temporal genetic variation in spawn timing. Genetic assignment tests indicated that 149 (82.8%) Lake Sturgeon were of Lake Michigan origin (Wolf River) and 5 (2.8%) Sturgeon assigned to the Goulais River (Ontario). Twenty-six of the genotyped samples assigned to reference population with less than 80% probability and were considered "unknown origin" (Figure 2.3, 2.4).

DISCUSSION

A majority of Lake Sturgeon sampled in the SLR during the spawning period were of Wolf River genetic origin suggesting that the restoration stocking efforts were successful. Conversely, no Lake Sturgeon of Sturgeon River genetic origin were detected in the St. Louis

River during the sampling periods. However, the lack of Sturgeon River stock fish was not completely surprising as these fish were stocked at very low rates compared to Wolf River stock Sturgeon and due to the Sturgeon River fish being much younger in age (relative to the stocked Wolf River fish). Hence, it was likely that most of the stocked fish of Sturgeon River genetic origin were not sexually mature yet. Additionally, the relatively low rates of stocking coupled with spawning periodicity may preclude sampling of Sturgeon River fish in some years even if these fish were sexually mature.

Lake Sturgeon from at least two other Lake Superior tributaries, the Pic and Goulais rivers, were captured in the SLR on the spawning grounds during the spawning season suggesting that geneflow is likely occurring among Lake Superior populations. Straying from other Lake Superior tributaries to the SLR was observed during all years of sampling. Straying appears to be a common migration strategy for Great Lakes Lake Sturgeon and has been previously documented in in Lake Michigan Sturgeon populations where straying rates were found to be upwards of 10% (Homola et al. 2012). Straying rates were estimated at 3.5% in the Sturgeon River, a Lake Superior tributary (Homola et al. 2010). The SLR Lake Sturgeon population appeared to be similar with an estimated straying rate of 2.76% during this study. However, this rate may be an underestimation of the true straying rate because of the high number of genetically unassigned Sturgeon in the 2018 sample.

While straying is a relatively common strategy in migratory fishes, different factors can lead to variable straying rates among populations. For example, in Pacific Salmon *Oncorhynchus spp.* it is hypothesized that straying is an evolutionary alternative to homing and that straying should be common in populations spawning in unstable streams (Quinn 1984). The condition of Lake Superior tributaries has been highly variable and unstable over the last 200 years as tributaries have been subject to habitat degradation, changes in water quality, and alterations of natural flow regimes by dams. Hence, straying by Lake Sturgeon could be expected under this hypothesis given the altered habitat and abiotic conditions in Lake Superior tributaries. Further, it is likely that straying is one of the mechanisms that has aided in the persistence of Lake Sturgeon as habitats have been disturbed or populations have become limited by resources. For example, in salmonids, it has been hypothesized that some fish stray to lessen kin and resource competition, along with buffering the donor population from disturbances in habitat quality (Lapointe et al. 2000; Hendry et al. 2004).

While straying may provide some evolutionary advantages, one possible complication of straying is outbreeding depression. Outbreeding depression is a possibility in Lake Superior due to the introduction of Lake Sturgeon from the Wolf River genetic stock (Lake Michigan origin). One major consequence of outbreeding depression is a loss of fitness due to the breakup of co-adapted gene complexes that have evolved under local conditions (). Possible differences in local adaptations that may hinder reproductive have also been expressed as a concern in the SLR because the Lake Sturgeon population was re-founded with Sturgeon from outside the basin (Welsh et al. 2018). Welsh et al. (2018) suggested that Sturgeon River Lake Sturgeon may be better adapted to spawning in the SLR than Sturgeon from the Wolf River genetic stock due to being adapted to a later spawning season. The peak spawning time of Sturgeon River Lake Sturgeon is early to mid-May of most years (Auer 1999) while the peak spawning time of Wolf River Sturgeon is mid-late April (Bruch and Binkowski 2002). Peak spawn timing in the SLR during this study was consistent with that of the Sturgeon River. However, differences in spawn timing among populations and years is more likely related to abiotic factors (e.g., temperature and flow) than it is to adaptive variation (Ecclestone 2012, Forsythe et al. 2012). Alternatively, it is possible that spawn timing will shift towards an earlier time frame due to climate change or increased inter-year variability punctuated by extreme weather events (GLISA 2014). Consequently, if spawn timing does shift, the Wolf River stock Sturgeon may be better adapted than other Lake Superior Lake Sturgeon populations because the Wolf River stock evolved at a lower latitude and in a warmer climate than Lake Superior populations. To illustrate this point further, Ecclestone (2012) observed Lake Sturgeon in the Pic River shifted the timing of their spawning migration approximately 54 days earlier compared to the previous two years. This shift was highly correlated to early ice melt and high spring temperatures. While it is not known if the Pic River Sturgeon that shifted their migration were successful in reproducing, the capability of responding to inter-year variability in spawn timing is likely a desirable trait for Lake Sturgeon.

While outbreeding depression is a possibility in Lake Superior Lake Sturgeon, it is relatively unlikely. Recent work by Frankham et al. (2011), predicted the probability of outbreeding depression to be low if the introduced species is of the same karyotype, the populations have been isolated (i.e. no gene flow across range) for <500 years, or if the populations inhabit different environments. According to Frankham et al. (2011), a meaningful difference in environment is defined as one environment possessing features to which the species is extremely sensitive to or if the species is a narrow specialist or broad generalist. Lake Sturgeon from the Wolf River likely have the same karyotype, have not been isolated from Lake Superior for >500 years, and inhabit similar environments (e.g. Great Lakes Basin). Lake Sturgeon are likely not sensitive to particular features of the Wolf River, Sturgeon River, or SLR due to the fact all these rivers are all tributaries within the Great Lakes Basin, and Lake Sturgeon occupy rivers and lakes comprised of a wide-range of biotic and abiotic conditions throughout the Great Lakes basin and their native range.

While the deleterious effects of outbreeding depression have not been documented in Lake Sturgeon populations, they have been observed in a non-native Lake Superior salmonid population (Miller et al. 2004). The unique life history traits of Lake Sturgeon including late sexually maturity, sex-specific differences in spawning periodicity, and broadcast spawning may also make outbreeding depression less likely to occur, but also harder to detect. To complicate the issue further, imperfect sampling methods and high variability in spawning success, not attributed to genetic issues (e.g., abiotic factors), provide an even more daunting task for managers hoping to examine the effects of outbreeding depression (Smith and King 2005).

Alternatively, low levels of outbreeding have been shown to increase fitness in populations suffering from inbreeding depression (Tallmon et al. 2004). However, DeHaan et al. (2006) found that none of the sampled Great Lakes Sturgeon populations sampled during their project suffered from inbreeding depression. One potential reason why Great Lakes Sturgeon populations are not experiencing inbreeding depression could be due to the low levels of natural straying among populations. For example, Welsh et al. (2018) detected larval Lake Sturgeon of Lake Huron genetic origins in the SLR (10.8% of the sample). I believe that this not likely an isolated event and it may even be a common occurrence, based on the frequency of strays from Goulais River stock observed in the SLR, which is closest to Lake Huron. Hence, if a remnant population was experiencing inbreeding depression it is possible that the remnant population may benefit from an increase in genetic diversity gained by low levels of introgression from adjacent populations.

Genetic diversity levels within the SLR Lake Sturgeon population were similar to those of other remnant Lake Sturgeon populations throughout Lake Superior (Schram et al. 1999; Schram 2008; Welsh et al. 2018). Genetic diversity levels are important because high levels of genetic diversity allow for a population to adapt to changes in the environment. Ultimately, high levels of genetic diversity leads to increased probability of persistence for a population by protecting the population against disease, habitat disturbances, extreme conditions or other perturbations in the SLR or Lake Superior (Lande and Shannon 1996; Watters et al. 2003; Fox 2005).

Ideally, a population restored via stocking should exhibit a high level of genetic diversity. All Lake Superior Lake Sturgeon populations have experience large demographic bottlenecks and therefore likely genetic bottlenecks due to the effects of severe overfishing, habitat degradation, and loss of water quality (Auer 1996). Due to these bottlenecks, appropriate levels of genetic diversity for a restored Lake Sturgeon population are difficult to define (Welsh et al. 2018). Therefore, future SLR stocking events, if they occur, should consider the probability of outbreeding depression, the historical success of previous stocking events, levels of natural reproduction, and the possible overall increase of genetic diversity in Lake Superior Lake Sturgeon populations due to straying. Continued genetic monitoring will be paramount to understanding the genetic diversity of all Lake Superior Lake Sturgeon and origin the of SLR Lake Sturgeon in making possible stocking decisions, especially as age classes in the SLR Lake Sturgeon population become sexually mature.

Management Implications

My results indicated that there was a relatively high level of genetic diversity present in the SLR Lake Sturgeon population and that much of the current adult population was comprised of Sturgeon of Wolf River genetic origins. Managing the SLR population in a way that continues to promote genetic diversity levels and allows the population to mature and naturally reproduce will allow genetic adaptive mechanisms to work while considering the unique life history characteristics of Lake Sturgeon. Stocking of Lake Sturgeon into the SLR by the MNDNR and WDNR is planned to resume in the autumn of 2019 (Dan Wilfond MNDNR, personal communication 2018). Stocking will follow the genetic guidelines put forth by Welsh et al. (2010), gametes are proposed to be obtained from the Sturgeon River, a Lake Superior tributary; however availability of that broodsource may be restricted due to the Sturgeon River currently serving as the broodsource for the restoration of the Ontonagon River, MI. Recommencement of stocking Sturgeon River stock individuals may increase genetic diversity within the SLR population. However, the probability of outbreeding depression may increase within the SLR as it is likely Sturgeon of Wolf River genetic origin will still persist in the SLR for many years. Additionally, I have demonstrated that Lake Sturgeon from the Wolf River genetic stock exhibited homing back to the SLR (where these fish were stocked). It is currently unknown if stocked individuals from the Sturgeon River will also exhibit homing back to the stocking site in the SLR. Hence, based on the presence of natural recruitment, high levels of genetic diversity, and homing of Wolf River genetic origin Lake Sturgeon in the SLR the recommencement of stocking of Sturgeon into the SLR could be viewed as a premature action. Unfortunately, the unique life history characteristics of Lake Sturgeon, specifically longevity and intermittent spawning periodicity, make Sturgeon extremely difficult to manage; the lifespan of a single generation of Lake Sturgeon could span the consecutive careers of several fish biologists. This fact, coupled with the young average age of the SLR Lake Sturgeon population, necessitates a careful and methodical adaptive management approach to help ensure that previous and future investments in stocking lead to the conservation of high genetic diversity levels and adaptive ability necessary for the SLR Lake Sturgeon to persist in perpetuity.

Future Research

In future years the genetic structure and diversity of the SLR Lake Sturgeon population will likely change as naturally reproduced Lake Sturgeon and stocked Sturgeon of Sturgeon River genetic origins become sexually mature. Intraspecific hybridization is likely between Lake Sturgeon with Sturgeon River and Wolf River genetic origins and Sturgeon from other genetic populations straying into the SLR from throughout the Upper Great Lakes. Annual genetic sampling examining a random subset of the adult SLR Lake Sturgeon population and naturally reproduced larval Sturgeon should continue in the SLR. Genetic testing from larval Sturgeon would be useful in estimating family and parental contributions, estimating effective population size, and identifying contributions of stocked and naturally reproduced Lake Sturgeon to the overall population. Genetic diversity metrics should be continued to be monitored for signs of inbreeding and outbreeding depression, and an overall loss of genetic diversity. Single nucleotide polymorphisms (SNPs) high throughput genetic technology should be employed for the next generation of Great Lakes basin Lake Sturgeon genetic studies (Leroy et al. 2018). This technology may further help to monitor inbreeding and outbreeding depression as well as identify possible genetic causes in Lake Superior Lake Sturgeon populations by possibly increasing the resolution of genetic data compared to microsatellites.

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Table 2.1. Numbers of Lake Sturgeon stocked in the St. Louis River by Minnesota Department of Natural Resources (MNDNR) and Wisconsin Department of Natural Resources (WDNR) from 1983 to 2000. Lake Sturgeon stocked from 1983-1994 were sourced from the Wolf River (Wolf R). Sturgeon stocked from 1998-2000 were stocked from the Sturgeon River (Sturgeon R), MI (Lake Superior stock). All fingerlings stocked by MNDNR received a coded wire tag in the snout cartilage. (Schram et al. 1999; Lindgren et al. 2016).

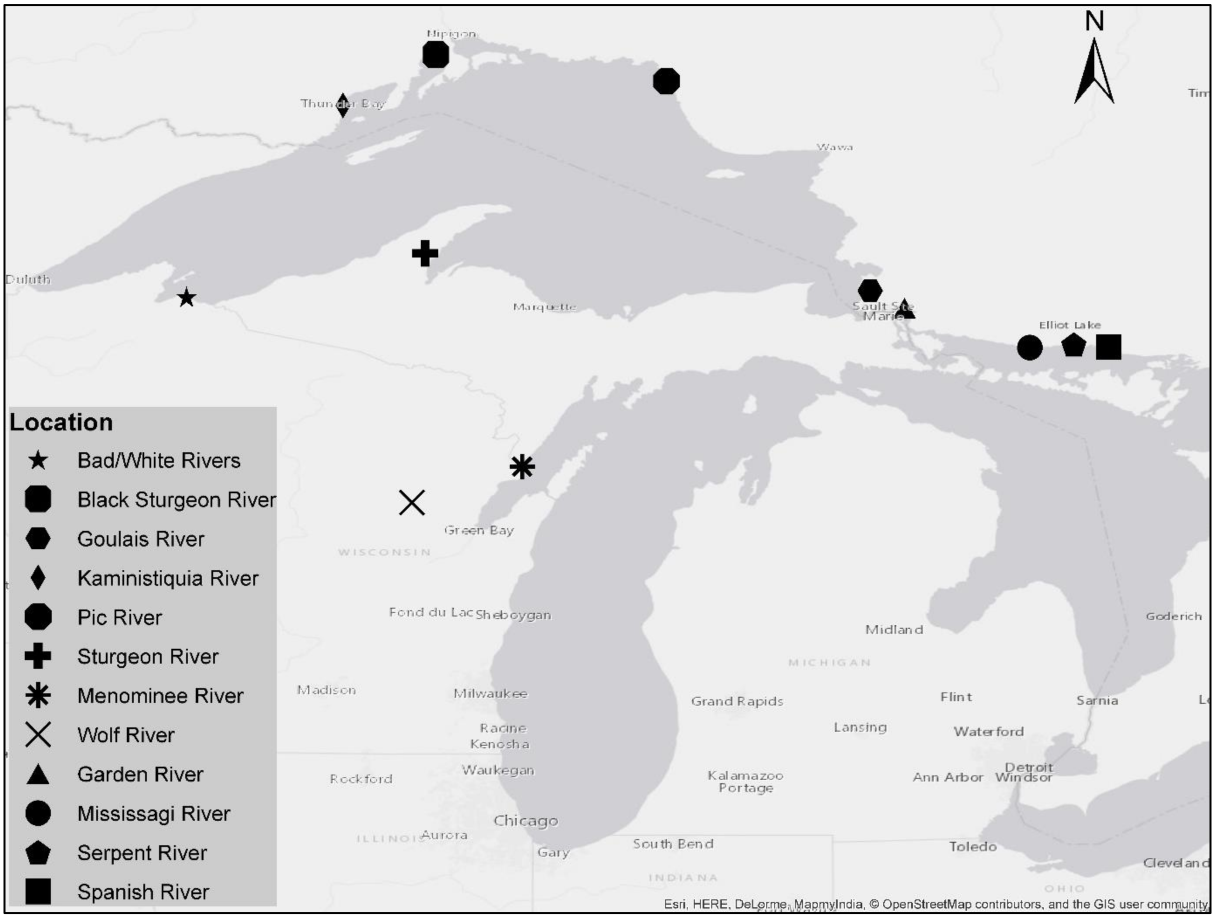
	MNDNR			WDNR			Total	
Year	Fry	Fingerling[a]	Stock	Fry	Fingerling[b]	Stock	Fry	Fingerling
1983			Wolf R	102,000	2,700	Wolf R	102,000	2,700
1984			Wolf R	162,000	18,000	Wolf R	162,000	18,000
1985		4900	Wolf R	59,000	2,700	Wolf R	59,000	7,700
1986		400[c]	Wolf R			Wolf R		400
1987			Wolf R			Wolf R		
1988		18,200	Wolf R		6,000	Wolf R		24,300
1989		7,200	Wolf R	50,000	100[c]	Wolf R	50,000	7,300
1990		10,300	Wolf R	25,000		Wolf R	25,000	10,300
1991		5,500	Wolf R	96,000	4,500	Wolf R	96,000	10,000
1992	83,000		Wolf R		13,500	Wolf R	83,000	13,500
1993			Wolf R	7,000	19,300	Wolf R	7,000	19,300
1994			Wolf R	151,000	14,500	Wolf R	151,000	14,500
1998		6,800	Sturgeon R			Sturgeon R		6,800
1999	46,000		Sturgeon R			Sturgeon R	46,600	
2000		7,980	Sturgeon R			Sturgeon R		7,980
Total	129,000	60,880		652,000	81,300		781,000	142,180

[a] Fall fingerlings (127-203 mm)
[b] Late-summer fingerlings (102-152 mm)
[c] Yearlings stocked in October

Table 2.2. Genetic Diversity metrics for St. Louis River and all populations included in baseline samples. Metrics include allelic richness A_r, adjusted using rarefaction method (Kalinowski 2005), observed heterozygosity H_o, expected heterozygosity H_e.

Population	N	A_r	A_r SD	H_o	H_o SE	H_e	H_e SE
Bad	136	2.95	0.93	0.529	0.068	0.551	0.065
Black Sturgeon	57	3.1	0.74	0.585	0.043	0.593	0.041
Goulais	43	3.08	0.94	0.607	0.042	0.585	0.040
Kaministiquia	85	2.87	0.83	0.548	0.070	0.542	0.061
Pic	63	3.11	0.97	0.525	0.058	0.557	0.062
White	43	2.86	0.98	0.487	0.062	0.517	0.067
Menominee	21	2.88	0.99	0.530	0.079	0.496	0.064
Wolf	30	3.14	1.15	0.528	0.063	0.549	0.059
Sturgeon	48	3	0.93	0.547	0.054	0.556	0.050
Mississagi	52	3.15	1.23	0.546	0.060	0.564	0.059
Spanish	47	2.99	1.05	0.608	0.056	0.564	0.046
Garden	34	3.29	1.21	0.642	0.045	0.606	0.045
Serpent	53	3.13	1.15	0.543	0.057	0.576	0.053
St. Louis	541	2.98	1.08	0.578	0.068	0.540	0.057

Figure 2.1. Arial photograph of Lake Sturgeon sampling area in the St. Louis River from Fond Du Lac Dam to Highway 23 bridge. Backpack electrofishing and netting area is shown in the orange circle and boat electrofishing area (transect) is delineated with yellow line and corresponding labels (Piszczek et al. 2016).



Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 2.2. Locations of Lake Sturgeon genetic stocks used in the genetic stock baseline (for genetic assignment testing). Genetic stocks included Bad/White, Black Sturgeon, Goulais, Kaministiquia, Pic, and Sturgeon rivers are in Lake Superior. Garden, Mississagi, Serpent, and Spanish rivers are in northern Lake Huron. The Wolf and Menominee rivers are in the Lake Michigan basin.

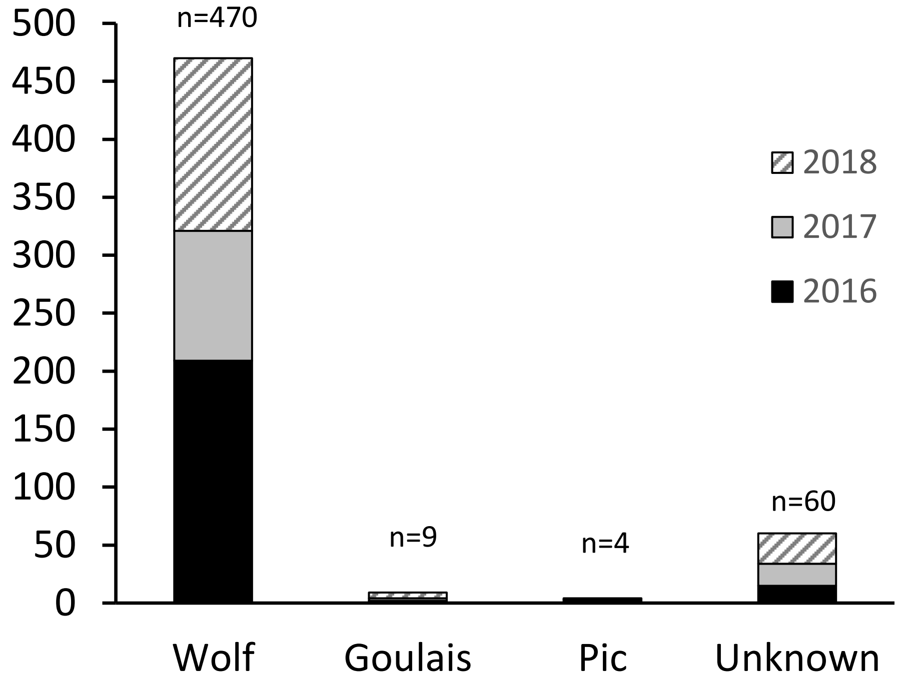


Figure 2.3. Genetic assignments of Lake Sturgeon sampled from the SLR from 2016-2018. Unknown fish did not assign to a genetic stock with greater than 80% probability. Stocks represented include the Wolf River (Winnebago; Lake Michigan stock), Goulais River (Ontario, CA), and Pic River (Ontario, CA).

