2019

Assessing Freshwater Mussel *(Bivalvia: Unionidae)* Assemblages and Effects of Eutrophication on *Pyganodon grandis* in Lakes of Eastern South Dakota

Katherine M. Wollman
South Dakota State University

Recommended Citation

Wollman, Katherine M., "Assessing Freshwater Mussel *(Bivalvia: Unionidae)* Assemblages and Effects of Eutrophication on *Pyganodon grandis* in Lakes of Eastern South Dakota" (2019). *Electronic Theses and Dissertations*. 3378.
https://openprairie.sdstate.edu/etd/3378

ASSESSING FRESHWATER MUSSEL (*BIVALVIA: UNIONIDAE*) ASSEMBLAGES AND EFFECTS OF EUTROPHICATION ON *PYGANODON GRANDIS* IN LAKES OF EASTERN SOUTH DAKOTA

BY

KATHERINE M. WOLLMAN

A thesis submitted in partial fulfillment of the requirements for the

Master of Science

Major in Wildlife and Fisheries Sciences

Specialization in Fisheries Science

South Dakota State University

2019

ASSESSING FRESHWATER MUSSEL (*BIVALVIA: UNIONIDAE*) ASSEMBLAGES AND EFFECTS OF EUTROPHICATION ON *PYGANODON GRANDIS* IN LAKES OF EASTERN SOUTH DAKOTA

KATHERINE M. WOLLMAN

This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Wildlife and Fisheries Science degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Nels H. Troelstrup, Jr., Ph.D.
Thesis Advisor — Date
Department of Natural
Resource Management

Michele Dudash, Ph.D.
Head — Date
Department of Natural
Resources Management

Dean — Date
Graduate School

ACKNOWLEDMENTS

I would like to first thank and express my gratitude to my advisor Dr. Troelstrup. He gave me such an amazing opportunity to further my education, improve my research abilities and expand my knowledge of freshwater invertebrates. Dr T., I am appreciative for you keeping me on track, your patience and your feedback. It was an honor to learn from you and work for you. I would like to also thank my committee members, Dr. Michael Brown and Dr. Thomas Brandenburger for their time and support.

I am so thankful for my two technicians, Katlyn Beebout and Blake Roetman, for their hard work during our sampling efforts. Their energetic and willing attitudes helped get the job done. I appreciated you both for always being willing to sample “just one more lake”, I know the days were long but it could not have been done without the both of you. Thank you for exploring some pretty cool lakes, late nights around the campfires and making the fieldwork fun and memorable. I wish you both the best in your futures.

A special thanks to all of the friends I have made here while at SDSU. I am not sure how I would have survived graduate school without all of you. Rebecca Kolstrom, Katie Schlafke, Sam Fino and Abby Blanchard; thank you is not enough for keeping me sane over the past two years, I will always cherish our times together. Thank you to Seth Fopma, Austin Galinat, Brandon Vanderbush, Will Gallman, Jake Comer, Travis Rehm, Aaron Sundmark, Cindy Anchor, Luke Zilverberg, Austin Wiesler, Tanner Davis, Cade Lyon, Stephen Jones, Bailey Gullikson and Tyler Garwood; you all have positively impacted my time here at SDSU and I will always be thankful to have met such kind people. I am excited to see what the future brings for all of you.

I am appreciative of the office support staff who were all willing to help make my life a lot easier. Kate Tvedt, Ji Young, Beth Byre, Dawn Van Ballegooyen and Terri Symens; your cheerful attitudes and smiles always made my day just a little brighter.

Lastly, thank you Mom, Dad and Jack for always supporting my dreams and goals. I could not have gone through this journey without you all, at the end of a hard day I could always count on one of you to listen to me. Thank you for your words of encouragement and always making sure I am laughing. You are all the reason I am who I am today, and I cannot be more grateful.

This research was made possible by the funding from South Dakota Game, Fish and Parks and the Agricultural Experiment Station. A special thanks to SDSU Department of Natural Resource Management and the Oak Lake Field Station for providing equipment and laboratory space.

TABLE OF CONTENTS

LIST OF FIGURES

Chapter 2

Chapter 3

Appendix 2-1

Appendix 2-2

Appendix 2-3

Appendix 3-1

Appendix 3-2

LIST OF TABLES

Chapter 1

Chapter 2

Chapter 3

ABSTRACT

ASSESSING FRESHWATER MUSSEL (BIVALVIA: UNIONIDAE) ASSEMBLAGES AND EFFECTS OF EUTROPHICATION ON PYGANODON GRANDIS IN LAKES OF EASTERN SOUTH DAKOTA

KATHERINE M. WOLLMAN

2019

Globally, the family Unionidae is the most threatened group of freshwater fauna. South Dakota is well known for its agricultural production, leading to cultural eutrophication from enhanced fertilizers and sediments. This impact can alter species presence, age, growth and mortality. Objectives of this study were to 1) implement the first comprehensive lake survey of freshwater mussels in eastern South Dakota lakes and document distribution, occurrence and relative abundance, 2) evaluate relationships between age, growth and mortality of *Pyganodon grandis* and lake trophic state. Freshwater mussels were sampled in 2017 from 116 proportionally and randomly selected natural lakes and reservoir basins throughout six major river basins of eastern South Dakota. We sampled a total of 1,789 specimens and nine unique species from two different orders. Mussel abundance was found to be negatively correlated with conductivity and positively correlate with lake transparency, whereas no significant relationships were found between mussel abundance and temperature, pH, dissolved oxygen or substrate particle size. *Pyganodon grandis* (Giant Floater) was the most abundant and frequently occurring species across all river basins and lake types. We also documented two invasive species during our sampling efforts, *Dreissena polymorpha* (Zebra Mussel) and *Corbiula fluminea* (Asian Clam). *P. grandis* from 21 survey sites were sectioned, aged and growth increments measured. The von Bertalanffy growth equation was utilized to evaluate growth rates and estimate length of natural lake and reservoir mussels. Mortality was assessed by implementing length-at-age keys to determine instantaneous and annual mortality rates. Age ranged from 4 to 11 years across all sampled sites. We found a significant negative relationship between *P. grandis* age and lake trophic state assessed from lake transparency data (R^2= 0.394, p= 0.022). No significant relationships were observed for growth and mortality. There was a marginal significant difference observed in age based on lake type (p= 0.054). Results of this effort suggest that life expectancy is shorter in more culturally eutrophic lake basins and support results reported elsewhere. This study generated the first South Dakota unionid lake survey and future work can entail monitoring sensitive species and invasive species impacts to lakes.

CHAPTER 1: INTRODUCTION

BACKGROUND

Unionid Background

The family Unionidae resides on all continents, excluding Antarctica, and their greatest diversity is found in North America (Strayer et al. 2004, Strayer 2008, Lopes-Lima et al. 2014). North America has the largest diversity of unionid mussels (294 of the 820 species), yet they are the most threatened aquatic fauna (Bogan 1993, Strayer et al. 2004). These species play critical roles in freshwater ecosystems. Their sessile behavior allows for sediment stabilization, while their non-selective filter-feeding provides improved water clarity (Downing and Downing 1992, Strayer 2008). Over time, mussels sequester nutrients which shortens nutrient spirals in water bodies (Vaughn 2018). Organisms from the terrestrial environment also benefit from their presence, especially raccoons, muskrats and birds which prey on mussels in shallow water (Grabarkiewicz and Davis 2008).