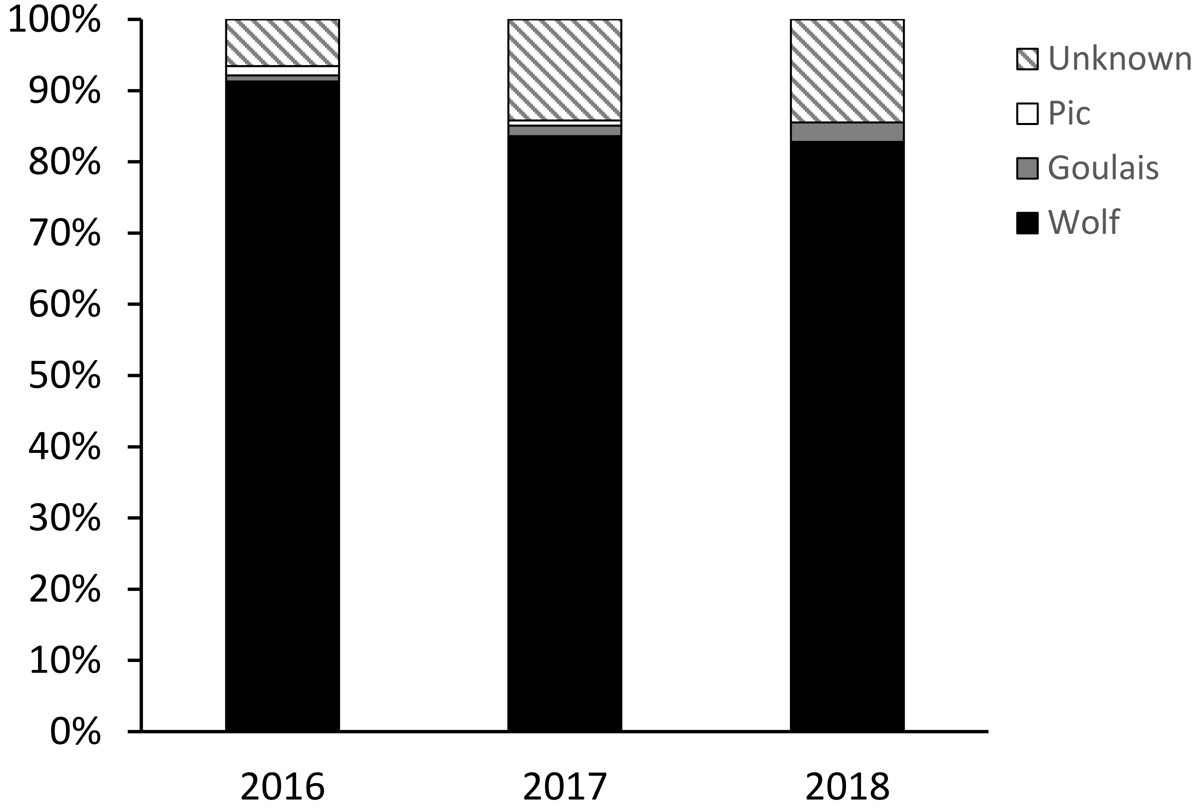


Figure 2.4. Genetic assignments of SLR Sturgeon from sampling years 2016-2018. Genetic stocks represented include Wolf River (Winnebago; Lake Michigan), Goulais River (Ontario, CA), and Pic River (Ontario, CA). Sampled Sturgeon that did not assign with greater than 80% probability were considered unknown (diagonal bars).

CHAPTER 3: MOVEMENT OF LAKE STURGEON IN THE ST. LOUIS RIVER AND WESTERN LAKE SUPERIOR

INTRODUCTION

Movement is a major determinant of the fate of individuals, the structure and dynamics of populations, communities, and ecosystems, and ultimately helps shape the evolution and diversity of life (Baker 1978; Greenberg and Marra 2005). For example, animals may move to find mates or food, or to avoid predators or adverse conditions (Liedvogel et al. 2013). Movement is often tied to life history strategies and movement often represents ecological tradeoffs. For example, an individual fish may move away from protective cover (e.g., dense vegetation) to seek food. However, when the fish leaves the cover it becomes more vulnerable to predation. This suggests movement can have positive and negative individual and population level repercussions. Therefore, having knowledge and characterizing animal movements in natural populations is considered a pre-requisite for effective conservation (Rubenstein and Hobson 2004).

Sturgeons Acipenseridae have been known to exhibit a wide variety of movements and migration strategies. For example, some White Sturgeon *Acipenser transmontanus* individuals prefer to remain in one area throughout the year, while others move among several different habitats. Individual White Sturgeon that have access to the ocean have even been observed migrating more than 1,000 km (Welch et al. 2006; Parsley et al. 2008). Fox et al. (2000) also found that migratory patterns of Gulf Sturgeon *Acipenser oxyrinchus* varied with reproductive status (e.g., ripe v. nonripe). Hence, for Sturgeons, understanding movement patterns and life history strategies is critical for management.

Lake Sturgeon *Acipenser fulvescens* are also known to exhibit complex movements including both resident and migratory life history strategies (Auer 1996; Rusak and Mosindy 1997; Borkholder et al. 2002a; Kessel et al. 2017). These variable and complex movement patterns and life history characteristics can potentially complicate management, especially in inter-jurisdictional areas (e.g., Great Lakes). For example, a recent telemetry study in the Huron-Erie Corridor (HEC; area between Lake Huron and Lake Erie) identified at least five distinct migratory behaviors from Lake Sturgeon tagged within the study area. The area is co-managed by the United States and Canada with several spawning tributaries in each country. Because of the variable movement patterns and interjurisdictional nature of the HEC, this study recommended that Sturgeon in the HEC could be considered independent populations based on their spawning locations and movement strategies (Kessel et al. 2017).

Lake Sturgeon in the St. Louis River (SLR) were considered to be extirpated by the early 1900's due to the combined effects of overfishing, habitat destruction and degradations, as well as loss of water quality (Auer 1996; Schram et al. 1999). To re-establish a Lake Sturgeon population in the SLR, the Minnesota Department of Natural Resources (MNDNR), Wisconsin Department of Natural Resources (WDNR), and the Fond Du Lac Band of Lake Superior Chippewa (FDLLSC) implemented a stocking program in 1983. Nearly one million fry and fingerling Lake Sturgeon were stocked during the program which ceased in 2000 (for more information see Chapter 2; Schram et al. 1999; Lindgren et al. 2006).

Targeted sampling for Lake Sturgeon in the SLR has taken place since 2007 after the observation of adult Lake Sturgeon spawning below the Fond Du Lac Dam. Before 2007, Lake Sturgeon were occasionally captured by crews performing routine assessments for other species within the SLR and in the adjacent waters of Lake Superior (Dan Wilfond MNDNR, personal communication 2018). Larval Lake Sturgeon were first captured in the SLR in 2011 by the 1854 Treaty Authority signaling successful natural reproduction. Although management agencies have been successful in capturing adult and larval Lake Sturgeon during recent sampling efforts, the population dynamics and behaviors (e.g., movement patterns) of the St. Louis River Lake Sturgeon population remain largely unknown. For instance, little is known about how many Lake Sturgeon are spawning in the SLR and whether spawning fish exhibit migratory, or year-round river resident life history strategies.

The section of the SLR that is available to Lake Sturgeon for migration, residence, and spawning is approximately 33 river kilometers (RKM), extending from the Duluth, MN and Superior, WI entries of the estuary from Lake Superior, upriver to the Fond du Lac Dam (Figure 3.1). Biologists believe that most of the historical spawning habitat is intact and accessible as a set of rapids near the present location of the Fond du Lac Dam was thought to be the historical upriver limit of Lake Sturgeon spawning activity (Schram et al. 1999). While reproduction has been observed below the dam, there has not been any other observed instances of reproduction further downstream in the SLR or estuary. However, little effort has been extended to determine whether additional spawning areas may be present within the SLR, estuary, or associated tributaries. The identification of additional spawning areas could lead to potential improvements, protections, and enhanced recruitment for the recovering SLR Lake Sturgeon population.

The Lake Sturgeon Subcommittee for Lake Superior has adopted specific fish community objectives that defined rehabilitation of Lake Sturgeon as a priority. The primary objective for the recovery is to rehabilitate and maintain self-sustaining populations. To reach this objective the Lake Sturgeon Subcommittee set the goal of having at least 1,500 adults, representing 20 year classes, spawning in each of the 17 major tributaries to Lake Superior that were known to have once supported spawning populations of Lake Sturgeon (Auer 2003). Additionally, adult fish from these populations should produce yearly evidence of reproduction measured by collecting viable eggs and juvenile Lake Sturgeon (ages 0-5) in tributaries (Horns et al. 2003). The SLR and estuary are listed as a critical management area for the overall health and recovery of the Lake Superior Lake Sturgeon population (Auer 2003). However, management agencies know little about Lake Sturgeon in the SLR and Western Lake Superior. Specifically, little is known about movement within the river, between the river and Lake Superior, and among Lake Superior tributary rivers. Information about movement is critical in guiding management of this population to meet the objectives of the Lake Superior Lake Sturgeon rehabilitation plan. Specifically, knowledge of movements will lead to more informed decision making with regards to population abundance and dynamics, harvest regulations, stocking efforts, and geneflow among populations within the Great Lakes. Currently, there is no harvest of Sturgeon allowed in the SLR, but there is a catch and release fishing season. However, one Lake Sturgeon over 50” may be harvested annually from Wisconsin Waters of Lake Superior (Wisconsin Department of Natural Resources Bureau of Fisheries Management 2018). Recently, there has been social pressure to open a season for harvest of Sturgeon in the SLR. However, current data are insufficient to determine the probable effects of a harvest season (Paul Piszczek, Wisconsin Department of Natural Resources, Dan Wilfond, Minnesota Department of Natural Resources, personal communication). I hypothesized that most Lake Sturgeon will emigrate to Lake Superior after spawning, however there will also be a resident population in the SLR. This hypothesis is based on research from other systems where there was shown to be a migratory and resident component to a population (Rusak and Mosindy 1997; Borkholder et al. 2002). I also hypothesized that the majority of spawning will take place immediately below the Fond Du Lac

Dam. This hypothesis is based on the belief that quality spawning habitat below the dam is likely not limited because of the low population density of Lake Sturgeon currently in the SLR.

The objectives of this research were to determine if (1) Lake Sturgeon in the SLR were migratory or resident, (2) the timing, frequency, and magnitude of Lake Sturgeon migrations between the SLR and Lake Superior were differed among genetic stocks, physical characteristics (sex, size) or environmental conditions (temperature, discharge) and (3) if spawning locations were influenced by genetic stock of origin, individual demographic characteristics, environmental conditions, and restored habitats.

METHODS

Study Area

The study area encompassed the extreme western shore of Lake Superior adjacent to the cities of Duluth, MN and Superior, WI, and the SLR and estuary below Fond du Lac Dam. The SLR and estuary partially form the border between the states of Minnesota and Wisconsin. The length of the river in my study area was approximately 33 RKM and at the greatest width measured approximately 20 km in the estuary and 1 km in the river. The study area was approximately 6,900 ha in surface area. This area was highly industrialized, including dredged shipping lanes and freight docks (Figure 3.1, 3.2). Discharge and water temperature data were downloaded from the USGS gauge #04024000 at Scanlon, MN. Average daily temperature from the gauging station was found to be significantly correlated with a temperature (unpublished data) data logger placed near the Oliver Bridge, so for ease of data downloading all temperature data presented were from the gauging station (Figure 3.3). The current known spawning area of Lake Sturgeon is directly below the Fond Du Lac Dam (Dan Wilfond, Minnesota Department of Natural Resources, Personal Communication). Other potential areas include a large riffle approximately 0.5 km below the Fond Du Lac Dam, a recent rehabilitation site at Chamber's Grove (Figure 3.4) and the Nemadji River.

Acoustic Receivers

During this study, 8 VR2W acoustic receivers were deployed from April 2016 to April 2017 and 32 VR2W and 8 VRTX Vemco© acoustic receivers (40 total receivers) were deployed from April 2017 to August 2018 (Figure 3.1). Receivers were strategically located to provide the highest probability of detecting movements of Lake Sturgeon within the study area. Specifically, receivers were placed in the Superior and Duluth entries to the estuary from Lake Superior, and in favorable locations to determine upstream and downstream movement (i.e. bridges, narrow channels, pinch points; Figure 3.1). The VRTX receivers were Bluetooth enabled and were placed in probable "high traffic" areas (i.e. narrowing channels, bridges). The VRTX receivers were monitored during mobile tracking (see mobile tracking section) to determine battery use and available memory, as well as number of total detections. Data were downloaded, batteries were changed, and basic maintenance was performed on all receivers once per year. Receivers were attached to a large cement block (approximately 61 cm x 61 cm) with a 1 m length of rebar cemented vertically. The VR2W or VRTX was then attached to the vertical piece of rebar using hose clamps. A length of steel cable (1/4 in diameter) was attached to the receiver anchor and to a separate smaller anchor (Figure 3.5). The two anchors were set apart so that the cable acted as an attachment point for a grappling hook used during the receiver retrieval process. Receivers were retrieved by use of GPS coordinates and transponding hydrophone (Vemco, Nova Scotia, Canada) to gain position above the receiver and then a specialized grappling hook was deployed from a winch onboard a MNDNR watercraft.

Range Testing

Placement of fixed receivers was also aided by preliminary range testing conducted by the MNDNR. The overall detection rate was >50% for a V-16 test tag placed at 400 meters for receivers in 1-8 meters of water at various sites within the SLR (Patrick J. Schmalz MNDNR, unpublished data). Detection rates decreased as distance between receiver and tag increased (Figures 3.6 A, B). This range testing occurred at sites where detection probability was believed to be reduced, such as channelized and dredged areas. Therefore, these detection distances were used as minimum detection ranges in establishing the current acoustic receiver array and we assumed most receivers would detect tags from greater distances (Patrick J. Schmalz MNDNR, personal communication 2017). Range testing for mobile tracking equipment also took place during the summers of 2017 and 2018. The VRTX receivers are equipped with test tags and hence the VRTX receivers were used to estimate detection ranges for mobile tracking equipment (Figure 3.7). Detection ranges estimated from mobile tracking were similar to the fixed receivers; sentinel tags in VRTX receivers were detected out to approximately 400 meters.

Fish Collection

Lake Sturgeon sampling commenced in the springs of 2016, 2017, and 2018 when water temperatures reached approximately 8-10°C, the temperature when Sturgeon are known to begin to spawning or staging for spawning (Auer 1996; McKinley et al. 1998; Bruch and Binkowski 2002). Lake Sturgeon samples were collected in 2016 through joint efforts by the MNDNR, WDNR and Fond Du Lac Band. In conjunction with agency sampling, I sampled through much of the spawning season, April–May in 2017 and early to mid-May- in 2018. Most sampling was done via boat electrofishing in the upper most reach of the river, primarily between the Fond Du

Lac Dam and Highway 23 bridge near Fond Du Lac, MN (Figure 3.8). Lake Sturgeon were also dip netted below the Fond Du Lac Dam for 1 day in 2016, 1 day in 2017 and 7 days in 2018. Angling was also used to collect Lake Sturgeon when boat electrofishing catch rates declined and flow rates were too high to safely dip net. All captured fish were measured for total length (TL; mm), girth (mm), and weighed (kg). Sex was determined visually by manually extruding gametes according to Bruch (2010). All captured fish were scanned for the presence of a coded wire tag (CWT) and PIT tag and noted if present; if no PIT tag was detected, fish received a PIT tag to aid ongoing mark-recapture studies. Captured fish were also visually inspected for presence of a Floy t-bar anchor tag and tagging authority and tag number were noted if present.

Acoustic Tagging

Each year, a subsample of captured Lake Sturgeon were implanted with V16-8H acoustic transmitters (Vemco©, Nova Scotia, Canada). All Lake Sturgeon positively identified as female Sturgeon received a transmitter, with the remainder of the acoustic transmitters being placed in males or Sturgeon of unknown sex. Transmitters weighed approximately 36 g out of water (<0.1% of body mass) and were 16 mm in diameter by 68 mm in length (Figure 3.9) making them appropriate for fish of this size (Webber 2009). Transmitters had a nominal delay of 120 seconds (±50%) to achieve approximately a 10-year battery life (Vemco©, Nova Scotia, Canada). A 10-year battery life was selected to help ensure that each tagged fish will complete ≥ 2-4 spawning cycles (dependent on sex; Peterson et al. 2007) during the lifetime of the transmitter.

The tagging procedure followed standard protocols currently approved for use on Lake Sturgeon by the UWSP Institutional Animal Care and Use Committee (UWSP IACUC Protocol 2015.03.01) and published methodology shown to have no adverse effects on Lake Sturgeon (Hondorp et al. 2015). After capture, Lake Sturgeon that appeared healthy (no obvious injuries/impairments), were placed ventral side up in a mesh sling, suspended over a large tank, with gills and head submerged in freshly pumped river water with oxygen stones providing oxygenation. Prior to the beginning of each surgery, all tools and transmitters were disinfected with chlorhexidine diacetate (Nolvasan®) and rinsed with sterile water before use. Then, a small incision, approximately 30 mm in length (1.5 times the diameter of the transmitter) was made in the abdomen of each fish approximately half way between the pectoral and pelvic girdles and 2 cm off the *linea alba* (Hondorp et al. 2015). The acoustic transmitter was placed into the body cavity, accessed through the incision. Incisions were closed using 3-5 interrupted sutures of monocryl suture material (Bridger and Booth 2003; Boone et al. 2013). Fish were monitored for excessive bleeding and regular opercular activity during and shortly after surgery. Fish were then moved back to the river in a sling and gently revived before release.

Mobile Tracking

Mobile tracking via boat and on foot occurred monthly from June to October 2017 and May (resumed following ice-out) to August of 2018. A Vemco© VR100 manual tracking receiver along with a Vemco© VH110 directional hydrophone and a Vemco© VH165 omni-directional hydrophone were used during tracking efforts. All areas of the SLR and estuary from Fond Du Lac Dam downstream to Lake Superior that were accessible by boat were mobile tracked. Mobile tracking was conducted by motoring slowly downstream at 2-4 knots while the VR100 continuously listened for acoustic tag signals. When a tag was detected I maneuvered the boat according to signal strength to gain the closest possible estimate of location using the VH110 directional hydrophone. Mobile tracking routes were logged via hand-held GPS unit to ensure coverage of all boat accessible areas and channels. During the spawning season of 2018, I mobile tracked on foot in the spawning area on 11 of the 18 sampling (spawning) days. Fish detection locations were recorded on the VR100 manual tracking receiver. Mobile tracking data were added to data collected by the fixed receivers throughout the study area to increase resolution of fish detections by detecting fish in areas without receiver coverage. My mobile tracking data was also supplemented through an on-going Muskellunge *Esox masquinongy* study being conducted simultaneously in the SLR (E. Schaeffer, University of Minnesota, unpublished data).

Analysis of Movement Data

Data were uploaded to Great Lakes Acoustic Telemetry Observation System (GLATOS) then imported into the GLATOS package (Binder et al. 2017) in Program R (R Development Core Team 2013) to develop movement histories of individual fish. Abacus plots were assembled for each fish to visualize a detailed detection (movement) history. Animations were also created based on tag detections to interpolate and visualize movements of individual Sturgeon throughout the study area. I included all movement immediately post-tagging because I tagged within the spawning period and did not want to exclude any potential movements into the spawning area.

Next, I calculated the Julian day that individually tagged Lake Sturgeon emigrated out of, or immigrated in to, the SLR and Lake Superior. I also calculated the percentage of Lake Sturgeon that resided in the SLR for the duration of the study. An emigration was defined as the time when a Lake Sturgeon was no longer detected on any receiver inside the entries to Lake Superior but was detected on a receiver outside the entries (i.e. Lake Superior). I compared total length and date captured between migratory (emigrated) and non-migratory fish with *t*-tests (Zar 1999) to determine if there was a biological component possibly attributed to movement and life history variation of individual Lake Sturgeon. I also compared the proportions of emigrants for each genetic strain using a two-proportions *Z*-test (Zar 1999).

Relationships between immigration and emigration dates with flow and temperature were analyzed using Spearman's correlation coefficient. The probability of emigration from the SLR to Lake Superior was fitted as a generalized linear model (GLM) in Program R by using a Poisson distribution with water temperature (°C) and discharge (CFS) as the predictor variables (Zar 1999; Auer 1999; Boase et al. 2011; Ecclestone 2012).

Daily, weekly, and monthly movement (number of RKM) was estimated for individual Lake Sturgeon by determining the differences in average RKM where the fish was present during each respective interval. Each receiver was assigned a RKM based on its location within the SLR. Linear daily movement was calculated as the cumulative movement observed daily from 2400 hours to 2359 hours. Linear weekly movement was calculated as cumulative movement over the calendar week starting on Sunday at 2400 hours and ending on Saturday at 2359 hours. Linear monthly movement was calculated as the cumulative movement during the period from the 1st day of a given month to last day of the given month. Because of the reduced acoustic array that was deployed in 2016, I chose to only calculate daily, weekly and monthly movements for the 2017-2018 data. However, 2016 data were included for estimates of emigration and immigration as the array encompassed both entries and exits available to Lake Sturgeon (Figure 3.1). Data immediately following tagging was included because sampling occurred throughout the spawning run and important movements may have been ignored by not acknowledging immediate movements upriver from the tagging area to the spawning area.