Unionids provide many important ecological services to freshwater systems, but many threats have caused drastic declines to their populations. Since the beginning of the industrial revolution humans have impounded streams and rivers, altered aquatic habitats, enhanced genetic isolation, increased exploitation and introduced invasive species (Metcalfe-Smith et al. 1998, Zieritz et al. 2016). These impacts have been linked to population declines. In North America today, 213 unionid species are listed as endangered, threatened, or of special concern, and since the 1900’s 35 species have become extinct (Ricciardi and Rasmussen 1999). The market for freshwater mussels was also very prominent in the early twentieth century because of the pearl button industry

(Bogan 1993, Grabarkiewicz and Davis 2008). Selective and non-selective harvesting methods were conducted to collect mussels (Williams et al. 1993). When populations became depleted, the industry declined. Increased agricultural practices and urbanization caused habitat destruction and degradation of water quality (Bogan 1993). Poor water quality, in-turn, has caused changes in freshwater mussel species composition, more pollution tolerant species thrive while sensitive species disappear (Du et al. 2011). Impoundment and flooding have also influenced unionid populations by increasing siltation and reducing fish host availability for reproduction (Bogan 1993, Lydeard et al. 2004). With the world becoming more interconnected, we have increased not only trade with other countries, but also introduced invasive species. Asian clams and zebra mussels have spread throughout North America, suffocating native unionid populations (Downing and Downing 1992, Bogan 1993, Lydeard et al. 2004, Strayer 2008). Zebra mussels attach to native mussels, which constricts movement, reduces feeding and diminishes growth (Haag et al. 1993, Baker and Hornbach 1997, Schneider et al. 1998). Eutrophication in lakes has caused increased nutrient loading and algae growth, which can cause pollution sensitive filter-feeders to struggle (Patzner and Muller 2001). Nutrient enrichment is also commonly observed in lentic water bodies of South Dakota (South Dakota Department of Environment and Natural Resources 2018), yet little work has focused on eutrophication and its effects to organisms that inhabit the lakes of South Dakota, and no previous studies have focused on eutrophication effects on unionid populations in lakes of South Dakota.

Unionids in South Dakota

Freshwater mussel research in South Dakota has been limited. In the early 1900's a survey was completed, but was poorly documented and not well designed to survey mussels statewide (Coker and Southall 1915). The latest research completed in the state was on assemblages of unionids in wadable streams, which was the first statewide freshwater mussel survey ever completed (Faltys 2016). Prior to Faltys survey, multiple agencies conducted unionid surveys primarily on mainstem rivers of eastern South Dakota (Perkins et al. 1995, Skadsen 1998, Perkins and Backlund 2000, 2003, Skadsen and Perkins 2000, Hoke 2003, Wall and Thomson 2004, Ecological Specialists 2005, Shearer et al. 2005, Perkins 2007). These surveys noted high siltation and shifting substrates within the region making some areas unhabitable for unionids (Coker and Southall 1915, Perkins and Backlund 2000, Shearer et al. 2005, Perkins 2007). Historical records of unionids within South Dakota suggest there were 33 species, two of which are presently listed as near threatened, *Leptodea leptodon* (Scaleshell) and *Ligumia recta* (Black Sandshell), and one listed as critically endangered, *Quadrula fragosa* (Winged Mapleleaf) (Table 1).

Eutrophication Background

Eutrophication has been cited as one of the leading causes of unionid decline. Cultural eutrophication is the accelerated addition of nutrients to a lake due to the increased runoff of chemicals and fertilizers from industrial and agricultural practices (Harper 1992, Smith and Schindler 2009, Callisto et al. 2014). This process occurs from the enrichment of watershed contributions of phosphorous and nitrogen (Callisto et al. 2014, Motew et al. 2017). Higher availability of nutrients leads to high phytoplankton biomass, lower water transparency, taste and odor issues, depressed dissolved oxygen and the presence of cyanotoxins in the water column (Smith and Schindler 2009). Decreased species diversity may occur in addition to mass mortality (Smith and Schindler 2009).

Cultural eutrophication is a pervasive environmental issue throughout South Dakota. The South Dakota Department of Environment and Natural Resources recently reported that 171 lakes across South Dakota were assessed for trophic status and 69% were reported to be eutrophic or hypereutrophic (SD DENR 2018). Most lakes in South Dakota are considered shallow and turbid (SD DENR 2016). Watersheds in the eastern half of the state are largely affected by sediment and nutrient runoff from agriculture (SD DENR 2018).

Unionids and Eutrophication

Although cultural eutrophication is a common problem in northern plains lakes, the literature suggests that mussel responses to eutrophication are mixed. Negative effects have been attributed to oxygen depletion and high algal biomass (Sparks and Strayer 1998, Galbraith et al. 2010). Positive effects have been attributed to enhanced food availability (Sawyer 1966, Patzner and Muller 2001, Smith and Schindler 2009, Strayer 2014).

High mortality in juvenile mussels has been observed in highly eutrophic lakes, because they are sensitive to increased sedimentation (Patzner and Muller 2001). Oxygen depletion can disrupt filter feeding abilities (Smith and Schindler 2009). Eutrophication causes an increase in food availability, but extreme levels of eutrophication can diminish food quality, cause oxygen deprivation and expose mussels to cyanotoxins associated with blue-green bacteria blooms (Strayer 2014). Cultural eutrophication can increase occurrences of fish kills, which causes loss of fish hosts for unionid reproduction (Smith and Schindler 2009). Growth rates of mussels in highly productive lakes have increased, but shorter life spans have been reported (Bauer 1992, Patzner and Muller 2001, Strayer 2014). Overall, cultural eutrophication may impact unionids through changes in sedimentation rates, fish host availability, phytoplankton composition, phytoplankton biomass and high toxin concentrations. Thus, the cumulative and combined effects appear to be situation specific (Skadsen 1998).

OBJECTIVES

The first objective of this study was to document freshwater mussel occurrence and abundance based on river basin and lake type in publicly managed and owned lakes in eastern South Dakota. We hypothesized the James River basin would have the highest abundance and species richness relative to other river basins. We also hypothesized that greater mussel abundance and richness would occur from basins with higher dissolved oxygen, lower conductance, higher temperatures, moderate pH, small-medium substrate particle size and higher transparency. The second objective of this study was to evaluate relationships between age, growth and mortality of *Pyganodon grandis* relative to lake trophic status in eastern South Dakota. We hypothesized that maximum age of *Pyganodon grandis* would be lower in more cultural enriched basins, and both growth and mortality rates would be higher from lakes which are more culturally enriched. Chapter 2 of this thesis will focus on a survey of freshwater mussels inhabiting a sample of lakes and reservoirs in eastern South Dakota. Chapter 3 will focus on the age, growth and mortality of *Pyganodon grandis* (Giant Floater), the most frequently occurring and abundant mussel species in relation to lake trophic status.

Results from this study will enhance our understanding of mussel responses to cultural eutrophication within South Dakota and the midwestern region. Survey results will provide the first documentation of region-wide unionid occurrence and abundance in eastern South Dakota lakes and reservoirs.

Table 1. State historical records of species presence from rivers and streams. Current status of each species is listed: CE= Critically endangered, LC= Least concerned, NE= Near threatened, UN= Unknown.

		Historical Records											
Species	Status	Coker & Southhall 1921	Perkins et al. 1995	Skadsen 1998	Perkins & Backlund 2000	Skadsen & Perkins 2000	Hoke 2003	Perkins & Backlund 2003	Wall & Thomson 2004	Eco. Specialists 2005	Shearer et al. 2005	Perkins 2007	Troelstrup, unpubl. data
Alasmidonta marginata	LC	X		X		X							
Amblema plicata	LC	X		X	X	X		X		X		X	X
Amphinaias pustulosa	LC	X				X		X					
Anodonta anatina	LC				X								
Anodontoides ferussacianus	LC		X	X		X		X					
Arcidens confragosus	UN	X			X	X		X					
Fusconaia flava	LC		X			X		X					X
Lampsilis cardium	LC	X	X	X		X		X					
Lampsilis radiata	UN		X										
Lampsilis siliquoidea	LC	X		X	X	X	X	X	X			X	X
Lampsilis teres	LC	X			X	X		X				X	
Lasmigona complanata	LC	X	X	X	X	X	X	X	X	X	X	X	X
Lasmigona compressa	LC		X	X		X							
Leptodea fragilis	LC		X		X	X	X	X	X	X	X	X	X
Leptodea leptodon	NT											X	
Ligumia recta	NT	X				X		X					X
Ligumia subrostra	UN			X		X	X	X					
Obliquaria reflexa	LC					X		X					X
Obovaria olivaria	LC					X		X					
Pleurobema sintoxia	LC	X											
Potamilus alatus	LC	X	X		X	X	X	X	X	X	X	X	X
Potamilus ohiensis	LC	X	X		X	X	X	X	X	X	X	X	