Habitat use was approximated using a combination of fixed-receiver and manual tracking detections, and the use of ArcGIS (Esri, Redlands, California). The number of individual fish and number of detections at each receiver were calculated for each season from April 2017 to September 2018. Seasons were defined as: March 1 to May 31 (Spring), June 1 to August 30

(Summer), September 1 to November 30 (Autumn) and December 1 to February 28 (Winter). Data were uploaded to ArcGIS and then a “heatmap” was developed based on this information using the Inverted Density Weighted (IDW) method in ArcMap (“How IDW works—Help | ArcGIS for Desktop” 2016). The IDW method was chosen because of its utility of describing irregular spaced spatial datasets (Ajemian et al. 2012). To interpolate data points, the IDW method gives a value to a measured point, and the value of surrounding cells decreases with distance away from the measured point. Two types of heatmaps were then developed based on (1) the total number of detections per receiver during each of the seasonal timeframes and (2) the total number of individual fish detected at each receiver during each of the seasonal timeframes. Two more heatmaps were also developed for an overall timeframe of April 2017 to September 2018; one for the total number of detections at each receiver and one for the total number of individual fish detected at each receiver. To validate the interpolated values of the habitat approximation maps I overlaid mobile tracking data from the summer of 2017 (Figure 3.23) The data generated from the heatmaps will inform managers of possible areas of interest in habitat restoration, improvement, or protection.

A multi-state capture-recapture model (Lebreton and Cefe 2002; Buchanan and Skalski 2010; Donofrio et al. 2017) was developed using WINBUGS (Lunn et al. 2000) and Program R (R Core Team 2013). This approach estimated Lake Sturgeon apparent survival, and transition and detection (recapture) probabilities among states (areas) over a chosen time scale. For this research I divided the study area into three sections: (1) Upper river area, from Fond Du Lac Dam (RKM 0) to Oliver Bridge (RKM 9.70), (2) the SLR estuary and lower reach area, from Oliver Bridge (RKM 9.70), downstream to the Duluth and Superior Entries (RKM 29.75 and 34.80, respectively) and (3) Lake Superior (Figure 3.10). The model incorporated a monthly time interval from the time each individual fish was tagged until August 2018. I recorded the last state (area) the fish was detected in at the final day of each month to develop a detection history. When an individual was not detected in a given month but was known to be in Lake Superior, it was assumed to be alive and in Lake Superior (zone 3). This assumption was made based on the low mortality estimates from another Lake Superior population (Schloesser and Quinlan 2010; Pratt et al. 2014). It is also important to note that apparent survival and detection probability estimates in the multi-state mark-recapture model were based on the method used to obtain locations of animals. In this case the recapture estimates were analogous to the probability of having the fish detected by a receiver in any given month during the study.

The multi-state capture-recapture model employed by WINBUGS (Lunn et al. 2000) incorporates Bayesian inference. Bayesian inference uses probability theory as a way of incorporating new data with prior information to make a direct probability statement about a hypothesis (Doll and Jacquemin 2018). WINBUGS uses MCMC (Markov-chain Monte Carlo) to sample from the posterior probability distribution and return parameter estimates (Kery and Schaub 2011). This method selects a set of random numbers that represent the parameters in the model. The selected numbers are then compared to the previous set of random numbers for model fit. This process can continue for hundreds or thousands of iterations until the parameter values have converged on the posterior probability distribution.

The multi-state mark recapture model was executed using settings of 20,000 iterations with a burn-in period of 4,000 iterations. A preliminary run using 10,000 iterations with a burn-in period of 2,000 iterations showed 12 of 15 parameters converging. Increasing iterations to 20,000 with a burn-in period of 4,000 iterations achieved convergence on all parameters. For all model runs thinning was set to six and three MCMC chains were constructed. Thinning values

>1 reduce autocorrelation and decrease model runtime (Lunn et al. 2000). Informative priors were used in the survival estimate of 0.85 for each zone and no informative priors were used to construct the transition or recapture estimates. Model convergence was considered achieved when $\hat{R} \approx 1.0$ for all parameters estimated.

Evaluation of additional spawning locations

To determine spawning locations of Lake Sturgeon throughout the SLR I built and deployed multiple gangs of egg mats. Sturgeon egg mat gangs consisted of 2-3 standard concrete cinder blocks, connected with ¼ inch diameter cable and the blocks were wrapped in furnace filter (Figure 3.11). The configuration of the egg mats were similar to a previous Lake Sturgeon egg collection study (Roseman et al. 2011). Based on *a priori* information from the MNDNR and after analyzing movement data and observing fish behavior during the 2017 spawning season, I deployed 2 gangs of 3 egg mats at the Chamber's Grove habitat rehabilitation site during the 2018 spawning season. I also deployed 2 additional gangs of 2 egg mats at a site 0.5 km below the Fond Du Lac Dam, in a spot where Sturgeon were observed congregating during sampling and also contained suitable spawning substrate, for the 2018 season. In addition to these areas having suitable spawning substrate, congregations of tailing sturgeon were seen at these areas on multiple occasions in 2017 and 2018. This was done to determine if Sturgeon spawning occurs at this newly created habitat feature (Chamber's Grove) or at any other probable areas in the SLR (Figure 3.4, 3.8). Additionally, the US Environmental Protection Agency (EPA) deployed approximately 30 additional egg mats in the known spawning area below Fond Du Lac Dam as part of an ongoing study. Egg mats were set on May 5, 6, and 10 of 2018. All egg mats were checked on May 17, 2018 and were checked again and retrieved by May 25, 2018. The timing for checking egg mats was likely sufficient to ensure no eggs had been deposited and hatched during this time period based on degree days and hatch timing of Lake Sturgeon eggs (Eckes et al. 2015). All potential spawning areas were also visually observed each day for the presence of “tailing Sturgeon” (indication of spawning). Lake Sturgeon eggs were identified by methodologies described in (Auer 1982). Additionally, the Nemadji River was identified as a potential spawning area. MNDNR fisheries specialist, Dan Wilfond and I spent one day surveying the Nemadji in late April 2017 upstream of the town of Superior, WI when water temperatures coincided with the known spawning temperatures for Lake Sturgeon. We boat-electrofished approximately 2 miles of river during the day of sampling. I also used aerial maps to identify possible spawning areas on the Nemadji River near Superior, WI. After identifying possible spawning areas, I observed these areas (on-foot) during the SLR Sturgeon spawning period to look for possible spawning activity (fish tailing, groups of Sturgeon) in this river.

RESULTS

Sturgeon Capture and Tagging

A total of 721 Lake Sturgeon were captured across the three spring surveys. Two hundred-fifty-eight Lake Sturgeon were captured in 2016, 134 in 2017, and 329 in 2018. The overall sex ratio of Sturgeon captured was 468 males to 6 females to 220 unknown sex. Among all years, TL of individual fish ranged from a minimum of 814 mm to a maximum of 1683 mm. Average TL of Lake Sturgeon captured each year increased successively. Average TL was 1181 (SE ±8) mm in 2016, 1202 (SE ±13) mm in 2017 and 1224 (SE ±6) mm in 2018. Average TL of captured female Lake Sturgeon was 1486 (SE ±55) mm. Across all years, male Lake Sturgeon average length was 1217 (SE ±5) mm and average length of unknown sex Sturgeon was 1175 (SE ±9) mm.

A total of 139 Lake Sturgeon were acoustically tagged during the study. In 2016, 45 Lake Sturgeon with an average TL of 1276 mm (SE=19) were tagged. In 2017, 60 Sturgeon (avg. TL = 1246 ±SE = 17) were acoustically tagged. In 2018, 34 Sturgeon were acoustically tagged with an average length of 1241 (SE=30) mm. The TL range of individual tagged Sturgeon was 971-1658 mm (Figure 3.12). All known (gravid) females were acoustically tagged. Zero known females (gravid) were acoustically tagged in 2016, four known females were tagged in 2017, and two known females were tagged in 2018. The remaining tagged Sturgeon were male (n = 84) or unknown sex (n = 47). All acoustically tagged Sturgeon were successfully revived and swam away indicating no initial mortality caused by tagging. Only one acoustically tagged Lake Sturgeon (Tag #15162) was not detected via fixed array or mobile tracking post-surgery.

Timing of Emigration

As of September 2018, a total of 78 of 139 acoustically tagged Lake Sturgeon had emigrated into Lake Superior (across all years). Twenty-six of 45 Lake Sturgeon tagged in 2016 emigrated from the SLR into Lake Superior. Dates of emigration ranged from June 2, 2016 to May 12, 2017. The average date of emigration was August 21, 2016 and the median date was June 28, 2017. Nineteen of the emigrant Sturgeon left the SLR through the Duluth entry and 7 exited via the Superior entry. A similar pattern was observed for Lake Sturgeon tagged in the spring of 2017. From spring 2017 to September 2018, 34 of 58 Lake Sturgeon from the 2017 tagging cohort exited the SLR into Lake Superior. The average date of emigration for this cohort of fish was calculated to be September 25, 2017. The median date of emigration was calculated to August 3, 2017. Sturgeon tagged in 2017 also preferred to use the Duluth entry to emigrate into Lake Superior as 21 of 34 emigrants used through the Duluth entry. Following emigration into Lake Superior in 2017, Sturgeon were almost exclusively (23 of 24) detected moving south towards the Wisconsin waters of Lake Superior immediately after exiting the SLR. Nineteen of the 32 Sturgeon tagged in 2018 emigrated to Lake Superior by September 2018. The average date of emigration was June 27, 2018 and the median date of emigration was June 8, 2018. (Figure 3.13). At least 11 of the tagged Sturgeon used the Duluth entry to emigrate into Lake Superior. Four were documented exiting the SLR through the Superior entry, and I was unable to determine which exit was used by 3 fish as some receivers were removed for data downloading before the fish emigrated. However, the remaining receivers allowed me to approximate the exit timing to ± 1 day.

There was no statistical difference in TL between migrant and resident fish (Figure 3.13. There was also no statistical difference in date captured between migrant and resident fish. Water temperature was found to be significant in predicting emigration (t = 5.582, d.f. = 867, $P < 0.0001$). As water temperature increased from 0°C towards the observed maximum of 25.9°C, the probability of emigration increased from 0.10 to 0.25 (Figure 3.14).

A total of 6 acoustically fish assigned to a genetic stock other than Wolf River with a probability greater than 80% (see Chapter 2 for genetic methods). All six of these Lake Sturgeon assigned to the Goulais River genetic stock. Three of these fish emigrated from the SLR at the time of the study. The proportions of Goulais River Lake Sturgeon that emigrated was 50% and the proportion of Wolf River strain sturgeon that emigrated was 55%. There was not a statistical difference in the proportion of Goulais River assigned Sturgeon and Wolf River strain Sturgeon that emigrated ($\chi^2 = 3.32\text{x}10^{-32}$, $P = 1.00$).

Lake-wide movements from emigrated Sturgeon

Through collaborations with the United States Fish and Wildlife Service (USFWS) on-going acoustic telemetry study on Lake Superior Lake Sturgeon and our membership with GLATOS were able to determine additional movements of Sturgeon that emigrated from the SLR into Lake Superior. The USFWS acoustic receivers along the south shore of Lake Superior detected 41 of 78 (52.5%) of the emigrating fish. These fish were detected between Bark Point, WI, and the Portage Canal Entrance, MI (Figure 3.15). Additionally, one female Lake Sturgeon was detected at Thunder Bay and Black Bay ON, CA. This female Sturgeon traveled approximately 300 km over the course of 13 days when migrating from Duluth, MN to Thunder Bay, ON.

Timing of Immigration

As of September 2018, six acoustically tagged Lake Sturgeon that had previously emigrated into Lake Superior had returned to the SLR. Five Sturgeon tagged in 2016 returned between August 7, 2017 and August 9, 2018. The time spent in Lake Superior for these five Sturgeon ranged from 281 to 716 days. Two of the five Sturgeon that returned from the 2016 tagging cohort likely spawned in 2018. Tagged Sturgeon #21468 (1187 mm, unknown sex, Wolf River Stock) returned to the SLR on August 7, 2017 and over-wintered near the Oliver Bridge. Sturgeon #21468 then proceeded to move to the spawning grounds near the Fond Du Lac Dam during the spawning period of 2018. Sturgeon #21468 was last detected near the downstream end of Spirit Lake (Figure 3.16). Tagged Sturgeon #21472 (1173 mm, unknown sex, Unknown Genetic Stock; see criteria for genetic assignment in Chapter 2) returned to the SLR July 20, 2017 and over-wintered in the lower harbor area between the Swing Bridge and the Blatnik Bridge (RKM = 26; Figure 3.1). Sturgeon #21472 moved upstream to the Fond Du Lac Dam and was detected during the spawning period; following the spawning period Sturgeon #21472 rapidly moved downstream and exited the SLR on June 1, 2018 (Figure 3.17). One Lake Sturgeon tagged in 2017 that had emigrated to Lake Superior returned to the SLR approximately one year later on May 18, 2018 but only moved upriver as far as the Oliver Bridge area (RKM = 10.5), before returning downstream to the Blatnik Bridge area.

Movement Estimates

The highest average monthly movement during 2017 occurred in June, and for 2018 occurred in May. Tagged Lake Sturgeon in the SLR moved an average of 20.20 linear km (SE = 2.14) during the month of June 2017. Average linear movement in May of 2018 was 15.96 km (SE = 1.57). The lowest average monthly movement occurred in March 2018 with an average of 2.70 linear kilometers (SE = 0.98; Figure 3.19).

Daily linear movements were significantly correlated with discharge ($\rho = 0.61$, $P < 0.05$). There was also a moderate, but statistically significant correlation ($\rho = 0.41$, $P < 0.05$) between water temperature and daily linear movements (Figures 3.20, 3.21). Movement at the weekly scale followed the same trends as the daily estimates with significant correlations with discharge ($\rho = 0.63$, $P < 0.05$) and water temperature ($\rho = 0.54$, $P < 0.05$).

Multi-State Capture-Recapture Model

The monthly multi-state capture-recapture model converged with 20,000 iterations, a burn-in period of 4,000 iterations and a thinning setting of 6. All $\hat{R}$ values for parameters were below 1.002 indicating model convergence (Figure 3.21). The values reported were based on the probability of an action occurring on any given month within the study time frame of April 2016 to September 2018. The transition probability of a Lake Sturgeon in zone 1 remaining in zone 1 was 0.599 (SD ± 0.031). The probability of a fish moving from zone 1 to zone 2 was 0.31 (SD ±0.03), and the probability of zone 1 fish moving to zone 3 was 0.091 (SD ± .018). The probability of a Lake Sturgeon in zone 2 remaining in zone 2 was 0.931 (SD ± 0.008), the probability of a Sturgeon in zone 2 moving upstream to zone 1 was 0.017 (SD ± 0.004), and the probability of Sturgeon in zone 2 emigrating to zone 3 was 0.052 (SD ± 0.007). Finally, the probability of a Lake Sturgeon in zone 3 remaining in zone 3 was 0.989 (SD ± 0.004), while the probability of a Sturgeon in zone 3 transitioning upstream to zone 1 was 0.000 (SD ± 0.000), and the transition of a Sturgeon in zone 3 moving into zone 2 was 0.011 (SD ± 0.004; Figure 3.22).

Apparent monthly survival in zone 1 was 0.988 (SD ± 0.007). Apparent survival in zone 2 was estimated to be 0.989 (SD ± .002) and apparent survival in zone 3 was 0.999 (SD ± 0.001). The probability of detection (recapture) for a Lake Sturgeon in zone 1 was 0.992 (SD ± .008). The probability of detecting a tagged Lake Sturgeon in zone 2 was 0.997 (SD ± 0.002) and the probability of detection in zone 3 was 0.999 (SD ± 0.001).

Habitat Use Approximation

Acoustically tagged Lake Sturgeon were detected throughout the SLR and estuary. Several “high detection” areas existed. Throughout the Summer, Autumn, and Winter seasons during both years, the highest concentrations of Lake Sturgeon were found in three areas: near the Spirit Island/Clough Island/Munger landing area, near the Oliver Bridge area, and near Boy Scout Landing (Figures 3.23-3.27). These areas were similar in that deeper channelized habitat was available, as well as being in close proximity to large flats (areas of uniform depth; Figure 3.2). Over-wintering habitat appeared to include the Blatnik Bridge area, Swing Bridge area, Munger Landing, Oliver Bridge, and Boy Scout Landing. These areas were pinch points in the

SLR and had deeper water habitat available, as well as access to large flats. These areas appeared to be the most complex bathymetric habitat in the SLR. During the Spring Lake Sturgeon were less concentrated and were dispersed throughout the SLR (Figure 3.26).

Identification of Additional Spawning Areas

Zero Lake Sturgeon eggs were collected via egg mats placed in the two possible additional Sturgeon spawning locations. Additionally, no Lake Sturgeon eggs were collected on 30 egg mats placed immediately below the Fond Du Lac Dam by the EPA. Eggs from several other species including White Sucker *Catostomus commersonii* and Walleye *Sander vitreus* were collected on the egg mats suggesting the mats fished effectively. Several Lake Sturgeon were observed "tailing" in the areas near the downstream egg mats, however no active spawning behavior was observed. The Nemadji River showed no signs of Lake Sturgeon spawning activity during the SLR Sturgeon spawning period in 2018. The electrofishing survey conducted on the Nemadji River in 2017 yielded zero Lake Sturgeon. Additionally, when I observed the Nemadji River on two occasions in May 2018 there only appeared to be a very limited section with potentially suitable spawning habitat. Most of the Nemadji River was likely unsuitable for Lake Sturgeon spawning due to excessive sedimentation and highly seasonal flows. The only spawning observed in the SLR was immediately below the Fond Du Lac Dam.

DISCUSSION

The SLR Lake Sturgeon population appears to be an open population with nearly half of the population using Lake Superior at some time during the study. The identification of both a migratory and resident component in a Lake Sturgeon population has also been documented in several other adult Lake Sturgeon studies (Rusak and Mosindy 1997; Borkholder et al. 2002b;

Kessel et al. 2017). The presence of variability in life history strategies is likely a key to the persistence of Lake Sturgeon over millions of years (Kessel et al. 2017). For example, in another Great Lakes Sturgeon population Kessel et al. (2017) tracked acoustically tagged Lake Sturgeon for 6 years in the Huron-Erie Corridor. During this study, five divergent migration histories were observed with several “clades” present within those migration histories. Kessel et al. (2017) also found that individual Lake Sturgeon repeated their migration history over time. Hence, it is likely that the SLR Lake Sturgeon exhibit different life history strategies to aid the population in persistence by possibly protecting the population against disease, habitat disturbances, extreme abiotic conditions or other perturbations in the SLR and Lake Superior (Watters et al. 2003; Fox 2005).

A fundamental tenant of life-history theory is that trade-offs must occur between somatic growth and reproduction (Charnov et al. 2001; Barneche et al. 2018). This is especially true for fishes because they have indeterminant growth and fecundity is generally positively related to body size. Hence, body size is often significantly related to life history strategy (Blueweiss et al. 1978; Winemiller 1989). However, in the SLR spawning population, Lake Sturgeon body size was not related to whether or not a fish emigrated into Lake Superior. The lack of a body size influence on life history strategy suggests that there may not be an increase in forage availability or quality for Lake Sturgeon who emigrate relative to Sturgeon who remain in the SLR. These findings were similar to Kessel et al. (2017) who found that total length did not differ among various life history strategies of Sturgeon in the Huron-Erie Corridor. However, the lack of difference in size of Lake Sturgeon between life history strategies in the SLR may change over time as much of this Sturgeon population (especially females) are just becoming sexually mature (Auer 1996).

Genetic factors can also determine life history traits in populations. For example, Salmonids exhibit population-specific growth and maturation schedules (Ricker 1981). Genetics can also control the onset of sexual maturation (Kallman 1983). However, genetic origin did not appear to be a factor in determining whether an individual Lake Sturgeon migrated to Lake Superior or exhibited residency within the SLR, nor was it related to the timing of emigration. However, most Lake Sturgeon collected in this study were from one genetic stock (Wolf River) with low numbers of fish from other Lake Superior and Lake Huron stocks which may have limited my inference. Natural variation in life history strategies of individuals within a population has been documented for other fishes like Bluegill *Lepomis macrochirus* (Gross and Charanov 1980; Aday et al. 2003; Spotte 2007) suggesting life history strategies may also be more related to an individual's genotype than at the population level. Alternatively, my ability to differentiate life histories genetically may have been limited by the power of the microsatellite markers used in this study. Increasing resolution by using single nucleotide polymorphisms (SNPs) in the future may be useful in explaining the variation in life histories. For example, Larson et al. (2017) found ecotypic variation explained by using SNPs from Sockeye Salmon *Oncorhynchus nerka* in one small drainage in southwestern Alaska.

Environmental factors (both biotic and abiotic) have also been shown to influence life history strategy. In an open system, as a fish population increases and resources become limited it is more likely that a subset of the population will become migratory or exhibit an alternative life history strategy. For example, Parker et al. (2001) studied Arctic Charr *Salvelinus alpinus* and found that the proportion of individuals exhibiting a certain life history strategy was dependent on environmental variables associated with juvenile growth rates. Variation in factors such as population density which changes the availability of resources, during one or many life stages may determine the life history strategy that is adopted by an individual (Hazlerigg et al. 2012). Additionally, Johnston and Post (2009) found that an overexploited population of Bull Trout *Salvelinus confluentus* in Northern Canada exhibited differential life history strategies as population density increased following the implementation of catch-and-release only fishing regulations. Additionally, Sloss et al. (2008) suggested that the Coaster (lake-run) Brook Trout *Salvelinus fontinalis* life history form of in Lake Superior may be a mechanism of population density and intraspecific competition.

Abiotic factors such as temperature and discharge are often related to the timing of immigration and emigration events in fishes (Quinn and Adams 1996; Sykes et al. 2009), and specifically in Lake Sturgeon (Rusak and Mosindy 1997; McKinley et al. 1998; Borkholder et al. 2002b). In the SLR, Lake Sturgeon movements were moderately related to temperature and discharge. During summer, the SLR often reaches temperatures near the anecdotal thermal limit of Lake Sturgeon (26° C; Wehrly 1995). When temperatures in the SLR increased to near the thermal limits of Lake Sturgeon, Sturgeon movements were greatly reduced. Conversely, the probability of emigration was shown to increase with increasing temperature suggesting Lake Superior may serve as thermal refuge for SLR Sturgeon. Similarly, Steelhead have been shown to utilize thermal refuge during their migrations when main-stem river conditions become unfavorable (Hess et al. 2016). Hence as climates continue to warm, Lake Superior may become an increasingly important thermal refugia for SLR Lake Sturgeon during the summer months. Therefore, I believe that the combination of summer water temperatures, combined with an increasing abundance of Lake Sturgeon in the SLR, and individual variability in life history have contributed to the timing and extent of Lake Sturgeon emigration into Lake Superior.

Immigrations of Lake Sturgeon from Lake Superior back into the SLR were expected to be limited over the duration of this study given the expected spawning periodicity of Sturgeon and the relatively short time that tags have been deployed (Lyons and James Kempinger 1992; Bruch and Binkowski 2002). Lyons and Kempinger (1992) found that a significant portion of the spawning migration of Lake Sturgeon in the Lake Winnebago system (Wolf River strain) occurred in the autumn prior to spawning the following spring. The timing of immigration shown by Lyons and Kempinger (1992) was consistent with this work as 3 of the 5 Sturgeon that emigrated into Lake Superior returned to the SLR in the autumn. These results suggest spawning periodicity for male Lake Sturgeon in the SLR is approximately 1-3 years and is similar to what has been reported in other systems (Lyons and Kempinger 1993; Auer 1999). Zero tagged females have returned to the spawning area yet, however that is not unexpected given that the published spawning periodicity of female Lake Sturgeon is 3 to 7 years and beyond the duration of our study period. I suspect that the spawning periodicity of females may be on the upper range of known values, likely due to the oligotrophic characteristics of Lake Superior. Alternatively, it may be possible that Lake Sturgeon that are SLR residents may spawn more frequently than migratory Sturgeon because of the possible increased productivity of the SLR relative to Lake Superior, mainly due to higher average water temperatures and higher productivity. Residing in the SLR where productivity is likely higher would be a possible fitness advantage because of the increased number of spawning opportunities over a lifetime. Then again, it is also possible that SLR Lake Sturgeon may spawn more often since the population is newly founded and is likely not operating near carrying capacity where density dependent growth or competition for resources may take place.

Interestingly, it is also possible that not all Lake Sturgeon sampled on or near the spawning grounds in the SLR were there to spawn. Instead it is possible that some Lake Sturgeon may move upriver during the spawning period to feed on fish eggs. Several other fish species such as Walleye and several catostomids spawn near the same time as Lake Sturgeon in the SLR. Hence, spring may be an important feeding period for both non-spawning and spawning Lake Sturgeon in the SLR, especially given the oligotrophic qualities of Lake Superior (Matheson and Munawar 1978). Ecclestone (2012) observed that Lake Sturgeon entering the Pic River (Lake Superior tributary) did not always enter the river to spawn and may possibly arrive early to partake in an increased forage opportunity in the spring. This possible foraging behavior may also help to explain the large number of “unknown” sex fish that were not excreting gametes during sampling.

The multi-state mark recapture model provided a statistical framework for predicting the probability of movement between the upper river, the middle to lower river and estuary, and Lake Superior. The transition probability from Lake Superior back into the SLR was low, likely due to the truncated timeline of our study (< 3 years) coupled with the spawning periodicity of Lake Sturgeon (Lyons and James Kempinger 1992; Bruch and Binkowski 2002). The transition from the upper river to middle river/estuary showed that the populations tended to move out of the upper river following the spawning period. This was expected because I tagged fish during the spawning season while fish were upriver, and it would be expected that fish would disperse after spawning. When a Lake Sturgeon reached the middle river/estuary zone it tended to stay there suggesting this was a preferred habitat within the river. This area has a variety of habitats (e.g., channel, deeper water and shallow flats) but is also relatively larger (spatially) than the upper river area. Apparent survival estimates from the multi-state model may be biased high, due to the fact that I was not able to track Sturgeon in Lake Superior with the same resolution as Sturgeon in the SLR. Therefore, we assumed that a Sturgeon that emigrated into Lake Superior was alive even when it was not detected by a receiver. However, given that fish were implanted with tags with an approximately 10-year battery life, and plans to maintain a portion of the acoustic array, researchers will be able to estimate return rates (transition probabilities), and spawning periodicity in the future. Hence, continuing to add data to the multi-state capture-recapture model will likely correct what appeared to be a likely artificial population sink in Lake Superior.

The highly skewed, male-dominated sex ratio I documented within the SLR Lake Sturgeon population could be explained in several ways. First, several other Lake Sturgeon populations have been shown to have a male to female ratio of close to 4:1 and up to 10:1 males to females (Bruch and Binkowski 2002; Lallaman et al. 2008; Schloesser and Quinlan 2010). It is not uncommon to have a skewed sex ratio when sampling Lake Sturgeon during the spawning period due to a younger age at maturation of males than females and differences in spawning periodicity coupled with the polygamous life history of male Sturgeon (Peterson et al. 2007). However, the relatively high skewness of the SLR population towards males was most likely due to age at maturation of female Sturgeon. Most fish collected in the SLR were of Wolf River descent, hence they were almost surely stocked fish from the rehabilitation efforts (Schram et al. 1999). The oldest Lake Sturgeon stocked into the SLR, at the time of this study, would have been 35 years old with some stocked fish being < 20 years old. In the Bad River, WI, the youngest gravid female sampled during the spawn was estimated to be 25 years old (Joshua Schloesser, USFWS, Ashland, WI, Unpublished Data). Age estimates of the Bad River Sturgeon were calculated from pectoral fin rays, which often leads to underestimation of age in older fish

(Rossiter et al. 1995). Therefore, it is probable that female Lake Sturgeon spawning in the Bad River were even older than estimated. The earliest known age at maturation for female Lake Sturgeon is 14 years old, however the majority mature between 24-26 years old (USFWS 2014.) suggesting that female Sturgeon from many of the year classes stocked into the SLR were likely not yet mature. Hence the sex ratio may become less skewed in subsequent years. Finally, there were also 220 unknown sex fish captured during the study. While it is possible some of the unknown sex fish may have been female, it was unlikely based on fish size when compared to known females in the SLR population and in other Great Lakes basin populations (Auer 1996; Smith and Baker 2005; Schloesser and Quinlan 2010).

In general, Lake Sturgeon in the SLR appeared to prefer relatively complex habitats that include a deeper channel adjacent to large shallow areas. These areas were generally located near “pinch points” or narrowing portions of the river channel and estuary where there was likely more concentrated flow. This result was similar to other studies where Lake Sturgeon were documented to prefer the deeper areas of rivers. For example, Eccelstone (2012) found that Lake Sturgeon in the Pic River preferred areas with steep banks and depths of greater than 6 meters. Rusak and Mosindy (1997) found that Lake Sturgeon in the Rainy River also preferred depths greater than 6 meters. Both studies hypothesized that preference towards depth was related to foraging preference. I suspect this was also true in the SLR, however this finding in the SLR may also be an artifact of receivers being placed near these pinch-points.

Overwintering habitat may also be very important as all acoustically tagged Lake Sturgeon that have returned from Lake Superior did not move to the spawning grounds after returning. Instead, these Sturgeon will likely overwinter and spawn the following spring, staging for nearly a year pre-spawn. Based on interpolations, overwintering habitat appears to be centered in deeper areas with some flow including the area underneath the Blatnik Bridge, as well as the mouth of and into Allouez Bay. Similar to habitat use during other seasons, these areas also represent narrowing of the channel with adjacent large flats. Conversely, the lower estuary and harbor, especially near Duluth, MN, has been extensively dredged for commercial shipping traffic and may not be preferred by Lake Sturgeon as the habitat is likely homogenized in these areas.

The interpolation of habitat use by Lake Sturgeon via fixed-receiver acoustic telemetry (heatmaps) represents a starting point in assessing Sturgeon habitat use in the SLR. A fine scale study such as a radio-telemetry study or use of depth recording acoustic tags, coupled with physical habitat quantification will be needed to further characterize habitat use. Furthermore, I caution the use of these maps in management decisions or planned restoration actions. These maps serve as a course approximation of the seasonal locations of Lake Sturgeon in the SLR. The constantly variable detection range of fixed receivers, our inability to constantly perform range testing on each receiver, along with irregular spacing likely contributed to several unrealistic interpolations within the maps.

Approximately 30% of all acoustically tagged Lake Sturgeon emigrated and were detected along the south shore of Lake Superior from Bark Point, WI, to the Portage Canal Entrance. The use of the south shore of Lake Superior by SLR Sturgeon had been documented prior to this study using both tag returns (Schram 2007) and genetic methodologies (Schram 2007; Welsh et al. 2017). Nevertheless, the fact that 30% of the SLR population uses these areas, coupled with result from other on-going Lake Sturgeon telemetry studies along the south shore of Lake Superior (Joshua Schloesser USFWS, Ashland, WI, unpublished data; Joshua Schloesser USFWS, Ashland, WI, unpublished data), should aid in future Sturgeon management (e.g., habitat conservation) in this area. Recent work by Welsh et al. (2017) in Lake St. Clair identified areas (conservation hotspots), by use of genetic criterion, where Lake Sturgeon from several stocks congregated outside of the spawning period. Welsh et al. (2017) suggested that conservation efforts in these areas may benefit several stocks simultaneously in a greater temporal fashion than focusing efforts on local spawning habitat because of the protracted spawning periodicity of Lake Sturgeon. The south shore of Lake Superior from Superior, WI to Ashland, WI, including Chequamegon Bay may fit the criteria of a conservation hotspot as Lake Sturgeon from the SLR, Bad River, and possibly other tributaries use this area outside of the spawning season (Joshua Schloesser USFWS, Ashland, WI, unpublished data). Hence conservation actions in this area may benefit several distinct stocks of Sturgeon simultaneously both temporally and spatially more than stock specific conservation actions.

Currently, spawning habitat does not appear to be limited in the SLR. While no eggs were collected by egg mats in 2018, larval Sturgeon were collected during annual driftnet surveys by the 1854 Treaty Authority suggesting fish were spawning in areas near the dam that were not sampled in this study due to treacherous boating and wading conditions. During spring sampling, I visually observed Lake Sturgeon spawning activity near the dam and what appeared to be several additional areas of suitable spawning habitat below the Fond Du Lac Dam. I believe that these areas would likely be used if the density of spawning Lake Sturgeon, especially females, increases in the SLR in the future. Additionally, I observed rapid declines in discharge following peak spawning events. It is possible that these rapid declines in discharge may be leaving eggs exposed to air before hatching.

Summary

Prior to this study the movements of Lake Sturgeon in the SLR were relatively unknown and the lack of information challenged the management of this recovering species. My results showed that there was both a migratory and resident component to the population with over half of the Sturgeon tagged during the study using Lake Superior. The fact that Lake Sturgeon from the SLR frequently use the Wisconsin waters of Lake Superior is also a critically important information in guiding the management of this stock, and Lake Sturgeon throughout Lake Superior and the Great Lakes basin. These results also add to the body of knowledge of movement ecology for Lake Sturgeon. More specifically, adding to the understanding of how re-introduced or recovering Lake Sturgeon populations may interact with their environment throughout the Great Lakes Region.

Management Implications

My results indicate that SLR Lake Sturgeon emigrate into Lake Superior and are often detected outside of the SLR in Wisconsin waters of Lake Superior. These movements may be cause for concern as harvest regulations differ between the SLR and the Wisconsin waters of Lake Superior. The current harvest regulation for Lake Sturgeon in the Wisconsin waters of Lake Superior is one fish per year > 50 inches. Any harvest of a recovering population is undesirable, and for Lake Sturgeon it is extremely undesirable because of their protracted life history and spawning periodicity. Annual harvest in the Wisconsin waters of Lake Superior has been variable since 1988 but is currently increasing with an all-time high of 16 Sturgeon harvested in 2016. This increased harvest could be cause for concern as the SLR population has likely still not reached the management goals set for by the Lake Sturgeon Subcommittee (Auer 2003). In 2020, a harvest regulation of one fish per year > 60 inches will likely be implemented for this area.

This regulation could be viewed as a positive as it may allow female Lake Sturgeon the opportunity to spawn once before reaching the minimum length limit, as opposed to the 50-inch minimum length regulation. However, the average size of sexually mature females captured in the SLR during this research was 1486 mm (58.5 inches). If a majority of female Sturgeon from the SLR do not become sexually mature until after they exceed 60”, then the new regulation could have detrimental effects as a majority of harvest would target females, some of which may not have had the opportunity to spawn. A potential way to determine the effects of the harvest regulations on the SLR Lake Sturgeon population would be to include genetic assessment of harvested Sturgeon collected during the mandatory registration. This would allow managers to determine the genetic origin of harvested individuals. These data could then be incorporated into estimates of fishing mortality of the SLR population. Recruitment for the SLR Lake Sturgeon population does not appear to be limited by numbers of males but is likely currently limited by low numbers of females, as evidenced by the skewed sex ratio documented during this study. While the number of sampled females will likely increase in subsequent years due to females reaching larger sizes and becoming sexual maturity, any harvest of these fish would be undesirable and counter-productive towards the recovery of the SLR Sturgeon population. Additionally, managers should focus on conserving and increasing deep, complex habitat within the SLR as it appears resident Sturgeon prefer these areas. Spawning habitat for Lake Sturgeon in the SLR does not appear to be limited at this time, however habitat use should continue to be monitored to better understand spawning habitat selection and make future plans for conservation and rehabilitation of spawning areas.

Future Research

Future research on SLR Lake Sturgeon movements and habitat use should foremost consist of continued operation and maintenance of an acoustic array complex enough to continue to examine the spawning periodicity of tagged fish for at least the next 10 years (through 2028). A juvenile Lake Sturgeon telemetry study may also benefit Lake Sturgeon management in the SLR. A combination acoustic and radio telemetry study would inform managers of both coarse and fine scale movements, allow for quantification of juvenile habitat use and allow for estimation of juvenile growth and survival rates. However, capturing juvenile Lake Sturgeon can be challenging (Snobl et al. 2017). Exploitation estimates for the SLR Lake Sturgeon population from the Wisconsin waters of Lake Superior should also be conducted to understand the possible effects of harvest on this recovering population. Exploitation could be estimated using both genetic and PIT-tag returns of harvested fish when anglers register them in with the WDNR. A diet study on Lake Sturgeon in the SLR should also be conducted to evaluate if the SLR Lake Sturgeon prefer prey that may be limited in the system and to determine if non-spawning Sturgeon sampled on the spawning grounds are using the area for foraging. Additionally, the effects of rapid declines in discharge on hatching success of Lake Sturgeon eggs in the SLR should be evaluated to help prevent reductions in natural recruitment. On a lake-wide level, an effort should be made to identify and protect areas where Lake Sturgeon congregate like Chequamegon Bay and the south shore of Lake Superior. This would aid in facilitating the recovery of Lake Sturgeon on a larger scale and possibly likely benefit more than one population simultaneously (Welsh et al. 2017).

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Table 2-1. Numbers of Lake Sturgeon stocked in the St. Louis River by Minnesota Department of Natural Resources (MNDNR) and Wisconsin Department of Natural Resources (WDNR) from 1983 to 2000. Lake Sturgeon stocked from 1983-1994 were sourced from the Wolf River (Wolf R). Sturgeon stocked from 1998-2000 were sourced from the Sturgeon River (Sturgeon R), MI (Lake Superior strain). All fingerlings stocked by MNDNR received a coded wire tag in the snout cartilage. (Schram et al. 1999; Lindgren et al. 2016).

	MNDNR			WDNR			Total	
Year	Fry	Fingerling[a]	Strain	Fry	Fingerling[b]	Strain	Fry	Fingerling
1983			Wolf R	102,000	2,700	Wolf R	102,000	2,700
1984			Wolf R	162,000	18,000	Wolf R	162,000	18,000
1985		4900	Wolf R	59,000	2,700	Wolf R	59,000	7,700
1986		400[c]	Wolf R			Wolf R		400
1987			Wolf R			Wolf R		
1988		18,200	Wolf R		6,000	Wolf R		24,300
1989		7,200	Wolf R	50,000	100[c]	Wolf R	50,000	7,300
1990		10,300	Wolf R	25,000		Wolf R	25,000	10,300
1991		5,500	Wolf R	96,000	4,500	Wolf R	96,000	10,000
1992	83,000		Wolf R		13,500	Wolf R	83,000	13,500
1993			Wolf R	7,000	19,300	Wolf R	7,000	19,300
1994			Wolf R	151,000	14,500	Wolf R	151,000	14,500
1998		6,800	Sturgeon R			Sturgeon R		6,800
1999	46,000		Sturgeon R			Sturgeon R	46,600	
2000		7,980	Sturgeon R			Sturgeon R		7,980
Total	129,000	60,880		652,000	81,300		781,000	142,180

[a] Fall fingerlings (127-203 mm)

[b] Late-summer fingerlings (102-152 mm)

[c] Yearlings stocked in October

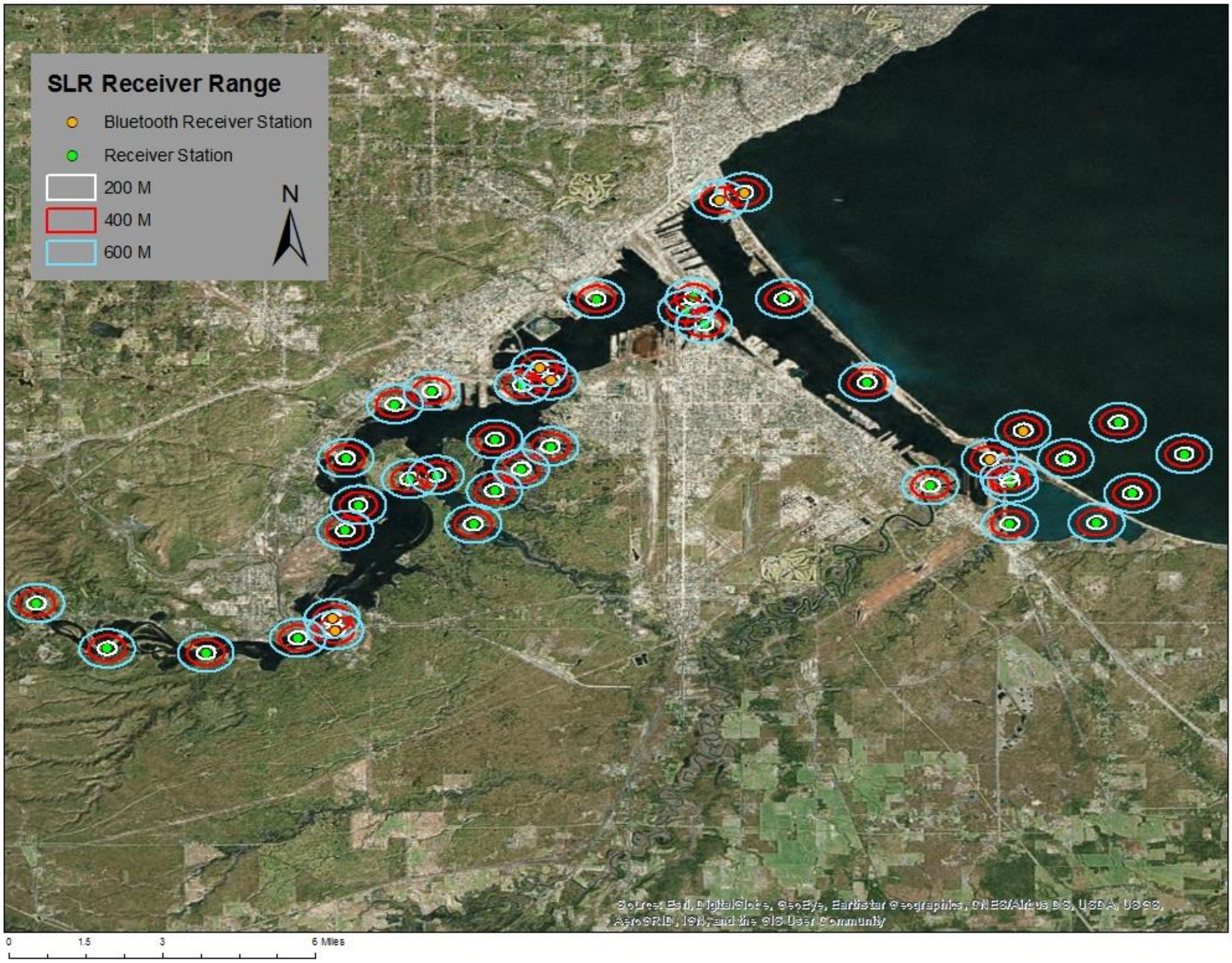

Figure 3.1. Map of hydroacoustic receivers [(VR2W; green dots) and bluetooth-enabled receivers (VRTX; orange dots)] placed in the St. Louis River and Western Lake Superior near Duluth, MN and Superior, WI. Circles around the receivers indicate buffers to illustrate detection radius.