Table 1 continued

			Historical Records										
Species	Status	Coker & Southhall 1921	Perkins et al. 1995	Skadsen 1998	Perkins & Backlund 2000	Skadsen & Perkins 2000	Hoke 2003	Perkins & Backlund 2003	Wall & Thomson 2004	Eco. Specialists 2005	Shearer et al. 2005	Perkins 2007	Troelstrup, unpubl. data
Pyganodon grandis	LC	X	X	X	X	X	X	X	X	X	X	X	X
Quadrula apiculata	UN					X							
Quadrula fragosa	CE	X				X		X					
Quadrula quadrula	LC				X	X				X	X	X	X
Strophitus undulatus	UN	X	X	X	X	X		X					X
Toxolasma parvum	LC		X		X	X						X	
Tritogonia verrucosa	UN	X				X		X					
Truncilla donaciformis	LC				X	X		X					
Truncilla truncata	UN				X	X		X		X		X	X
Utterbackia imbecillis	LC										X	X	
Utterbackia suborbiculata	UN					X						X	

CHAPTER 2: DISTRIBUTION AND COMPOSITION OF FRESHWATER MUSSELS IN EASTERN SOUTH DAKOTA

ABSTRACT

Documenting unionid abundance and occurrence is a crucial step in monitoring native species throughout North America. We implemented the first lake survey of freshwater mussels in eastern South Dakota and examined differences in abundance and richness between publicly owned and managed natural lakes and reservoirs. Our goal was to determine the abundance, occurrence and species richness based on river basins and lake type. Our survey found nine species from two different orders. The James River basin had the greatest abundance and richness of species. *Pyganodon grandis* (Giant Floater) dominated abundance and occurrence in all river basins and lake types. We observed no significant difference in mussel abundance or species richness between lake types or among river basins. Mussel abundance was negatively correlated with conductivity (rho = -0.3618, $p < 0.01$) and positively correlated with transparency (rho = 0.23, $p = 0.01$). We documented two invasive species during our sampling efforts, *Dreissena polymorpha* (Zebra Mussel) and *Corbiula fluminea* (Asian Clam). Conservation measures are needed for *Amblema plicata* (Threeridge), *Fusconaia flava* (Wabash Pigtoe), *Lasmigona complanata* (White Heelsplitter), *Potamilus alatus* (Pink Heelsplitter) and *Truncilla truncata* (Deertoe).

INTRODUCTION

North America is a hotspot for unionid mussels, containing 294 of the 820 globally described species (Bogan 1993, Strayer et al. 2004, Strayer 2008, Lopes-Lima et al. 2014). Yet today, unionid mussels are the most threatened and endangered aquatic fauna worldwide (Bogan 1993, Strayer et al. 2004). There are 35 species that have gone extinct in North America and 213 species are endangered, threated, or of special concern (Ricciardi and Rasmussen 1999). Unionid mussels provide valuable ecosystem services to rivers, streams and lake systems, but these services are jeopardized as populations continue to decline. Their filter feeding abilities allow the removal of particles from the water column (Vaughn et al. 2008, Vaughn 2018). Since freshwater mussels are sessile they provide substrate stabilization, but this sedentary mode of life also renders them susceptible to predation from humans and wildlife (Downing and Downing 1992, Grabarkiewicz and Davis 2008, Strayer 2008). Populations began to decline during the era of the pearl button industry, as a result of both selective and non-selective, uncontrolled harvest (Bogan 1993, Williams et al. 1993, Grabarkiewicz and Davis 2008). Habitat destruction from agriculture and urbanization has led to degradation of water quality, such as nutrient loading and algae growth, causing decline in sensitive species (Bogan 1993, Patzner and Muller 2001, Lydeard et al. 2004). Impoundments have altered the natural flow of streams and rivers, causing reduction of fish hosts for reproduction and altering water chemistries (Bogan 1993, Lydeard et al. 2004). Invasive species, like Asian clams and zebra mussels have also accelerated unionid decline by smothering native beds and reducing food availability (Haag et al. 1993, Baker and Hornbach 1997, Schneider et al. 1998, Strayer 2008).

Freshwater mussel research in South Dakota has been limited. In the early 1900's a survey was completed, but was poorly documented and not well designed to survey mussels statewide (Coker and Southall 1915). The latest research completed in the state focused on assemblages of unionids in wadable streams, which was the first statewide freshwater mussel survey ever completed (Faltys 2016). Prior to Faltys survey, multiple groups had conducted unionid survey studies within mainstem of eastern South Dakota (Coker and Southall 1915, Perkins et al. 1995, Skadsen 1998, Perkins and Backlund 2000, 2003, Skadsen and Perkins 2000, Hoke 2003, Wall and Thomson 2004, Ecological Specialists 2005, Shearer et al. 2005, Perkins 2007).

Coker and Southall (1915), were the first to explore the James River noting that about two-thirds of their findings were dead shells due to the large pearl industry at the time, but the James River was considered a unionid hotspot. Perkins and Backlund (2003) documented lower abundances than Coker and Southall's (1915) original survey. A survey of rivers and streams throughout Day, Deuel, Grant and Roberts counties, provided the first documentation of *Lasmigona compressa* (Creek Heelsplitter) within South Dakota and the most commonly collected specimen was *Anodontoides ferussacianus* (Cylindrical Papershell) (Perkins et al. 1995). The Big Sioux River and tributaries contained rare species consisting of *Alasmidonta marginata* (Elktoe), *Lasmigona compressa* (Creek Heelsplitter), *Strophitus undulatas* (Squawfoot) and *Ligumia subrostrata* (Pondmussel) (Skadsen 1998). Fluctuating water levels were determined to be a limiting factor to mussels near Gavin's Point Dam, causing mussels to be exposed quickly and not able to retreat to deeper waters (Perkins and Backlund 2000, Ecological Specialists 2005, Perkins 2007). A survey of Lake Oahe reservoir on the

Missouri River found *Ligumia subrostrata* (Pondmussel) and *Potamilus alatus* (Pink Heelsplitter) to be the rarest species (Hoke 2003). *Pyganodon grandis* (Giant Floater) was the most common species found in multiple surveys within the Big Sioux River, Missouri River and James River basins (Skadsen 1998, Perkins and Backlund 2000, Wall and Thomson 2004).

Historical records from these surveys documented occurrence of 33 species, two of which are listed as near threatened, *Leptodea leptodon* (Scaleshell) and *Ligumia recta* (Black Sandshell), and one listed as critically endangered, *Quadrula fragosa* (Winged Mapleleaf) (Chapter 1). However, none of these surveys focused on unionid fauna inhabiting South Dakota lakes and reservoirs. To date, there are only sporadic references to mussels in South Dakota lakes (Coker and Southall 1915). Thus, there is a need for a lake survey in South Dakota to document species occurrence and relative abundance.

The objective of this effort was to document unionid mussel species occurrence and relative abundance in lakes and reservoirs of eastern South Dakota. We hypothesized that mussels would be most abundant and the highest species richness would occur from those basins with higher dissolved oxygen, lower conductance, higher temperatures, lower pH, small-medium substrate particle size and moderate transparency. We hypothesized that higher mussel abundance and richness would be observed in natural lake basins when compared to reservoirs. We also hypothesized that basins within the James River basin would have higher abundance and species richness than those from other river basins consistent with observations from historical stream and river surveys (Coker and Southall 1915, Faltys 2016).

METHODS

Study Area

South Dakota is divided by the Missouri River, separating glaciated and unglaciated regions within the state. Eastern South Dakota was formed by melted ice deposits during the Late Wisconsin glaciation, creating large numbers of wetland basins of varying sizes, which is commonly referred to as the prairie pothole region (Johnson et al. 1997). This region is comprised of two major level III ecoregions, the Northern Glaciated Plains (NGP) and Northwestern Glaciated Plains (NWGP) (U.S. Environmental Protection Agency 2013). The NGP comprises over half of the eastern portion of the state and includes large number of glacial lake basins. Dominant natural vegetation is mixed grass prairie, which has largely been converted to cultivated farmland (Auch 2015). The NWGP follows the Missouri River and includes shallow lakes and reservoirs. It is identified as a transitional ecoregion between the drier western and more humid eastern portions of the state. This mixed grass prairie's primary land uses are cultivated crops and livestock grazing (Taylor 2015). Six major river basins drain the land area of eastern South Dakota, including the Big Sioux, James, Minnesota, Missouri, Red and Vermillion rivers (Johnson et al. 1997, Gewertz and Errington 2015).