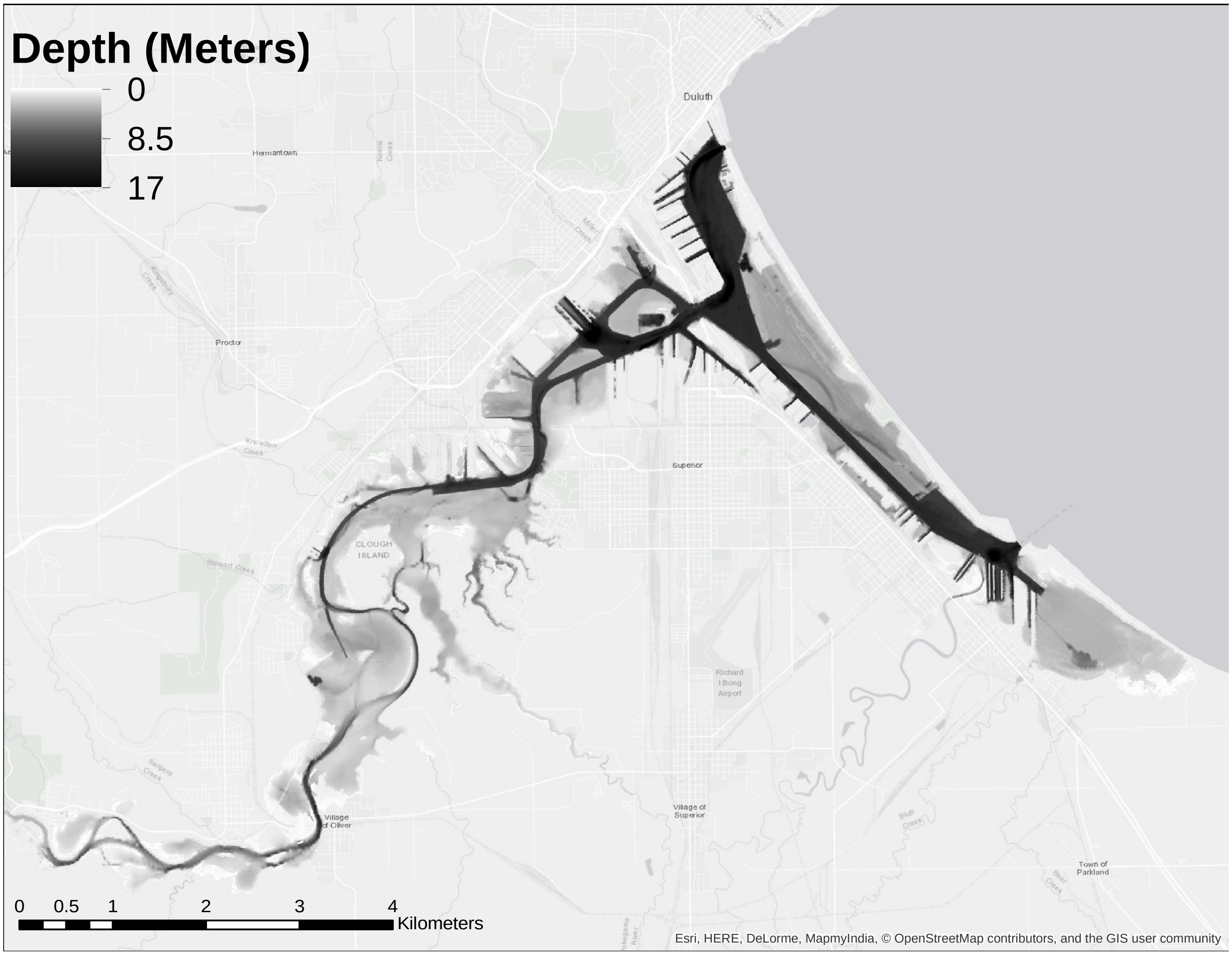

Figure 3.2 Bathymetric map of St. Louis River in study area from Fond Du Lac Dam to Lake Superior. Depth (gray scale) shown in meters. Depth ranges from 0 to 17 meters.

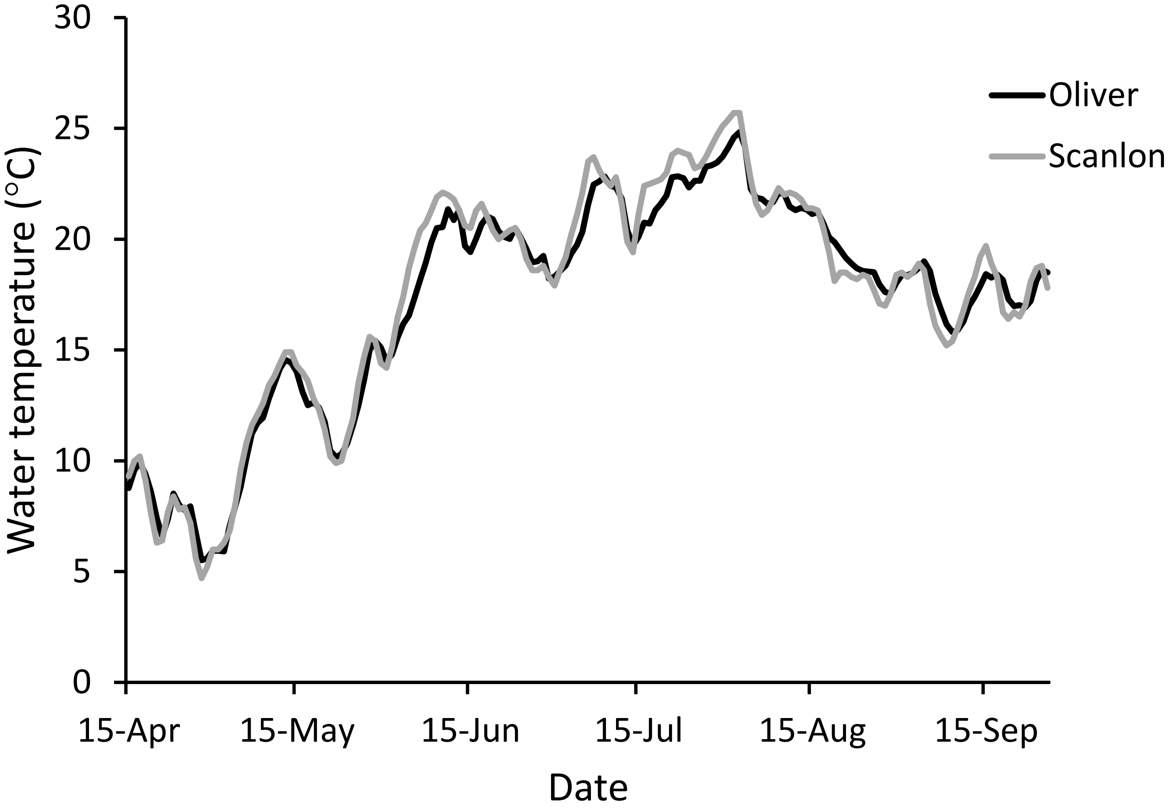

Figure 3.3 Water temperatures from April 15, 2007 to September 25, 2007 from USGS Station 04024000 on the St. Louis River at Scanlon, MN (gray line), and temperature data from HOBO temp logger at Oliver Bridge acoustic receiver set

Figure 3.4. Ariel imagery depicting Chambers Grove habitat rehabilitation site on the St. Louis River near the Highway 23 bridge (bridge in photo). White circles represent areas of wing dam construction.

Figure 3.5. Anchor stand for placement of Vemco© VR2W acoustic receivers in the SLR and Western Lake Superior. A section of one-quarter inch steel cable, of a length equal to or slightly longer than the depth measurement at which the receiver will be placed, is connected between the anchor stand (near in photograph) and the small anchor (distant in photograph). An acoustic receiver is then mounted to the anchor stand vertically using hose clamps and duct tape.

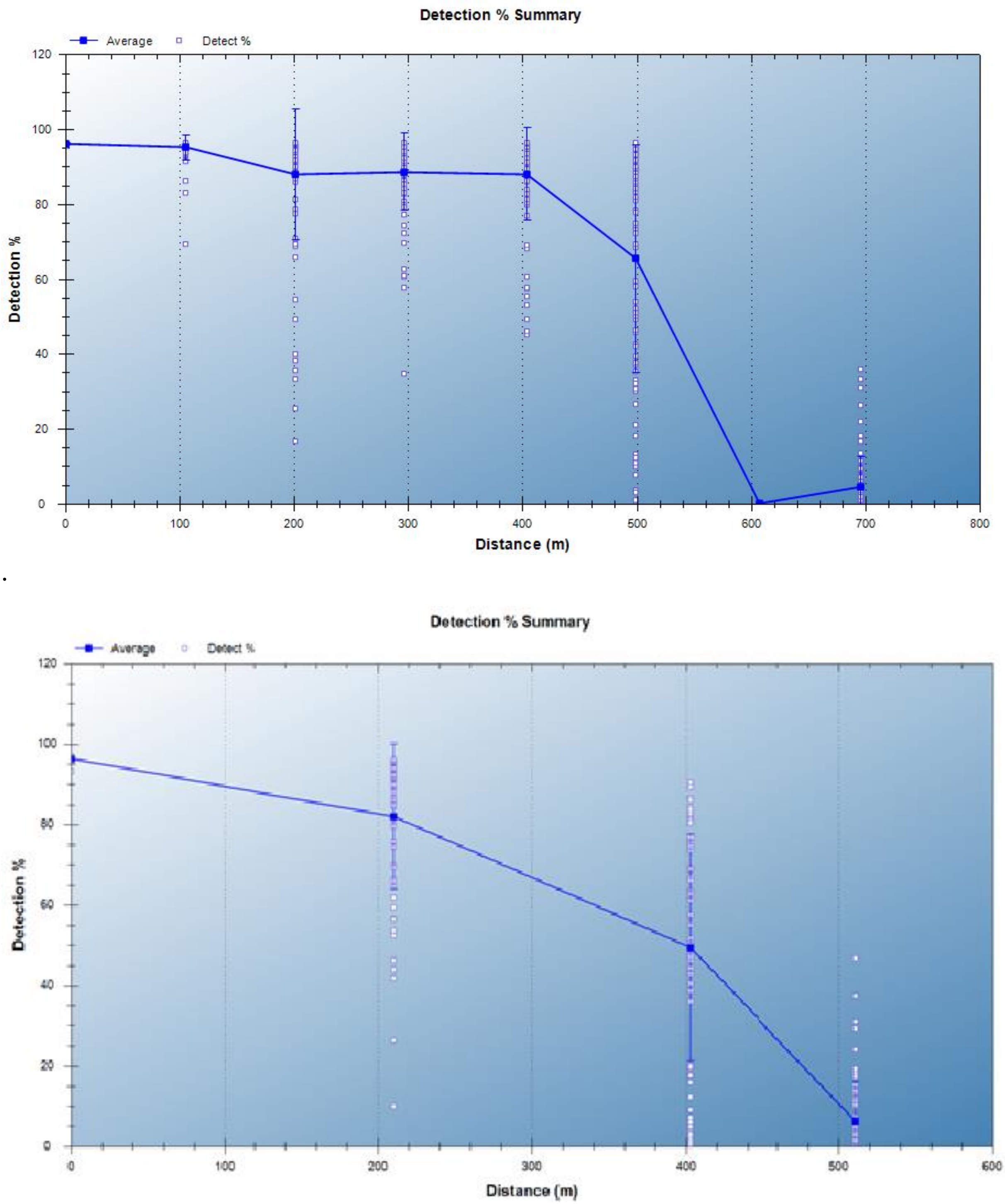

Figure 3.6 A and B. Range testing summary from 5 shallow set (A) and 5 deep set (B) acoustic receivers in the upper SLR near Chamber's Grove (A) and in the shipping channel near the Blatnik Bridge (B) in the lower SLR Estuary. For the shallow set receivers detection percentage stays above 90% until the tag is nearly 400m away from the receiver. For the deep-set receivers detection percentage stays above 50% until the tag is greater than 400m from the receiver (Patrick Schmalz, Minnesota DNR, unpublished data).

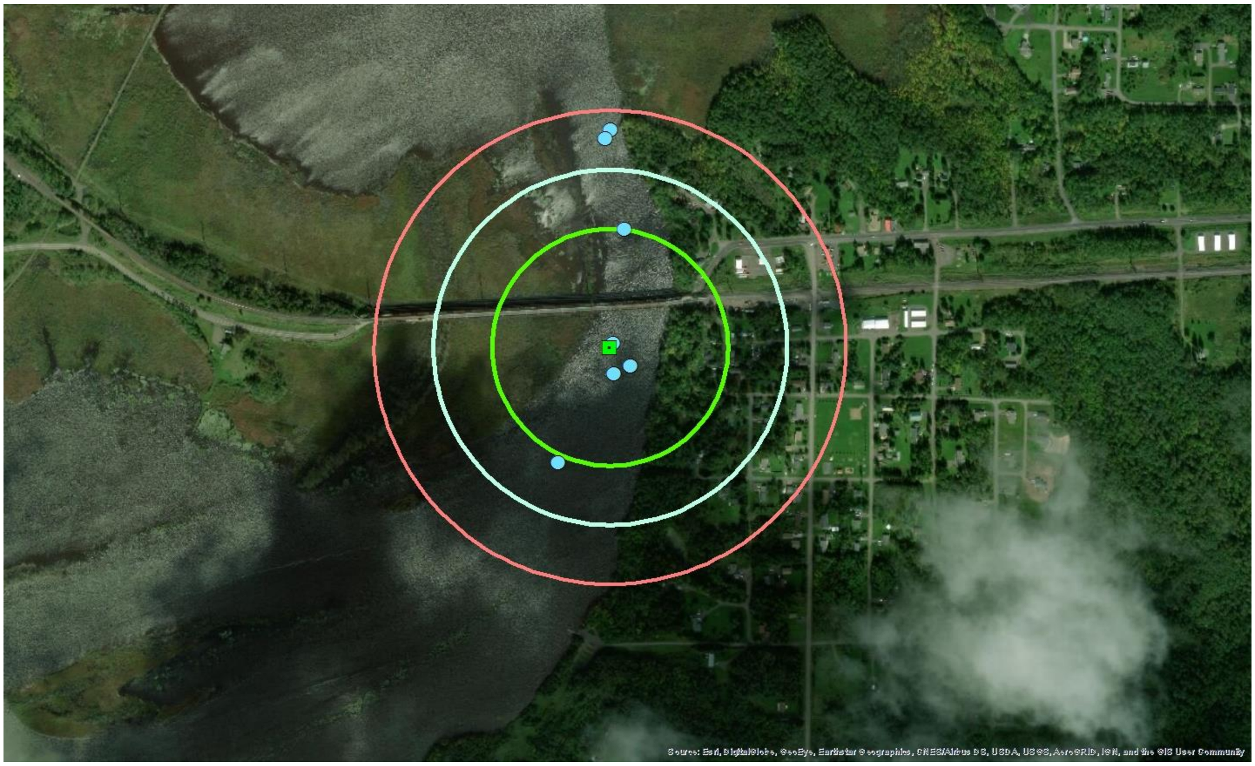

Figure 3.7. Example of mobile tracking range testing. VRTX receiver (green square) and detection points (blue circles). Green buffer is equal to 200 meters from VRTX receiver, White buffer is equal to 300 meters from receiver. Red buffer is equal to 400 meters from receiver. Sentinel tag in VRTX receiver was detected beyond 350 meters using omnidirectional hydrophone and VR-100 mobile receiver.

Figure 3.8. Arial photograph of Lake Sturgeon sampling area in the St. Louis River from Fond Du Lac Dam to Highway 23 bridge. Backpack electrofishing and netting area is shown in the circle and boat electrofishing area is delineated with yellow line and corresponding labels (Piszczek et al. 2016).

Figure 3.9. Vemco©V-16 Transmitter with a battery life of approximatley 10 years and a nominal delay of 120 seconds ± 50%. Transmitters were surgically implanted into the body cavity of Lake Sturgeon.

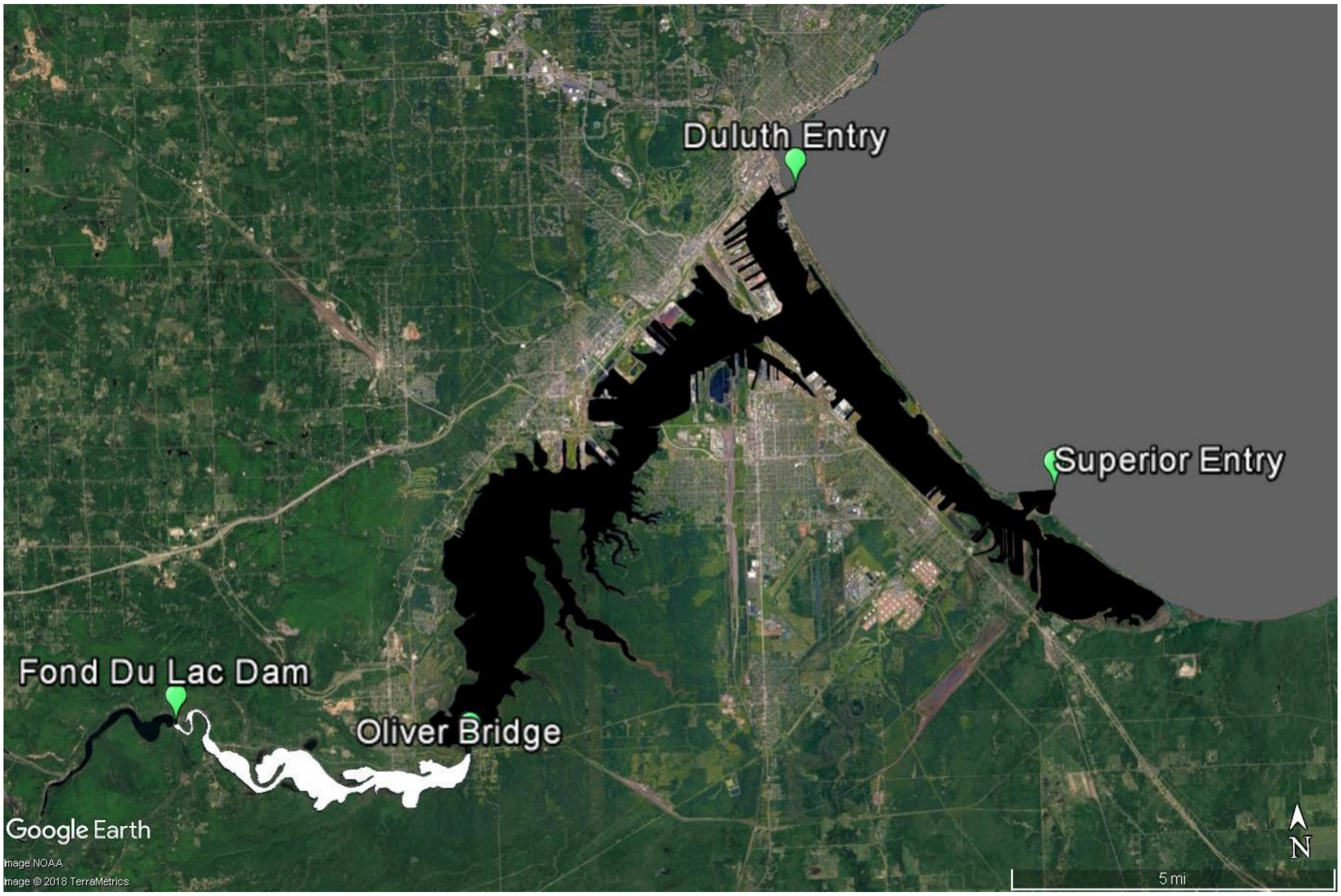

Figure 3.10. Multi-state mark recapture (areas) for SLR Lake Sturgeon multi-state mark-recapture model. Upriver area (white) depicts state from Fond Du Lac Dam (RKM 0) downstream to Oliver Bridge (RKM 9.70). SLR estuary (black) extends from Oliver Bridge (RKM 9.70) downstream to Duluth and Superior entries (RKM 29.75 and 34.80 respectively). The third state is Lake Superior (gray).

Figure 3.11. Egg mats for capturing Lake Sturgeon eggs. Egg mats consist of a cinder block wrapped with furnace filter and secured with bungee cords. Egg mats were cabled together in gangs of 2 or 3 depending on area placed.