There are approximately 575 publicly owned and managed natural lakes and reservoirs scattered across South Dakota, most characterized as either eutrophic or hypereutrophic (SD DENR 2018). Reservoirs represent 70% of the publicly owned and managed lakes in South Dakota, while natural lakes only represent 30% (SD DENR 2018). Stream impoundment occurs throughout the state but more frequently in the drier regions west of the Missouri River, allowing more efficient water management, reduced flooding and providing water sources for livestock and crops.

Field Surveys

A freshwater mussel survey of eastern South Dakota lakes was conducted in the summer of 2017. Sample sites (n=116) were selected from the South Dakota Department of Environmental Natural Resources (SD DENR) publicly owned and managed lakes data set, following the statewide stream survey's site selection protocol (Faltys 2016). Survey sites (n=116) were proportionally and randomly assigned to publicly owned and managed lakes and reservoirs within each of the six major river basins based upon river basin size. If landowner permission was not obtained to access a lake or there was a lack of water, that lake was replaced randomly with a different lake within the same river basin.

We implemented two person-hour timed searches at each lake survey site (DeLorme 2011, Faltys 2016). Timed searches provide an effective means of surveying larger areas for the purpose of documenting species occurrence of broader areas (Smith et al. 2001). Each selected lake was searched starting at the nearest lake access point or most optimal habitat (i.e. avoiding cattail dominated shoreline). Lakes within this region have poor visibility, therefore searching for mussels was done by feel and using a zig-zag motion parallel to the shoreline (out to ~1.5 m in water depth). The two person-hour search was divided into two equal intervals to allow for specimens from the two surveyors to be combined and properly recorded (DeLorme 2011). GPS coordinates were taken at the start, middle and end of the search area to calculate total length of the search area and mussel location within the search area. At the end of each search, all living and dead shells were measured (i.e. anterior-posterior, dorsal-ventral and depth) and properly identified based upon regional identification keys (Oesch 1984, Cummings and Mayer 1992, Sietman 2003). Vouchers and photo documentation of new species were taken for the South Dakota Aquatic Invertebrate Collection located at South Dakota State University in Brookings, SD. Any additional specimens were returned to the lake.

Abiotic parameters were measured during the sampling efforts of each lake. Lake transparency was measured with a Secchi tube at each lake site, while Secchi disk readings were only taken at lakes sampled between 10 A.M. and 2 P.M (Carlson 1977). During the search efforts, water quality parameters (i.e. pH, conductivity, dissolved oxygen and temperature) were taken with a YSI multiparameter sonde. Readings were taken towards the bottom of the water column, at the start, midpoint and endpoint of search (Appendix 2-3). Water depth and substrate particle size (i.e. gravelometer) was recorded wherever a mussel was found.

Analysis

Distribution, species occurrence and abundance were summarized based on river basin, and basin type (natural lake or reservoir). Distribution was based on species occurrence using ArcMap and Microsoft Excel to determine presence and absence of species within each river basin. Occurrence was determined based on the number of lakes with species present, represented by live and dead shells. Relative abundance was calculated based upon the total counts of live and dead shells of each species relative to all species (river basin and basin type). Species richness was calculated based on river basin and basin type. A Spearman rank correlation was used to evaluate relationships between mussel abundance and measured abiotic factors (pH, dissolved oxygen, conductivity, temperature, substrate particle size, water depth and water transparency).

RESULTS

A total of 1,789 freshwater mussels were collected during our survey, including 1,053 (59%) live specimens and 736 (41%) dead shells (Figure 1). Evidence of freshwater mussels occurred at 50 (43%) lake sites and 41 (35%) lake sites had live mussels. A total of nine species, from two different orders, were found throughout five of the six major river basins (Table 1; Appendix 2-1, 2-2).

Abiotic factor ranges were recorded from lakes containing freshwater mussels (Appendix 2-3). Dissolved oxygen ranged from 5.26 – 21.13 mg/L, conductivity ranged from 352 – 4096 uS/cm, temperature ranged from 10.65 – 31.69 °C and pH ranged from 7.66 – 10.05. Transparency ranged from 16 – 120 cm, substrate ranged from 1 – 17.79 mm and depth ranged from 17.67 – 150.36 cm.

Occurrence and Distribution

Pyganodon grandis was the most frequently occurring species across all sampled lake sites, found at 36% of sites (Figure 2, Figure 3-A). *Amblema plicata*, *Dreissena polymorpha*, *Fusconaia flava* and *Truncilla truncata* occurred in low abundances (except D. polymorpha) across all sampled lakes, being found at 0.86% of sites (Figure 3-A).

P. grandis was the most frequently occurring species in all river basins, excluding the Red River basin where no mussels were collected. *P. grandis* occurred in 48% of sites in the Big Sioux River basin, 45% of sites in the James River basin, 17% of sites in the Minnesota River basin, 30% of sites in the Missouri River basin and 14% of sites within the Vermillion River basin (Figure 3-A). *Lampsilis siliquodea* occurred in the Big Sioux (16% occurrence), James (6% occurrence) and Minnesota (17% occurrence) river basins (Figure 3-B). *Lasmigona complanata* only occurred in the Big Sioux (3% occurrence) and James (9% occurrence) river basins (Figure 3-B, Appendix 2-1). Occurrence of some species were only found in one river basin, *A. plicata* only occurred in the Big Sioux river basin, *F. flava* and *T. truncata* were only found in the James river basin, and invasive species *C. fluminea* and *D. polymorpha* were found in the Missouri river basin (Figure 3-B, Appendix 2-1). *Potamilus alatus* had a low occurrence of 3% in both the James and Missouri river basins (Figure 3-B).

P. grandis was the most frequently occurring species in both lake types, occurring in 39% of sampled natural lakes and 35% of reservoir basins (Figure 3-C). *L. siliquodea* only occurred in 12% of natural lakes and did not occur in reservoirs (Figure 3-C, Appendix 2-1). There was a 1.5% occurrence of *A. plicata, L. complanata* and *P. alatus* within natural lake basins (Figure 3-C, Appendix 2-1). *D. polymorpha* only occurred in natural lakes, while *C. fluminea* only occurred in reservoir basins (Figure 3-C). *L. complanata* was the second most frequently occurring species within reservoirs, comprising 6% of sampled sites (Figure 3-C, Appendix 2-1). *F. flava, P. alatus* and *T. truncata* only occurred in 2% of reservoirs (Figure 3-C, Appendix 2-1).

Abundance

The most abundant species from all sampled sites was *Pyganodon grandis*, representing 75.9% of all mussels found (Table 1). The second most abundant species from all sampled sites was *Lampsilis siliquodea,* comprising 19.61% of all mussels collected (Table 1). All remaining native species, *Amblema plicata, Fusconaia flava,* *Lasmigona complanata*, *Potamilus alatus*, and *Truncilla truncata,* each represented less than 1% of abundance from all sampled sites (Table 1).

The James River basin contained 55.9% of all mussels collected (Table 1). Within the James River basin, *P. grandis* had the highest abundance of 67.3% of all specimens collected (Table 2). *L. siliquoidea* was the second most abundant species within the James River basin, comprising 30.5% of specimens found (Table 2). Few individuals were collected for *F. flava, L. complanata, P. alatus* and *T. truncata* within the James River basin (Table 2). Mean abundance of mussels per lake basin was highest from the James River basin (30.3 mussels), but there was no statistical significance among river basins (K-Wallis, p=0.657) (Table 4).

The Missouri River basin ranked second in total mussel abundance, with26.22% of all mussels collected (Table 1). There was a mean abundance of 12.7 mussels per lake basin found within this river basin (Table 4). *P. grandis* was the most abundant species collected, comprising 84.65% of the basin's abundance (Table 2). *L. siliquodea* comprised 3.41% of abundance and *P. alatus* represented 0.43% of the abundance (Table 2). Invasive species *C. fluminea* and *D. poloymorpha* were only collected in this river basin.

The Minnesota River basin contained 9.89% of all mussels collected (Table 1). Mean abundance of mussels collected per lake site was 26.5 mussels (Table 4). *P. grandis* was the most abundant species within this river basin, comprising 89.27% of the abundance (Table 2). *L. siliquoidea* compried 9.60% of the basin's abundance and *L. complantata* represented 1.13% of the abundance (Table 2).