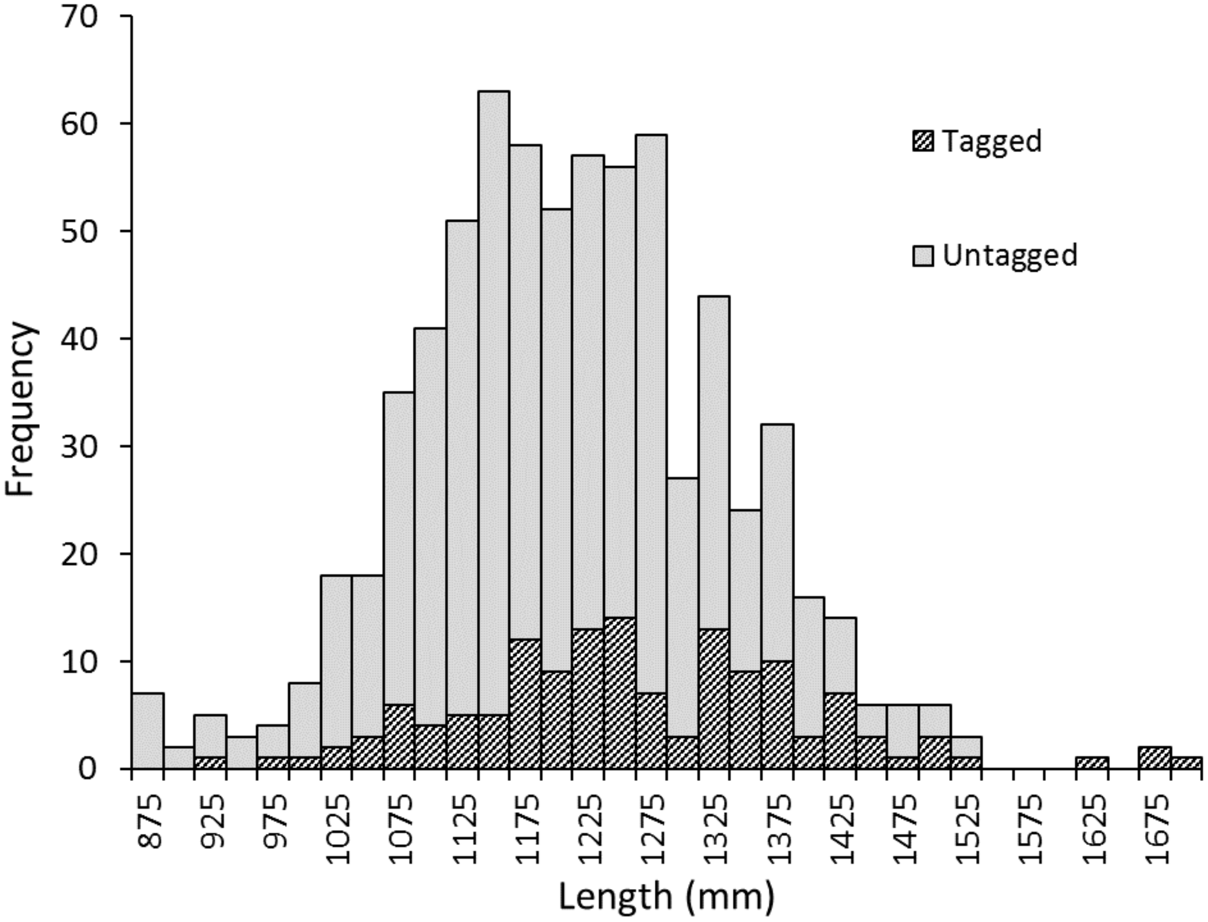

Figure 3.12. Length frequency histogram of captured Lake Sturgeon in the SLR (N=694). Groups are divided into 25 mm length bins from 875-1700 mm. Solid gray bars represent length frequencies of untagged Lake Sturgeon (n=555). Diagonal patterned bars represent length frequencies of Lake Sturgeon tagged in 2016, 2017, and 2018 (n=139).

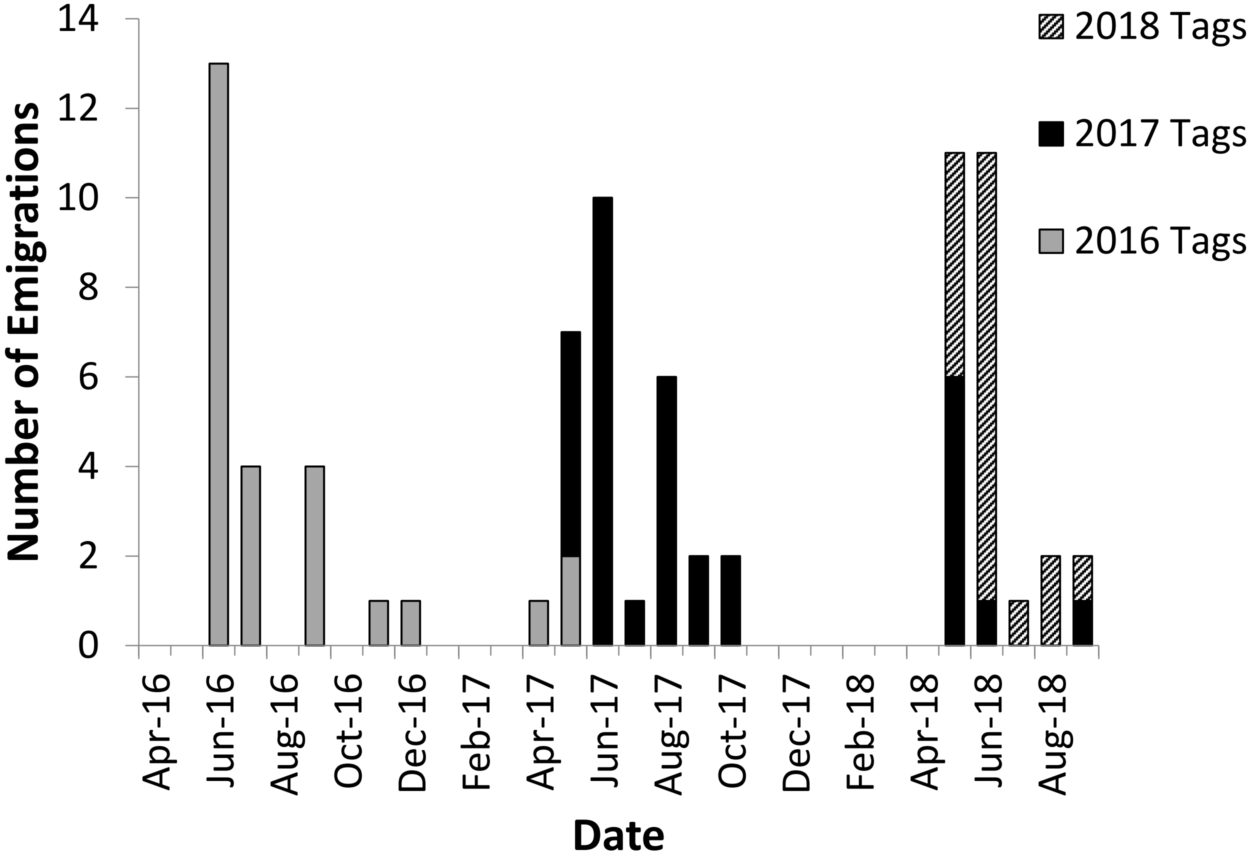

Figure 3.13. Emigrations of tagged Lake Sturgeon from the SLR to Lake Superior by month from April 2016 to September 2018. Gray bars represent Sturgeon tagged in 2016, black bars represent Sturgeon tagged in 2017, and cross-hatched bars represent Sturgeon tagged in 2018. Sturgeon were tagged in late April and early May of 2016 and 2017. In 2016, 2017, and 2018 tagged Lake Sturgeon emigrated to the SLR at similar rates. The peak month for emigration was June for each year. Three Sturgeon tagged in 2016 emigrated during April and May of 2017, 7 Sturgeon tagged in 2017 emigrated in May and June of 2018.

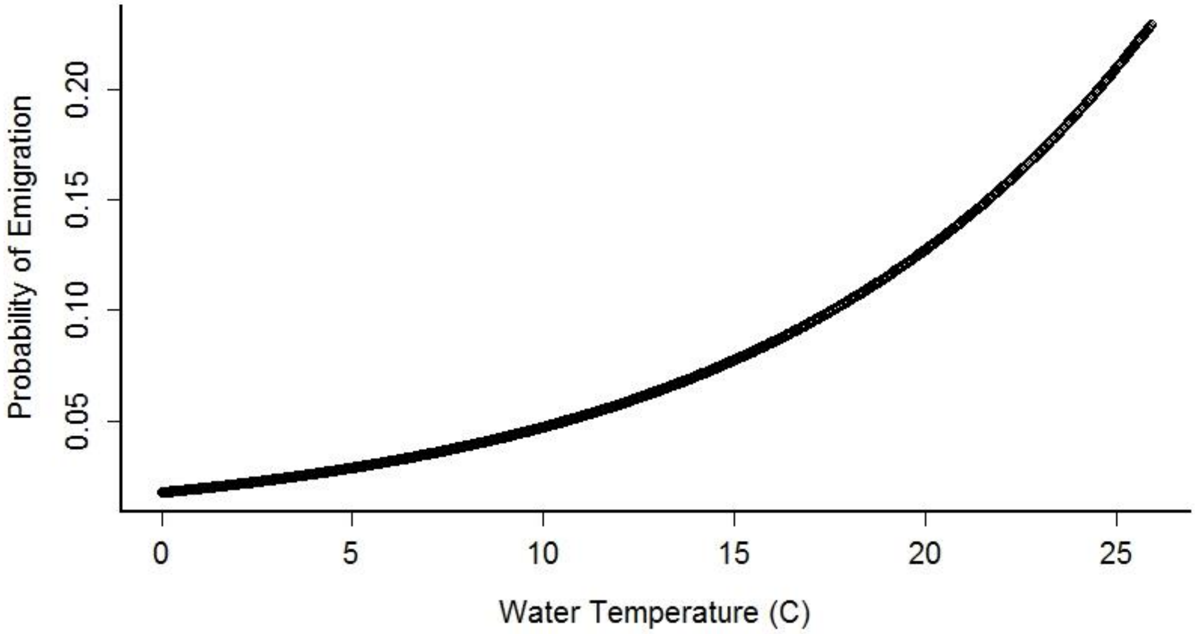

Figure 3.14. Probability of emigration and water temperature modeled in a generalized linear model with a Poisson distribution in Program R. Range of temperatures observed in the SLR during study time period ranged from 0 to 25.9°C. Probability of an emigration occurring increases from 0.0962 to 0.249 with increasing water temperature to max observed temp.

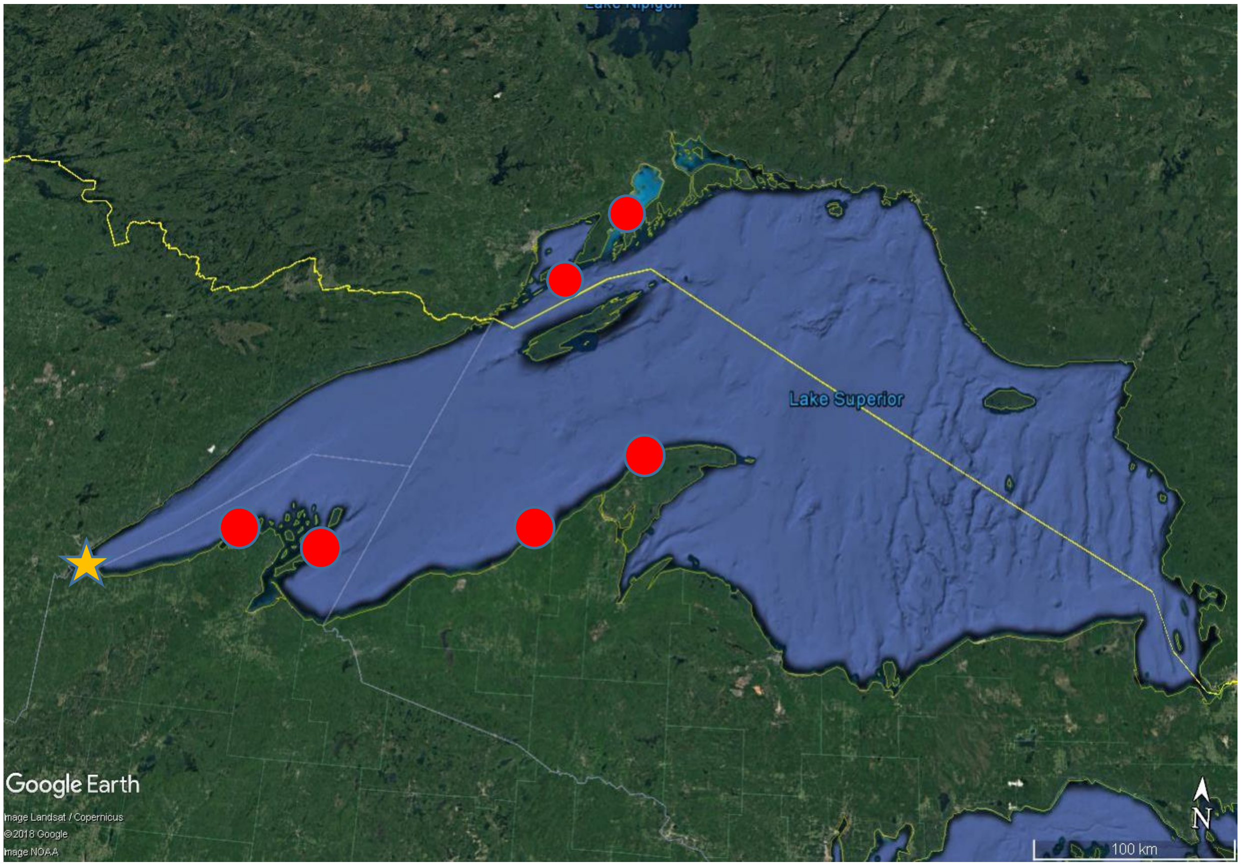

Figure 3.15. Map of Lake Superior and locations (red dots) where acoustically tagged Lake Sturgeon from the St. Louis River (gold star) have been detected by other GLATOS acoustic arrays.

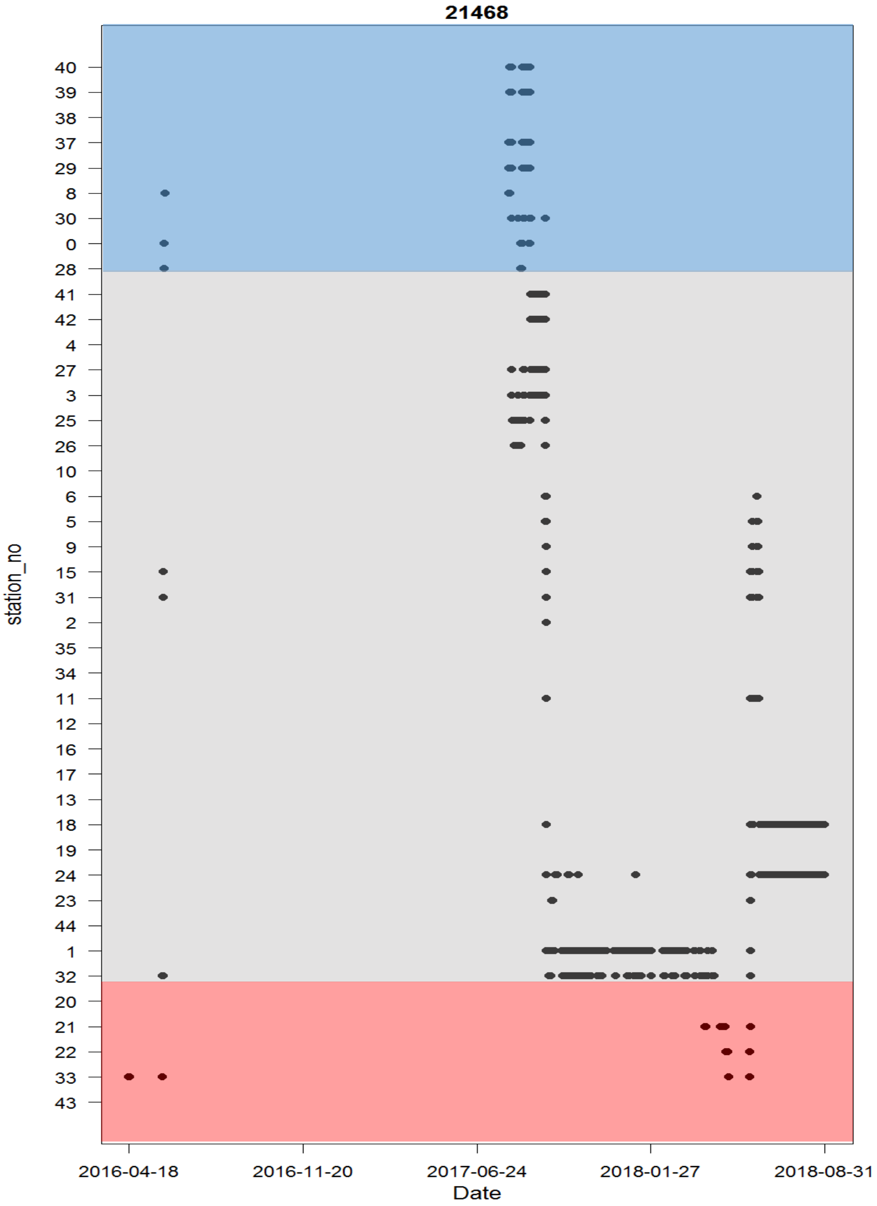

Figure 3.16. Abacus plot of tagged Sturgeon #21468 (1187 mm; unknown sex; Wolf River origin). The x-axis represents dates and the y-axis is divided into color coded zones. Each dot represents a detection at a receiver (receiver numbers are along the y-axis). The red zone represents the upper SLR, from the Fond Du Lac Dam downstream to Oliver Bridge. The gray zone represents the lower river/estuary from the Oliver Bridge downstream to the Superior and Duluth entries. The blue zone indicates Lake Superior. Tagged Sturgeon #21468 was tagged near the Highway 23 Bridge on 4-17-16 and then proceeded to move upstream into the spawning area. After presumably spawning # 21468 rapidly exited the SLR and spent 481 days at large in Lake Superior before returning to the SLR on 8-7-17. Sturgeon #21468 then over wintered near the Oliver Bridge and again appeared to spawn in spring 2018. After presumably spawning #21468 returned to Lake Superior.

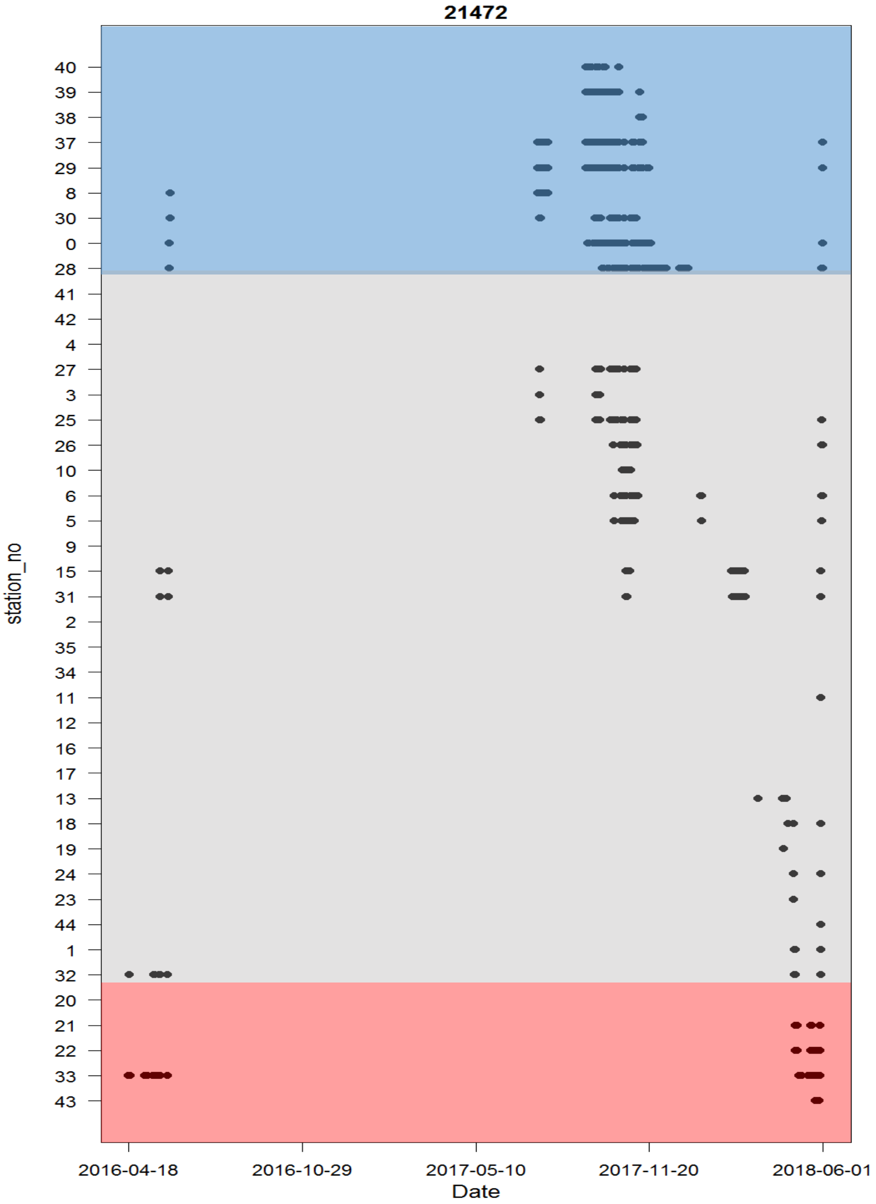

Figure 3.17. Abacus plot of tagged Sturgeon #21472 (1173 mm, unknown sex, low assignment to Pic River origin. The x-axis represents dates and the y-axis is divided into color coded zones. Each dot represents a detection at a receiver (receiver numbers are along the y-axis). The red zone represents the upper SLR, from the Fond Du Lac Dam downstream to Oliver Bridge. The gray zone represents the lower river/estuary from the Oliver Bridge downstream to the Superior and Duluth entries. The blue zone indicates Lake Superior. Sturgeon #21472 was tagged on 5-2-16 near the HWY 23 bridge. Sturgeon #21472 proceeded to spend time in the spawning area and the rapidly emigrated to Lake Superior on 7-20-17 where it was at large for 411 days. Upon returning on 6-1-18 Sturgeon #21472 proceeded to over winter in the lower estuary before returning upstream to presumably spawn in late May 2018 before rapidly emigrating again to Lake Superior on 7-20-17.