The Big Sioux River basin contained 7.94% of all mussels collected (Table 1). Mean abundance of mussels collected per lake basin was 4.6 mussels (Table 4). *P. grandis* was the most abundant species within the river basin, representing 90.14% of the basin's abundance (Table 2). A few individuals were represented for *L. siliquoidea* (9.16%) and *A. plicata* (0.70%) (Table 2). The Vermillion River basin represented 0.05% of all mussels collected (Table 1). There was only one specimen collected of *P. grandis.* There were no specimens collected within the Red River basin.

P. grandis was the most abundant species found in natural lakes (59.93%) and reservoirs (92.37%) (Table 1). *L. siliquoidea* was the second most abundant species within sampled natural lakes, comprising 38.53% of specimens collected (Table 1). Abundances of *A. plicata, L. complanata* and *P. alatus* were all comprised less than 1% of abundance within natural lakes (Table 1). *L. complanata* represented only 1.59% of the abundance found in reservoir sites (Table 1). *F. flava* and *T. truncata* were only found within reservoirs, each representing relative abundances less than 1% (Table 1).

Species Richness

The James River basin had the greatest richness of six species collected from natural lakes and reservoirs (Table 1). The Big Sioux River and Missouri River basins each had four species collected throughout sampled sites (Table 1). Two species were collected from the Minnesota River basin and no species were collected from lakes in the Red River basin (Table 1). Species richness based on lake type showed there to be six species found in both natural lakes and reservoirs (Table 1).

Relationship to Abiotic Environment

We used the Spearman rank correlation to determine what abiotic factors were correlated with mussel abundance. Conductivity was negatively correlated with abundance (rho = -0.37, p= 0.0001); as conductivity increases, mussel abundance decreases (Table 3). Lake transparency was positively correlated with abundance (rho = 0.23, p= 0.014); as Secchi depth increased, mussel abundances also increased (Table 3). No significant correlations were observed with dissolved oxygen, temperature, pH, depth and substrate particle size (Table 3).

Invasive Species

Our survey indicated the occurrence of two invasive species, *Corbicula fluminea* (Asian calm) and *Dreissena polymorpha* (Zebra mussel). Zebra mussels were documented from McCook Lake (Union Co.), while Asian clams were found in Yankton Lake (Yankton Co.) and Westside Community Fishing Pond (Yankton Co.) (Appendix 2-1). Zebra mussels have been documented in South Dakota since August of 2015 (Hult 2015). Asian clams were first documented near Gavin’s Point Dam in 2009 (Edgar and Schilling 2009). All occurrences were within the Missouri River basin near Gavin’s Point Dam (Appendix 2-1).

DISCUSSION

There has been limited unionid research conducted within South Dakota, with the first statewide survey of wadable streams only completed in 2016 (Faltys 2016). In the past, mussel research in South Dakota has only focused on streams and rivers (Perkins et al. 1995, Skadsen 1998, Perkins and Backlund 2000, 2003, Skadsen and Perkins 2000, Hoke 2003, Wall and Thomson 2004, Ecological Specialists 2005, Perkins 2007), but with this study we have looked at distribution, species occurrence and abundance in natural lakes and reservoirs stratified by major river basin, and basin type in the eastern half of the state. Since there is no historical data on unionids in lakes of South Dakota, we cannot examine past records to determine if species have been lost or gained in these systems. Faltys (2016) estimated loss of 58% of the state's wadable stream species over the past 20-30 years. Our survey found two invasive species, *C. fluminea* and *D. polymorpha*, that are new additions to South Dakota's overall mussel assemblages.

The James River basin had the highest species abundance and richness among the river basins. Coker and Southall (1915) were the first to document unionids on the James River, stating that there was high abundance and economic value of mussels in this river compared to other rivers within South Dakota. Nearly 90% of specimens collected were *Amblema plicata* which was highly sought out by fisherman (Coker and Southall 1915), but during our searching efforts we did not find any evidence of *A. plicata* from James River basin lakes or reservoirs. All native species during our survey were also documented from a survey done by Perkins and Backlund (2003) on the James River, their findings still had a high representation of mussel abundance similar to Coker and Southall's (1915). A survey of the James River tributaries found only six species, four of those species were documented within our survey (*Pyganodon grandis, Lasmigona complanata, Potamilus alatus and Lampsilis siliquoidea*) (Wall and Thomson 2004). Our collections were comprised of reservoir-tolerant species that are able to adapt to more turbid and silty sediments (Lydeard et al. 2004, Grabarkiewicz and Davis 2008) When comparing our findings to historical stream and tributary data, all species within the James River basin have been accounted for in past surveys but there were other species that were not documented during our survey (Chapter 1, Table 1).

There were two significant relationships observed in our correlation analysis of abundance and abiotic factors. We observed a significant negative correlation between mussel abundance and conductivity, while there was a positive correlation between abundance and water transparency. Dissolved oxygen, temperature, pH, depth and substrate were not found to be highly correlated with mussel abundance. Studies have observed when conductivity levels increase, species abundances decline (Begley 2013, Vander Laan et al. 2013). Our results also suggest a negative relationship between abundance and water transparency. Reduced water transparency can result from enhanced primary production and resuspension of sediment from the bottom of shallow prairie lakes. Many of South Dakota's lake basins are considered eutrophic or hypereutrophic (SD DENR 2018). These lakes experience seasonal blooms of noxious blue green bacteria which may impede filter feeding of mussels. As these blooms die-off, oxygen deficits may also stress gill-breathing mussels.

Pyganodon grandis (Giant Floater) was the most abundant and frequently occurring species throughout all river basins and lake types within our study. In many studies within South Dakota river and stream surveys, *P. grandis* was the most frequently occurring and abundant species (Skadsen 1998, Perkins and Backlund 2000, Wall and Thomson 2004). *P. grandis* has thrived in various habitats and has been referred to as a habitat generalist (Vanleeuwen and Arruda 2001, Grabarkiewicz and Davis 2008). Results from a survey below Gavin's Point Dam showed that *P. grandis* was commonly found within the muddy substrate in backwaters of tributaries, similar to the environment of many prairie pothole lakes (Perkins and Backlund 2000).

The second most abundant and frequently occurring species during the survey was *Lampsilis siliquoidea* (Fatmucket). It has been well documented throughout historical surveys within South Dakota, as it is a widespread, highly silt tolerant species (Perkins and Backlund 2000, Grabarkiewicz and Davis 2008). Surveys have noted that some freshwater mussel species, like *L. siliquoidea*, are not able to adapt to canal or reservoir habitats (Hoke 2011). We found this species only from natural lake basins. Our results suggest that *L. siliquoidea*, although frequently occurring within the region, might not be adaptable to reservoir basin morphology.

Amblema plicata (Threeridge), *Fusconaia flava* (Wabash Pigtoe) and *Truncilla truncata* (Deertoe) were all collected from our survey. *A. plicata* is a highly tolerant, widely distributed mussel within North America (Grabarkiewicz and Davis 2008). *A. plicata* was harvested extensively for making ornaments and kitchen utensils, it was not as valuable in the pearl-button industry as it lacked uniformity of color (Stein 1973). In South Dakota, *A. plicata* use to be one of the most frequently occurring and abundant species within the James River (Coker and Southall 1915). *F. flava* has only been documented three times within the state, with minimal abundances being found (Perkins et al. 1995, Perkins and Backlund 2003, Faltys 2016). Although *F. flava* is found in many types of water systems and substrate types, they do prefer a more stable substrate of sand, gravel or cobble (Grabarkiewicz and Davis 2008). Both *A. plicata* and *F. flava* were not documented historically within the Upper (Headwaters) Mississippi River drainage in Minnesota, but during a statewide survey both species were documented and noted as recent introductions (Minnesota Department of Natural Resources 2004). *T. truncata* was not documented in South Dakota until 2000 (Perkins and Backlund 2000). Due to *T. truncata* being smaller in size and a burrower compared to *F. flava*, who resides on the substrate surface, predators will select other larger, easier to find unionids (Tyrrell and Hornbach 2006). Our results show that these species are present, but occur infrequently and are not abundant in our lakes and reservoirs.

Lasmigona complanata (White Heelsplitter) and *Potamilus alatus* (Pink Heelsplitter) were documented at low abundances during our survey. Both species have a distinctive dorsal wing, overall size and color of nacre vary between species (Sietman 2003, Grabarkiewicz and Davis 2008). *L. complanata* is well adapted to reservoirs and a wide range of substrates, being commonly found in silt similar to many lake bottoms within eastern South Dakota (Grabarkiewicz and Davis 2008). Highest abundance of *L. complanata* from our study were found in reservoirs. *P. alatus* is known for its quick re-burrowing into disturbed substrates, similarly to shifting silty substrates in this region (Levine et al. 2014). Juvenile *P. alatus* have exhibited stronger survival in finer sediments when compared to sandy substrates, this is because of more beneficial bacteria and organic material for juvenile populations (Hau 2005). Our survey indicates that both of these species are present, but occur infrequently and are not abundant in South Dakota lakes and reservoirs.

We documented the occurrence of *Dreissena polymorpha* (zebra mussel) and *Corbicula fluminea* (Asian clam) in three lakes of eastern South Dakota. These invasive species have high fecundity, rapid dispersal rates, filter large amounts of water, and compete effectively for food resources (Mackie 1991, Sousa et al. 2009). It is important to monitor the larval, juvenile and adult stages within infested lakes to determine how quickly the spread is occurring (Stangel and Shambaugh 2005). Having knowledge of native mussels in infested and invasive free lakes is beneficial for historical records to facilitate future management.

Globally, freshwater mussels are the most threatened and endangered aquatic fauna (Bogan 1993, Strayer 2014). With increased habitat destruction and invasive species introductions, this fauna remains in a critical state (Bogan 1993, Patzner and Muller 2001, Lydeard et al. 2004, Strayer 2008). This is why management and conservation strategies need to be implemented to conserve and protect remaining populations (Downing and Downing 1992). Surveys of unionid populations can be used to document populations declines, changes to assemblage structure and changes in distributions (Williams et al. 1993). When implementing survey studies, there is a high importance of being able to find rare or endangered species for documentation purposes (Metcalfe-Smith et al. 2000, Smith et al. 2001). Populations such as *A. plicata, F. flava, L. complanata, P. alatus* and *T. truncata* whose populations have declined or have been minimally documented within South Dakota need to be properly managed and monitored.

We successfully completed the first unionid mussel survey in eastern South Dakota lakes, but there are still more lakes to be sampled to determine where other mussel assemblages might exist. We suggest that conservation strategies should be implemented for species that were minimally documented within sampled lakes. Continued monitoring of lakes with invasive species needs to be done. A mussel monitoring program would be beneficial for the S.D. Game, Fish and Parks as it would provide information on distributions and population estimates of species (Dolloff et al. 2013). Volunteer mussel monitoring programs have been created by state agencies to gain a better perspective of mussel species occurrences and populations statewide (Weinzinger 2018).

Table 1. List of all freshwater mussels found during the 2017 survey of eastern South Dakota lakes. Counts include live and dead shells to calculate relative abundance (R.A.) (total found of a species divided by the overall total count of freshwater mussels collected). Relative abundance in calculated for all sampled sites, natural lakes and reservoirs.

	River Basins						All Sampled Sites			Natural Lakes			Reservoirs		
Species	Big Sioux	James	Minnesota	Missouri	Red	Vermillion	Alive	Total Found	R.A. %	Alive	Total Found	R.A. %	Alive	Total Found	R.A. %
Unionida															
Unionidae															
Amblema plicata	X						1	1	0.05	1	1	0.11	0	0	0.00
Fusconaia flava		X					2	2	0.11	0	0	0.00	2	2	0.23
Lasmigona complanata	X	X					7	16	0.89	1	2	0.22	6	14	1.59
Lampsilis siliquoidea	X	X	X				340	351	19.61	340	351	38.53	0	0	0.00
Potamilus alatus		X		X			3	4	0.22	1	2	0.22	2	2	0.23
Pyganodon grandis	X	X	X	X		X	667	1357	75.90	198	546	59.93	469	811	92.37
Truncilla truncata		X					4	4	0.22	0	0	0.0	4	4	0.46
Veneroida															
Corbiculidae															
Corbicula fluminea				X			20	45	2.50	0	0	0.00	20	45	5.12
Dressenidae															
Dreissena polymorpha				X			9	9	0.50	9	9	0.99	0	0	0.00
TOTAL	4	6	2	4	0	1	1053	1789	100.0	550	911	100.0	503	878	100.0

Table 2. A list of all freshwater mussels collected based on river basin from the 2017 survey of eastern South Dakota lakes. Counts include live and dead shells to calculate relative abundance (R.A.). Relative abundance is calculated for all sampled sites based on river basin.

	Big Sioux		James		Minnesota		Missouri		Vermillion	
Species	Total Found	R.A.	Total Found	R.A. %	Total Found	R.A. %	Total Found	R.A. %	Total Found	R.A. %
Unionida										
Unionidae										
Amblema plicata	1	0.70								
Fusconaia flava			2	0.20						
Lasmigona complanata			14	1.40	2	1.13				
Lampsilis siliquoidea	13	9.16	305	30.50	17	9.60	16	3.41		
Potamilus alatus			2	0.20			2	0.43		
Pyganodon grandis	128	90.14	673	67.30	158	89.27	397	84.65	1	100.0
Truncilla truncata			4	0.40						
Veneroida										
Corbiculidae										
Corbicula fluminea							9	1.92		
Dressenidae										
Dreissena polymorpha							45	9.59		
TOTAL	142	100.0	1000	100.0	177	100.0	469	100.0	1	100.0

Table 3. Spearman rank correlations of abiotic factors based on mussel abundance.

Abiotic Factors	Correlation	p-value
Dissolved Oxygen	0.03	0.779
Conductivity	-0.36	< 0.01
Temperature	0.07	0.415
pH	-0.14	0.137
Transparency	0.23	0.014
Depth	-0.02	0.727
Substrate	-0.15	0.101

Table 4. Mean values of species abundance based on river basin.

River Basin	*N*	Species Abundance	Range
Big Sioux	31	4.6	0 – 45
James	33	30.3	0 – 289
Minnesota	6	26.5	0 – 155
Missouri	37	12.7	0 – 100
Red	2	0.0	0 – 0
Vermillion	7	0.1	0 – 1

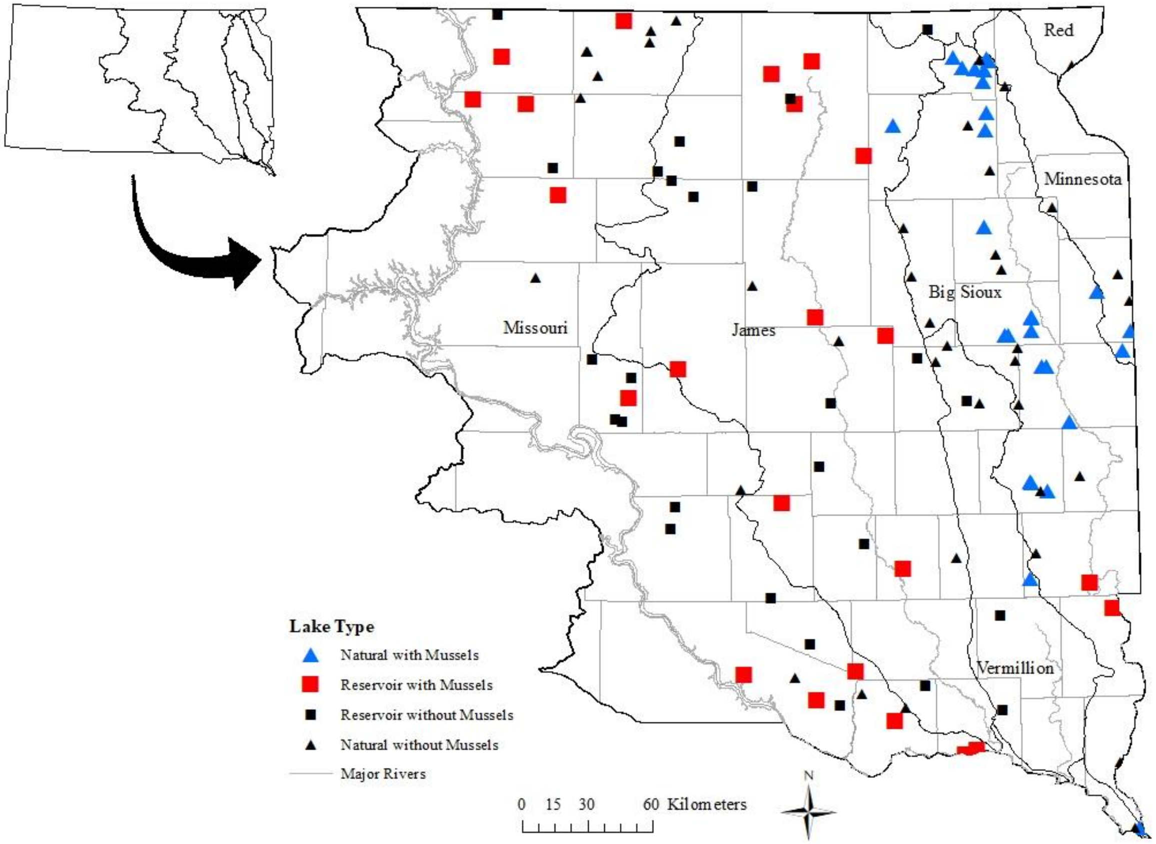

Figure 1. Map illustrating where mussel surveys (n=116) occurred within the six major river basins of eastern South Dakota. Natural lakes and reservoir are denoted by a triangle and square, respectively if mussels were present. Sites with no mussels are denoted with either a black triangle for natural lakes or a black square for reservoirs.