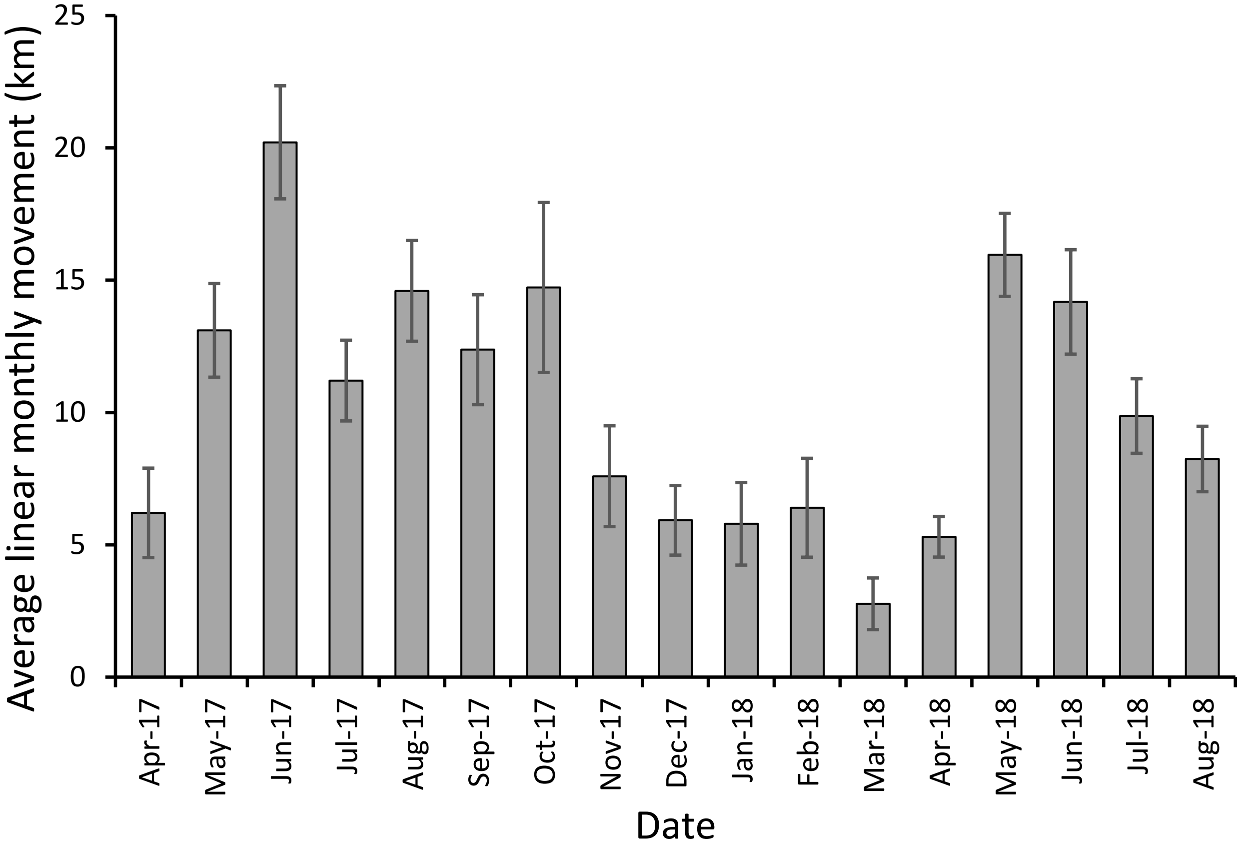

Figure 3.18. Average linear monthly movement (km) of Lake Sturgeon in the St. Louis River from April 2017 to August 2018. Error bars represent ± 1 SE. Peak movement was observed in June 2018 and May 2018.

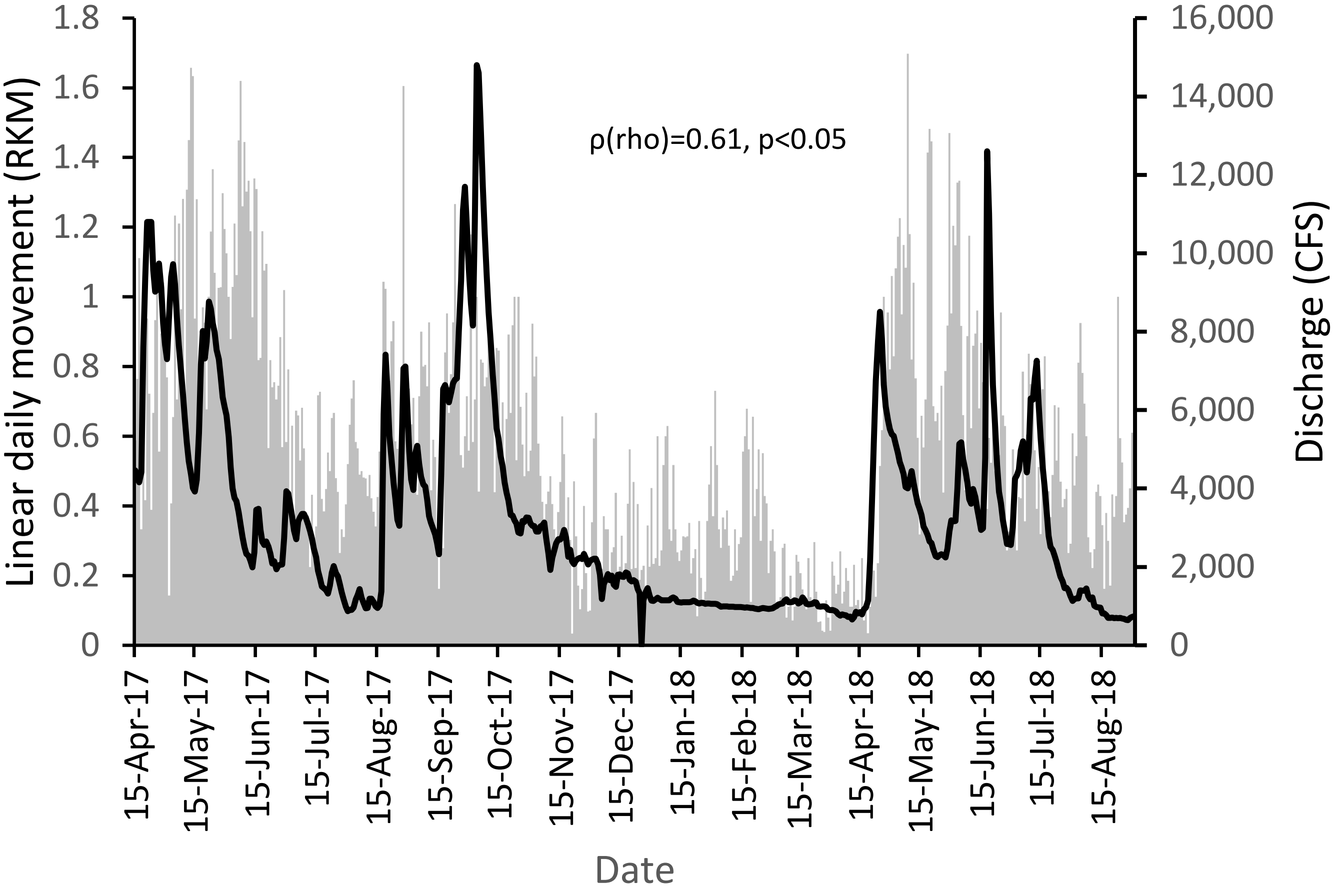

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Figure 3.19. Average linear daily movement (river kilometers; RKM) of Lake Sturgeon (gray bars, primary y-axis) and average daily discharge (cubic feet per second, black line) from USGS gauge 04024000 on the St. Louis River in Scanlon, MN, and date from April 15, 2017 to September 1, 2018. Spearman's correlation, ρ = 0.61 *P* < 0.05, suggests a moderate to strong correlation between average linear daily movement of Lake Sturgeon and average daily discharge in the St. Louis River.

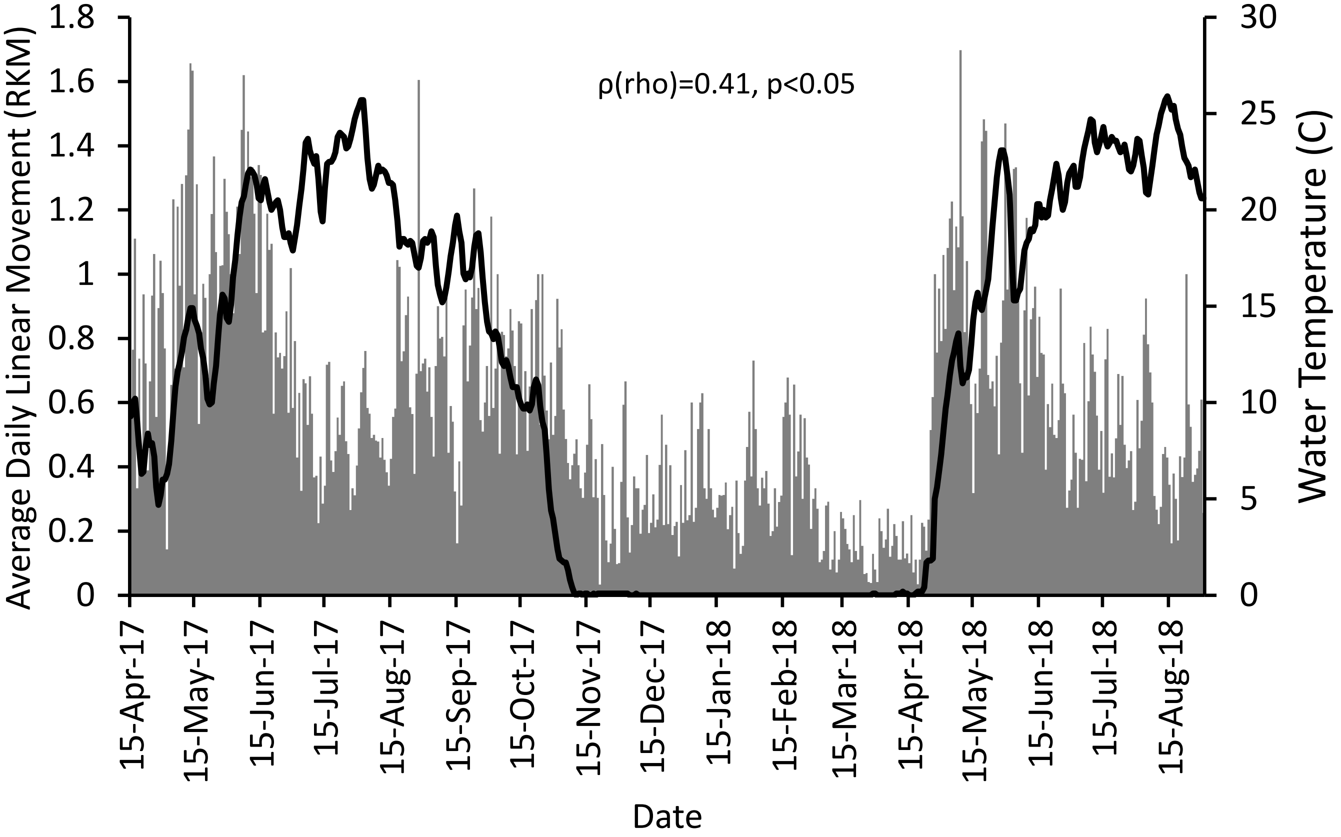

Figure 3.20. Average daily linear movement of Lake Sturgeon (gray bars, primary vertical axis), water temperature from USGS gauge 04024000 on the St. Louis River at Scanlon, MN (°C, secondary vertical axis), and date from April 15, 2017 to September 1, 2018. Spearman's correlation ρ= 0.41, *P* < 0.05, showing a moderate correlation between average daily linear movement and water temperature of the St. Louis River.

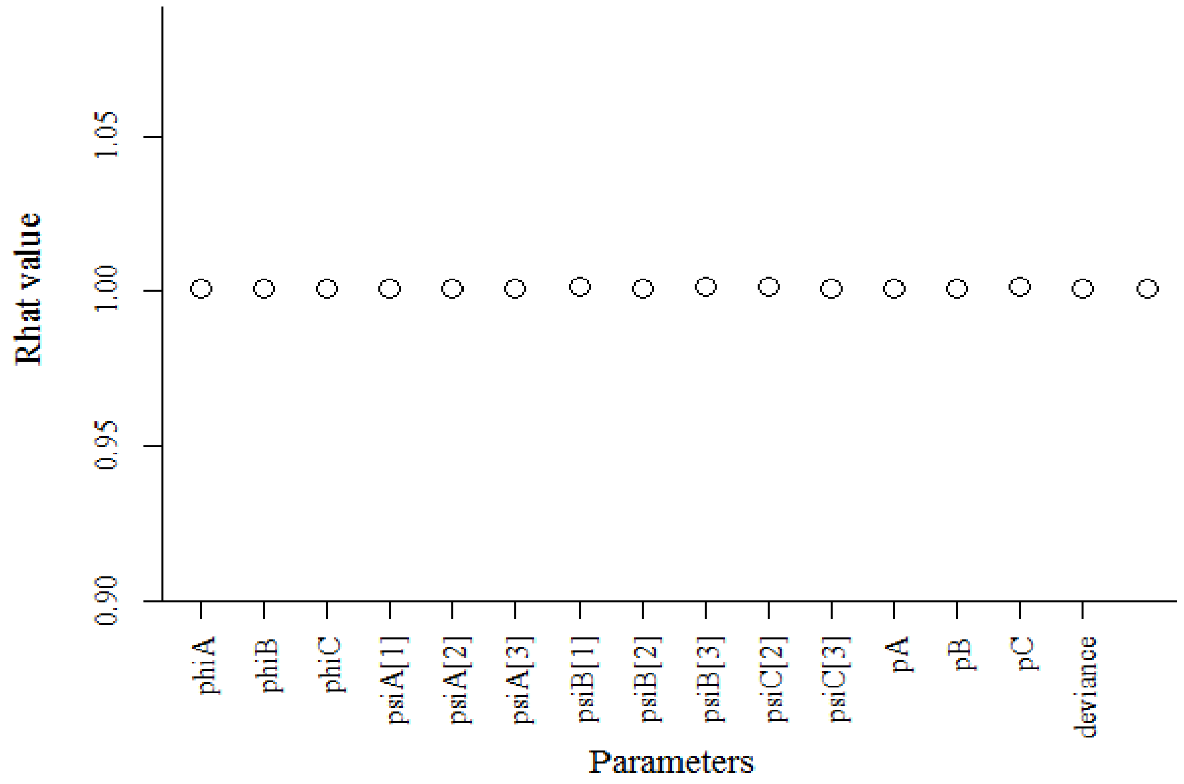

Figure 3.21. R̂ (convergence) values for parameters in monthly multi-state mark-recapture model constructed in Winbugs and Program R for SLR Lake Sturgeon. All R̂ values are below 1.002. R̂ ≈ 1.0 are considered optimal in the model. On the x-axis parameters phiA, phiB, phiC correspond to the survival estimates of Lake Sturgeon in zones 1,2, and 3, respectively. Parameters psiA[1], psiA[2], and psiA[3] correspond to the transition probabilities to stay in zone 1, move from zone 1 to zone 2 or move from zone 1 to zone 3. Parameters psiB[1], psiB[2], and psiB[3] correspond to the transition probabilities of a Sturgeon to move from zone 2 to zone 1, stay in zone 2, or move from zone 2 to zone 3, respectively. Parameters psiC[1], psiC[2], and psiC[2] correspond to the transition probabilities of Sturgeon to move from zone 3 to zone 1, zone 3 to zone 2 or to stay in zone 3, respectively. Parameters pA, pB, and pC correspond to recapture probability estimates.

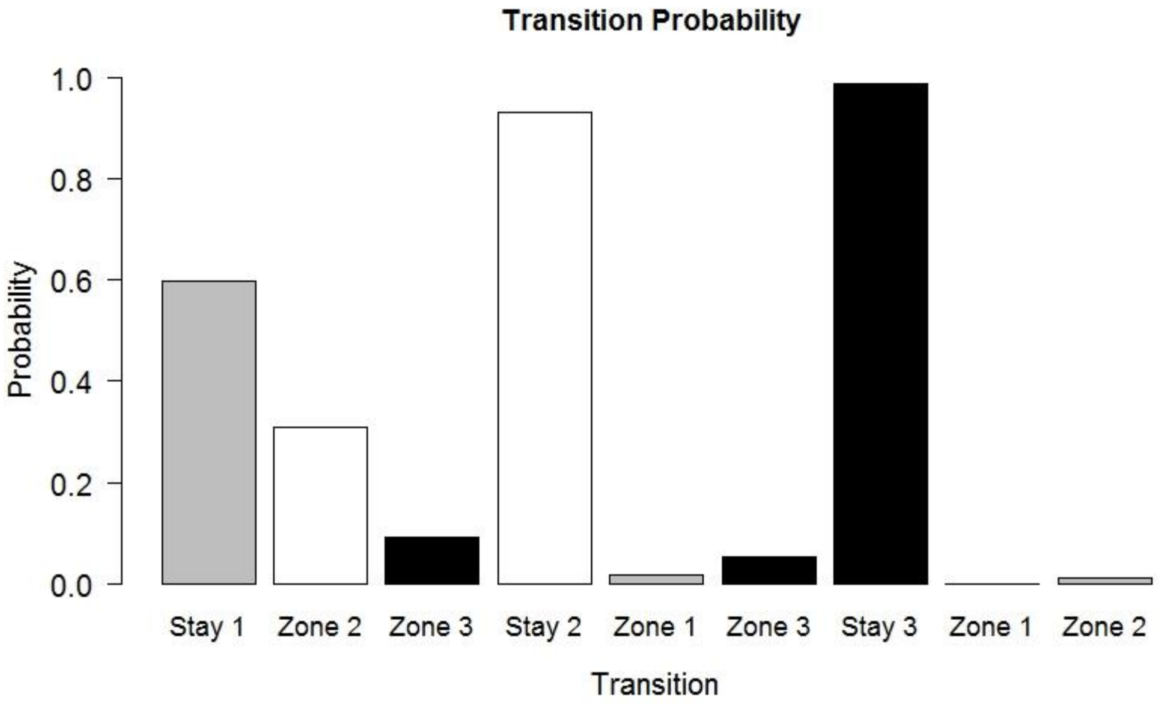

Figure 3.22. Monthly transition probabilities from multi-state mark recapture model. Zones are color coded; zone 1 (upper river) is represented by gray bars, zone 2 (middle river/estuary) is represented by white bars, and zone 3 (Lake Superior) is represented by black bars. Error bars represent standard deviation. The first three bars represent the probabilities of Sturgeon in zone 1 to stay in zone one, move to zone 2, or move to zone 3. The second group of bars represent the probabilities of Sturgeon in zone 2 to stay in zone 2, move to zone 1, or move to zone 2. The last group of bars represents the probabilities of a Sturgeon to stay in zone 3, move to zone 1, or move to zone 2.

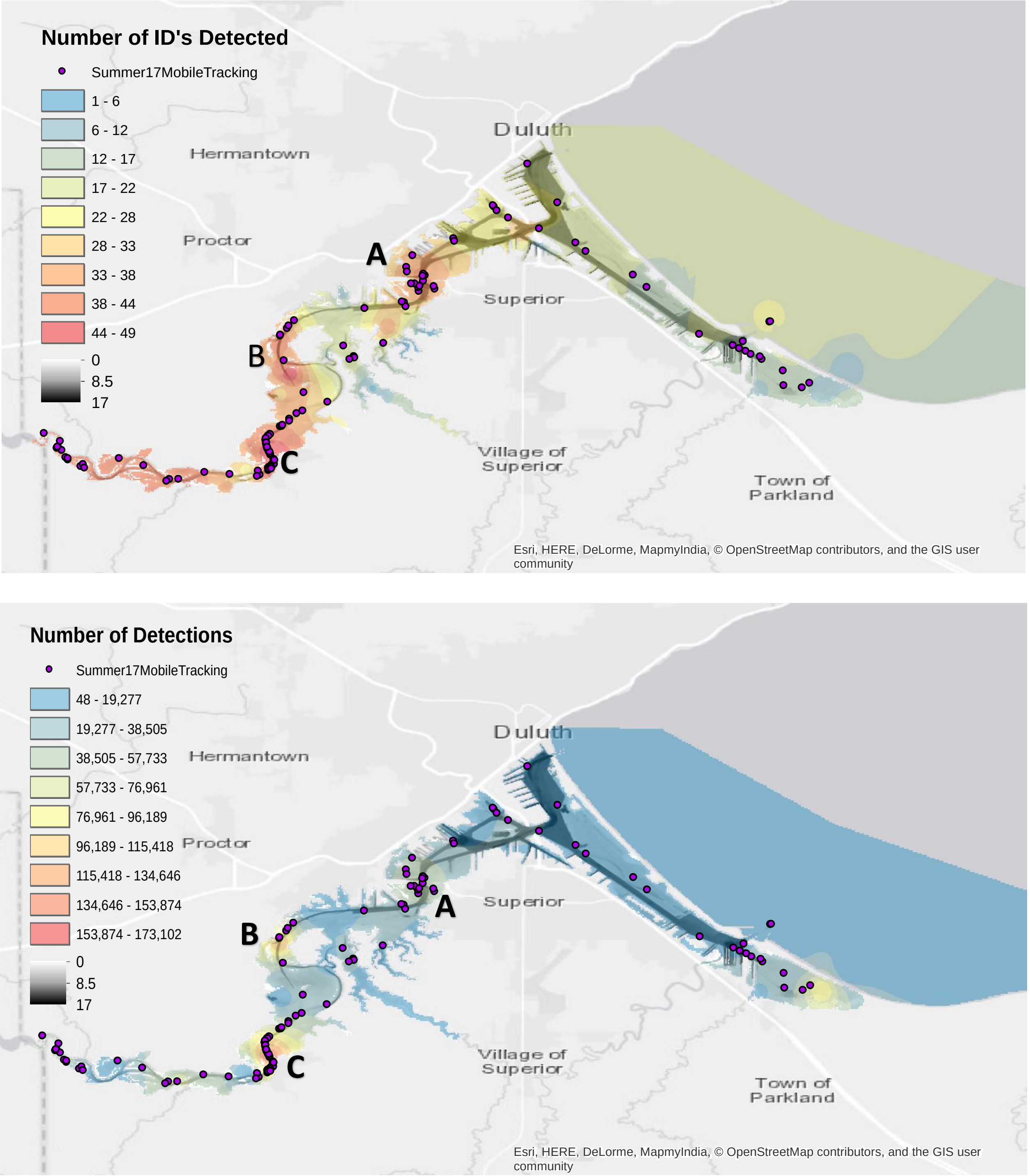

Figure 3.23 Interpolated heatmap of Lake Sturgeon detections in the SLR and Western Lake Superior using Inverse Density Weighted method in ArcGIS overlaid with mobile tracking detections (purple diamonds) and bathymetry (gray scale; depth in meters) from Summer 2017 (June 1 to September 1, 2017). Top figure depicts the number of individual fish detected and the bottom figure depicts the sum of all fish detections for Summer 2017. High concentration areas shown near Swing Bridge (A), Munger Landing (B), and Oliver Bridge (C).

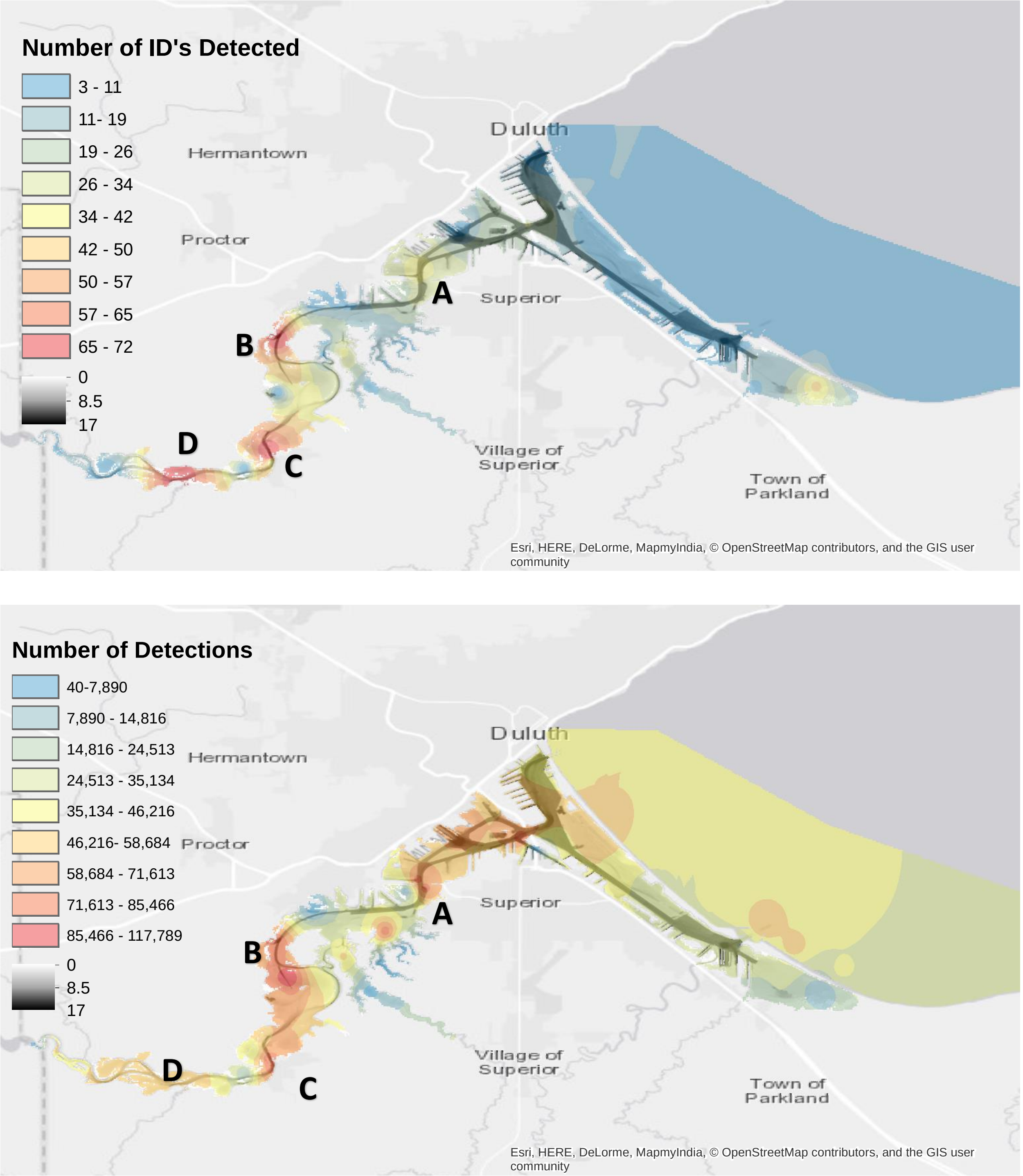

Figure 3.24. Interpolated heatmap of detections in the SLR and Western Lake Superior using Inverse Density Weighted method in ArcGIS underlaid with bathymetry (gray scale; depth in meters) from Autumn 2017 (September to November 1, 2017). Top figure depicts the number of individual fish detected and the bottom figure depicts the sum of all fish detections for Autumn 2017. High concentration areas shown near Swing Bridge area (A), Spirit Island (B), Oliver Bridge (C), and Boyscout Landing(D).

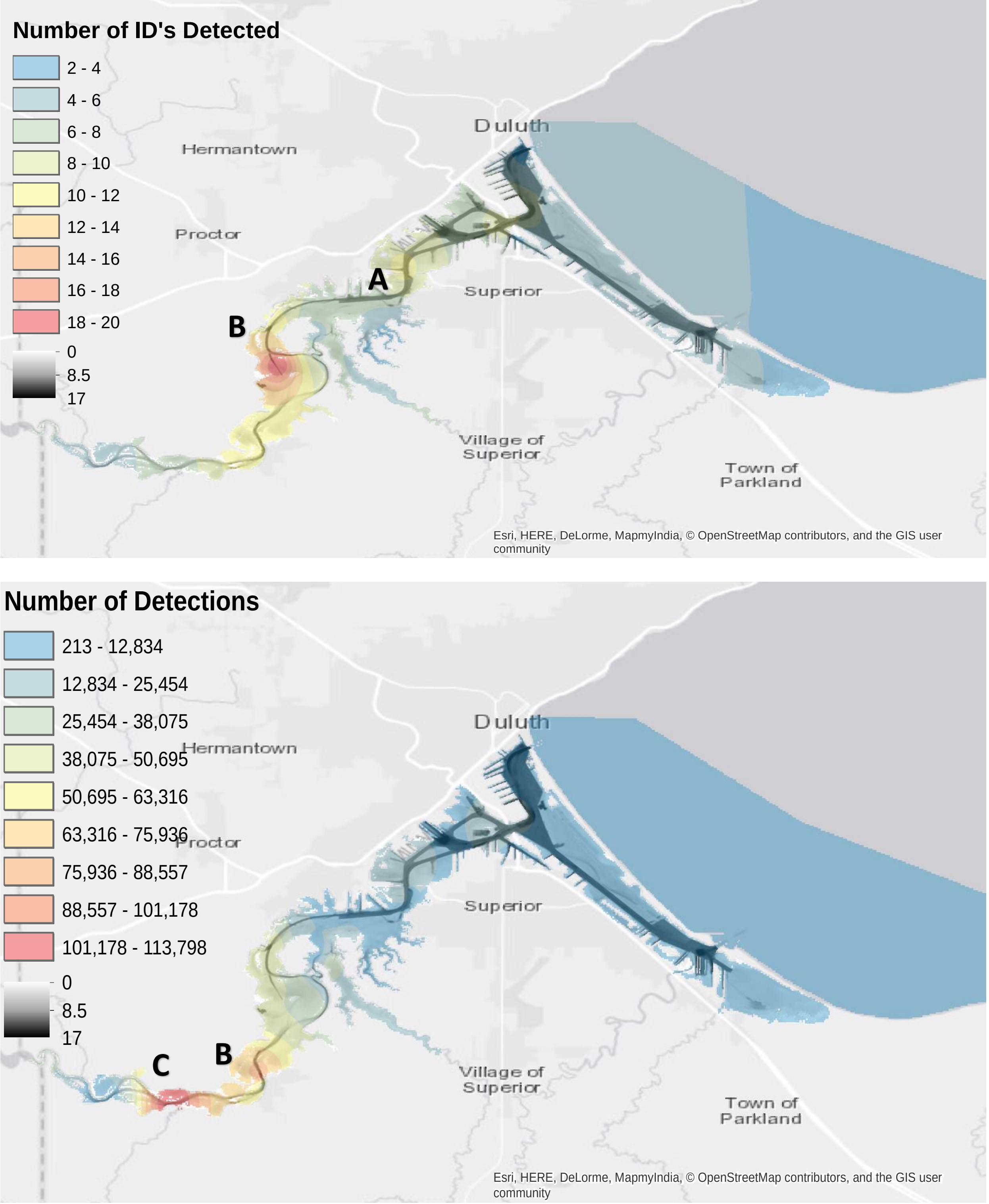

Figure 3.25. Interpolated heatmap of detections in the SLR and Western Lake Superior using Inverse Density Weighted method in ArcGIS underlaid with bathymetry (gray scale; depth in meters) from Winter 2017-2018 (November 1, 2017 to March 1, 2018). Top figure depicts the number of individual fish detected and the bottom figure depicts the sum of all fish detections for Winter 2017. High use areas are depicted at Swing bridge (A), Spirit Island (B), Oliver Bridge (C), and Boyscout Landing (D).

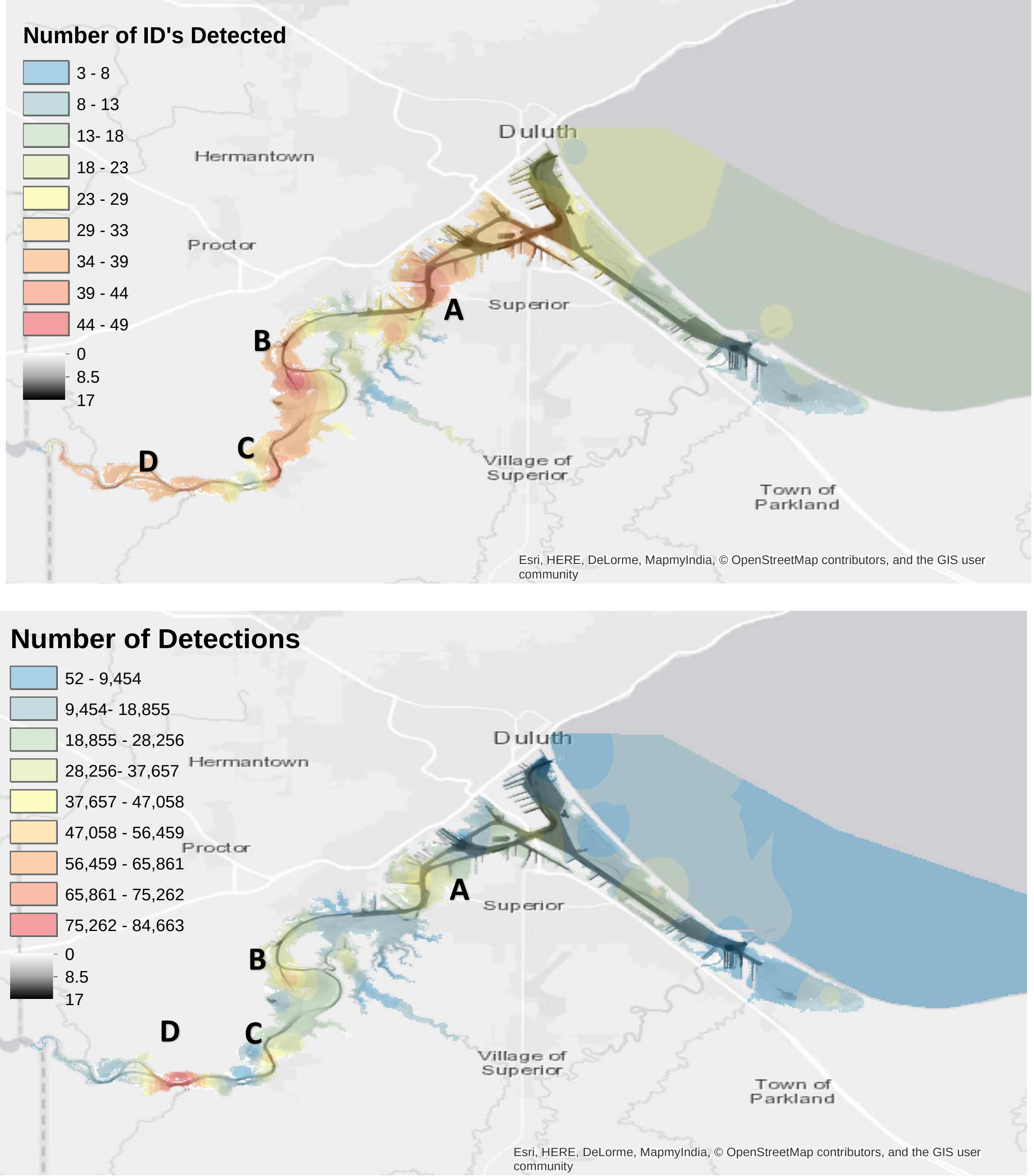

Figure 3.26. Interpolated heatmap of detections in the SLR and Western Lake Superior using Inverse Density Weighted method in ArcGIS overlaid with bathymetry (gray scale; depth in meters) from Spring 2018 (March 1 to June 1, 2018). Top figure depicts the number of individual fish detected and the bottom figure depicts the sum of all fish detections for Spring 2018. High concentration areas include the Swing Bridge area (A), Spirit Island/Spirit Lake, (B), and Oliver Bridge(C), and Upriver (D)

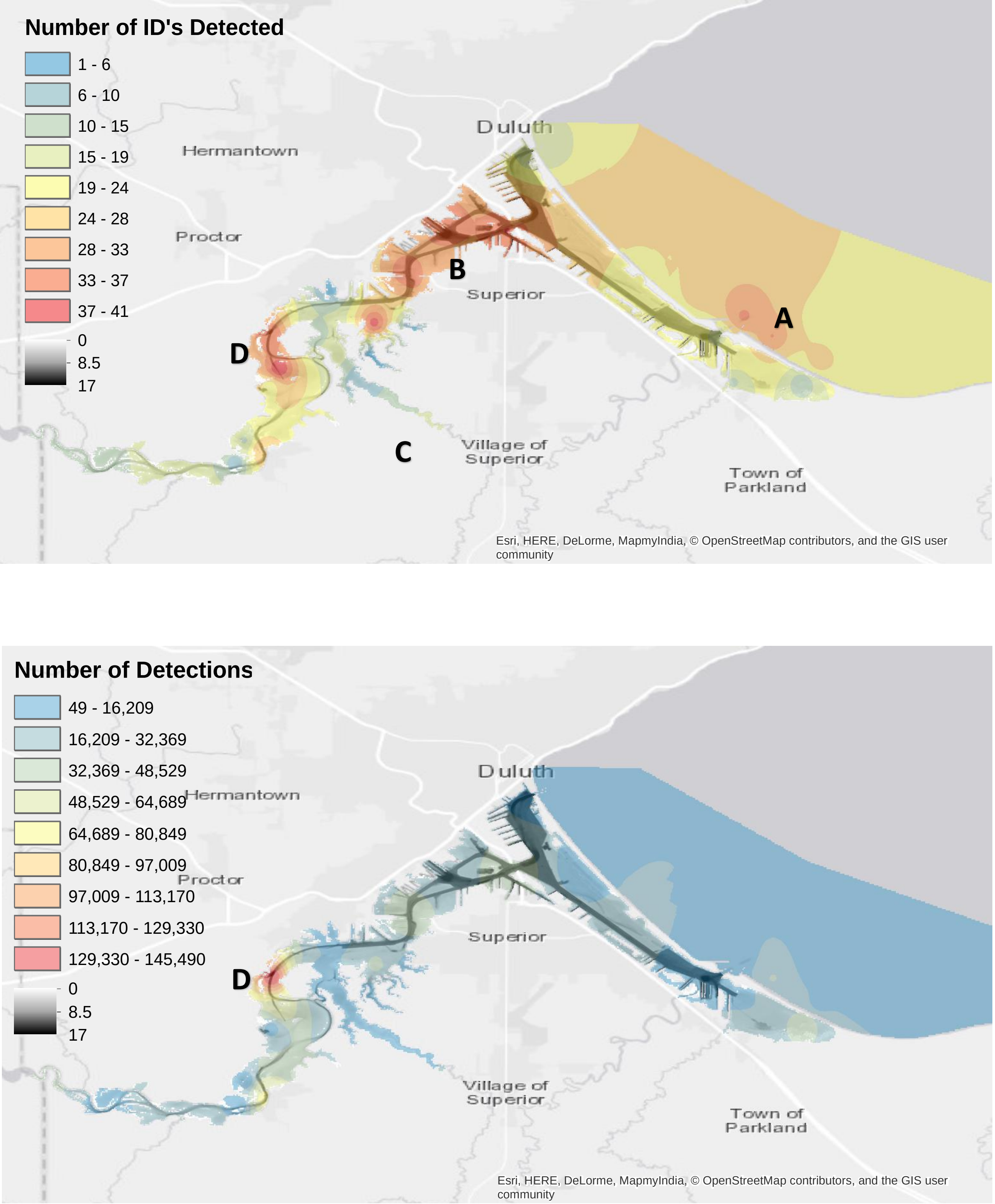

Figure 3.27. Interpolated heatmap of detections in the SLR and Western Lake Superior using Inverse Density Weighted method in ArcGIS underlaid with bathymetry (gray scale; depth in meters) from Summer 2018 (June 1 to September 1, 2018). Top figure depicts the number of individual fish detected and the bottom figure depicts the sum of all fish detections for Summer 2018. High concentration areas include the Duluth Port entry (A), Lower Harbor, (B), and Swing Bridge (C), and Munger Landing (D)

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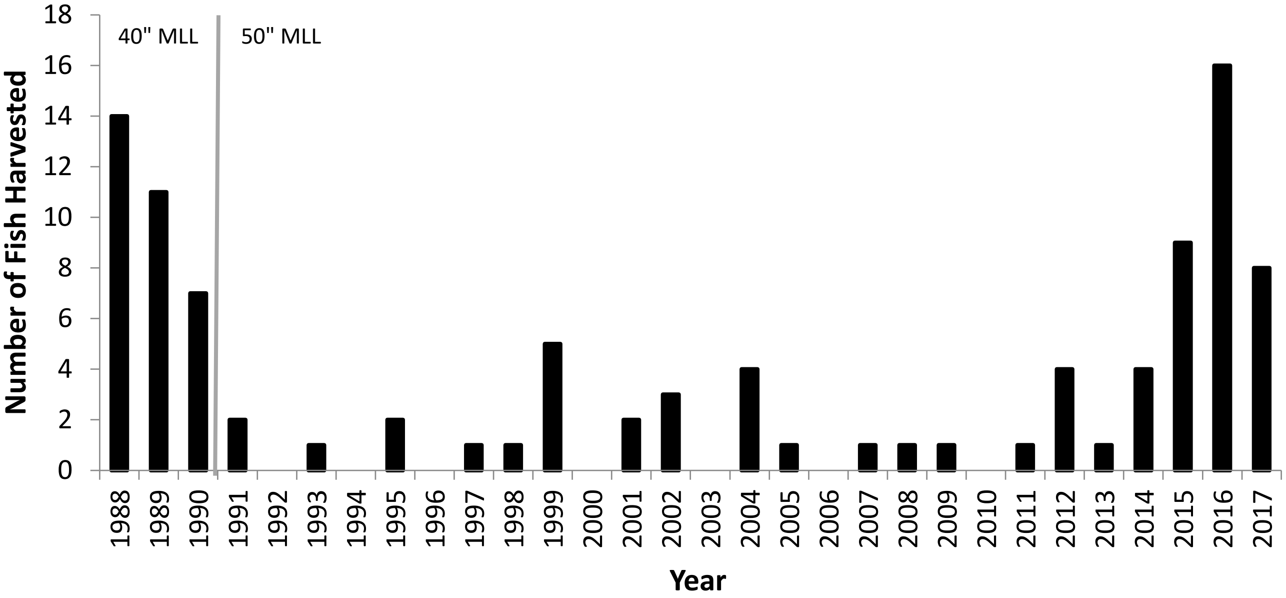

Figure 3.28. Lake Sturgeon Harvest from Wisconsin Waters of Lake Superior (mostly Chequamegon Bay) from 1988 to 2017. Data were primarily from Ashland, WI. Prior to 1991 (left of the grey vertical line) the minimum length limit (MLL) to legally harvest a Lake Sturgeon was 40 inches. Minimum length limit was increased to 50 inches in 1991 (Paul Piszczek, Wisconsin DNR, unpublished data).