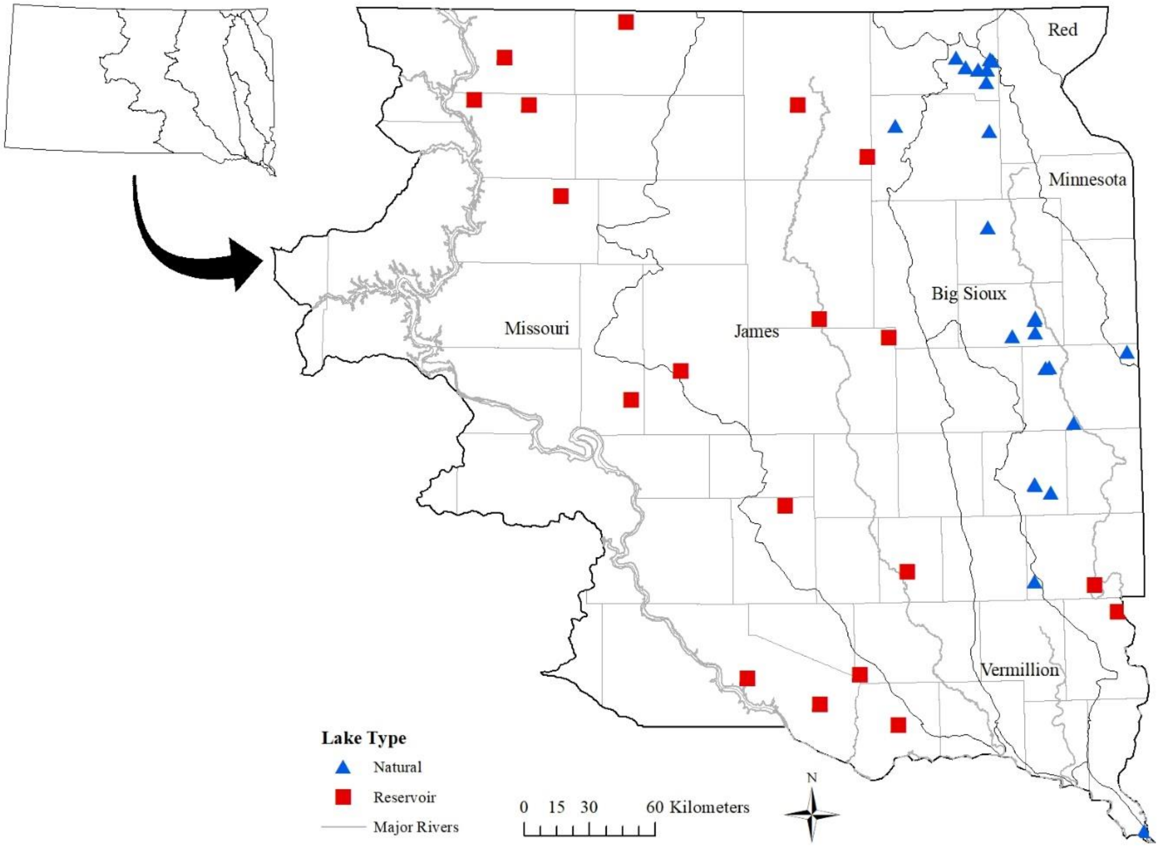

Figure 2. Site locations that had evidence of *Pyganodon grandis* (n=42). Sites are labeled by their corresponding lake types, natural and reservoir.

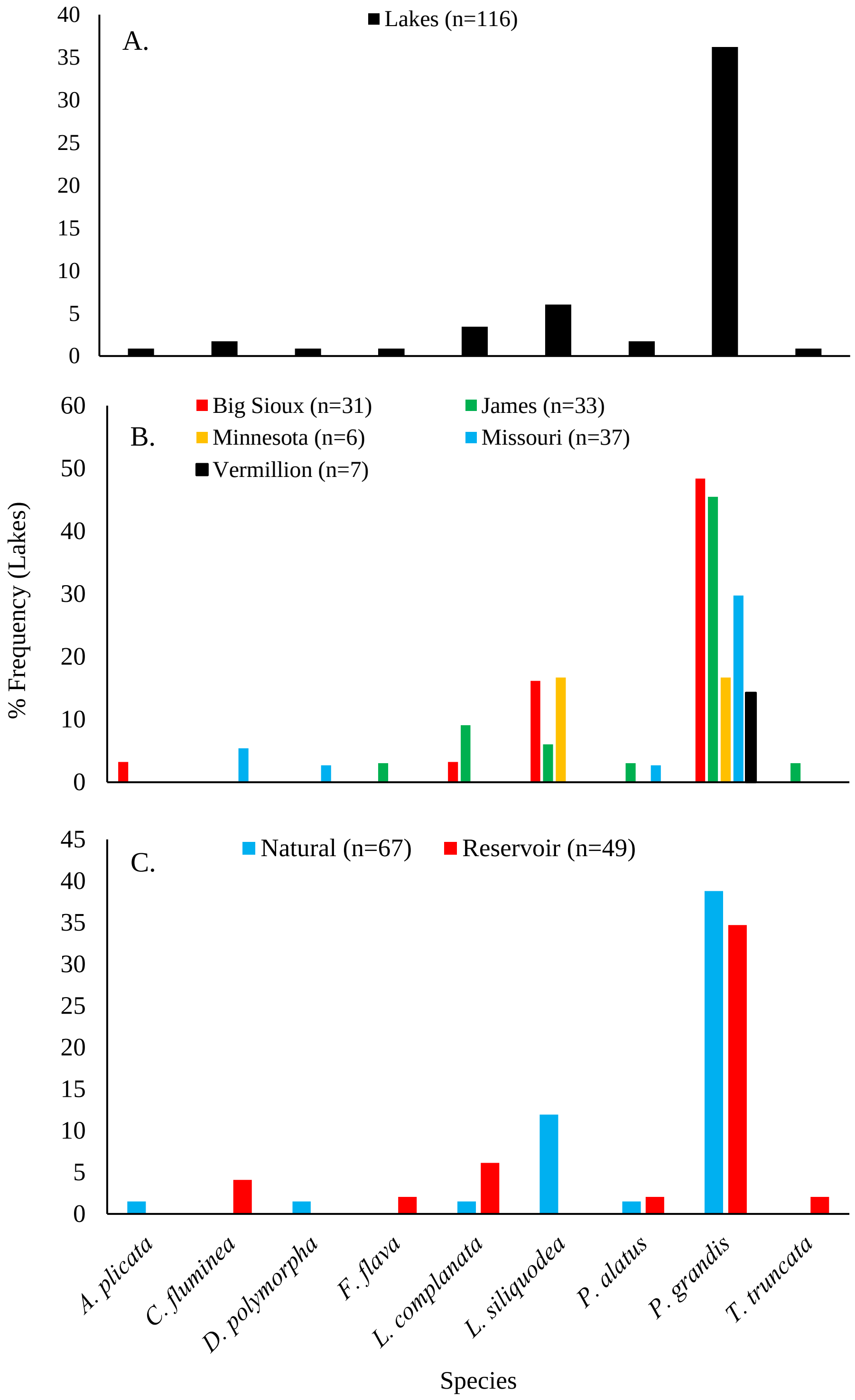

Figure 3. Relative frequency of occurrence of species within sampled lakes (n=116) based on A. all sampled lakes, B. river basins and B. lake type.

CHAPTER 3: AGE, GROWTH AND MORTALITY OF PYGANODON GRANDIS IN SOUTH DAKOTA NATURAL LAKES AND RESERVOIRS IN RELAION TO TROPHIC STATE

ABSTRACT

Environmental impacts to a body of water can be assessed using freshwater mussels due to their long-lived, sessile behavior. Cultural eutrophication can cause impacts to lake basins through enhanced sediment, phosphorus and nitrogen loading. South Dakota is well known for its agricultural production, which in return causes lakes to have high levels of runoff of fertilizers and sediments. Our goal was to evaluate relationships between age, growth and mortality of *Pyganodon grandis* (Giant Floater) and lake trophic state. Using data collected from our 2017 eastern South Dakota freshwater mussel lake survey, we found 21 sites that contained live and dead *P. grandis*. Shells were thin-sectioned, aged and growth increments measured under microscopy. von Bertalanffy growth curves were generated to estimated growth rates, estimated length and estimate length-at-age keys to estimate instantaneous and annual mortality rates. *P. grandis* age was found to be negatively correlated with lake trophic state (R^2= 0.394, p= 0.022). We observed no significant relationships for growth rates and rates of mortality. Mean age was marginally higher from reservoirs versus natural lakes (p= 0.054). Results indicate that *P. grandis* occupying more culturally enriched natural lake basins have shorter lives. As this species is considered a generalist, we consider our results to be conservative with respect to the effects of cultural eutrophication on mussels within the northern plains.

INTRODUCTION

Freshwater mussels are some of the longest lived organisms, with ages surpassing 100 years and reaching ages up to 280 years (Bauer 1992, Dunca et al. 2005). Globally invertebrates comprise almost 99% of all animal diversity, yet they are underrepresented in research and conservation (Lydeard et al. 2004). Greater attention should directed to unionid study as 65% of North American unionid mussels are listed as threatened, vulnerable or endangered (Haag and Williams 2014). Studies of mussel shells have been conducted to assess environmental impacts (Carell et al. 1987, Ostrovsky et al. 1993). Each year a mussel grows a layer primarily composed of calcium carbonate, but contaminants may also be deposited (Carell et al. 1987). Age and growth based upon shell measurements can be used to evaluate the influence of factors such as water velocity, food availability, substrate composition and environmental degradation on resident populations (Bauer 1992, Fritts et al. 2017).

Declines of unionid populations in North America can be linked to various types of habitat deterioration (Downing et al. 2010). Invasive species, alteration of flow regimes, toxic substances, siltation and eutrophication have all been connected to unionid declines (Ricciardi et al. 1998, Lydeard et al. 2004, Downing et al. 2010). These environmental impacts have influenced mussel age and growth. Mussels of smaller size and shorter lifespans have been associated with habitat alterations (Bauer 1992). Impaired water chemistries such as low oxygen levels and elevated nitrates can reduce metabolic rates, decrease shell growth, reduce lifespans and increase mortality (Bauer 1992, Dunca et al. 2005). Juveniles and sensitive species are often particularly vulnerable to changes associated with nutrient enrichment (Moorkens 1999, Skinner et al.

2000). Others have observed higher growth rates from mussels found in more nutrient enriched water bodies due to enhanced food availability (Ostrovsky et al. 1993, Dunca et al. 2005).

Lakes within the Great Plains occur in agricultural landscapes, with culturally enhanced inputs of sediment and nutrients (Hall et al. 1999). In South Dakota, 69% of reported publicly owned and managed lakes that are assessed for trophic state were reported to be eutrophic or hypereutrophic (SD DENR 2018). This is due to lakes in eastern South Dakota being affected by sediment and nutrient runoff from agricultural fields (SD DENR 2016).

This study focused on the age, growth and mortality of *Pyganodon grandis* in relation to lake basin (natural vs reservoir) trophic state. We chose *P. grandis* as our model organism due to its widespread occurrence, abundance and tolerance over a variety of habitat conditions. We hypothesized that mean and maximum age of *P. grandis* would be shorter in more culturally eutrophic lake basins. We hypothesized that growth rates of *P. grandis* would be faster and mortality rates would be higher from lakes experiencing greater cultural eutrophication.

METHODS

Study Area

South Dakota is divided in half by the Missouri River, separating glaciated and unglaciated regions. The present day landscape of eastern South Dakota was formed by melted ice deposits during the Late Wisconsin glaciation, creating large numbers of lake basins of varying sizes, commonly referred to as the prairie pothole region (Johnson et al.

1997). This region is comprised of two major level III ecoregions, the Northern Glaciated Plains (NGP) and the Northwestern Glaciated Plains (NWGP) (U.S. Environmental Protection Agency 2013). The NGP dominates over half of the eastern portion of the state with large numbers of glacial lake basins. Historically it is known for its mixed grass prairie, which has largely been converted to cultivated farmland (Auch 2015). The NWGP follows the Missouri River and is identified as a transitional ecoregion since between mid and tall grass prairie. This mixed grass prairie's primary land use is cultivated crops and livestock grazing (Taylor 2015). Six major river basins drain the land area of eastern South Dakota, including the Big Sioux, James, Minnesota, Missouri, Red and Vermillion rivers (Johnson et al. 1997, Gewertz and Errington 2015).

There are approximately 575 publicly owned and managed natural lakes and reservoirs scattered across South Dakota, most characterized as either eutrophic or hypereutrophic (SD DENR 2018). Many of these basins are impounded drainages which provide for better water management, reduced flooding and water sources for livestock and crops. Reservoirs represent 70% of the publicly owned and managed lakes in South Dakota, while natural lakes only represent 30% (SD DENR 2018).

Study Organism

Pyganodon grandis, commonly referred as the Giant Floater (Say, 1829) is an ideal candidate for this study in eastern South Dakota. It was the most frequently occurring and abundant species observed from a recent statewide survey of wadable streams (Faltys 2016). *P. grandis* is one of the most tolerant unionids in North America, adapting to impoundments and increased levels of silt (Grabarkiewicz and Davis 2008). This generalist mussel species has over 35 fish host species, making its populations stable

(Williams et al. 1993, Grabarkiewicz and Davis 2008). *P. grandis* is found throughout the Mississippi River basin, several Gulf drainages and into Canada (Oesch 1984, Cummings and Mayer 1992, Grabarkiewicz and Davis 2008). Key features for identification include a thin, elongated shell, younger shells periostracum is yellowish-tan to green while older shells are light to dark brown, thickened hinge and elevated beak, white and light pink nacre with underdeveloped teeth (Oesch 1984, Cummings and Mayer 1992, Sietman 2003, Wisconsin Department of Natural Resources 2003, Grabarkiewicz and Davis 2008). Shell lengths can reach up to 23 centimeters (Grabarkiewicz and Davis 2008). Aging studies have shown *P. grandis* to have shorter life spans averaging 12 years in age (Hanson et al. 1988, Haag and Rypel 2011).

Collection of Mussels

P. grandis specimens were hand-collected from 21 sites randomly selected throughout the NGP and NWGP ecoregions (Figure 2). Live specimens and dead shells were retrieved from these sites and returned to the lab for sectioning, aging, morphological measurements and determination of growth.

Lake Trophic Status

We measured water transparency and employed the use of the Carlson Trophic State Index (Carlson 1977) to evaluate trophic state of each sampled lake. Because our survey involved site visits outside the recommended window for Secchi depth measurements, we measured water transparency using a Secchi tube at every site. In addition, Secchi disk (SD) measurements were taken from those sites sampled between the times of 10 A.M. and 2 P.M. (Lind 1979). Carlson's Trophic State Index (TSI) was used to categorize each lake site along a trophic state gradient (Carlson 1977).

$$Secchi\ Depth\ (SD):\ TSI(SD) = 60 - 14.41 \ln(SD)$$

Secchi tube measurements were converted to Secchi disk equivalents based on regression of paired (n=42) Secchi depth and Secchi tube readings (R^2=0.694, $p < 0.01$) (Figure 1). Predicted Secchi disk readings were then applied to the TSI equation to generate an index value.

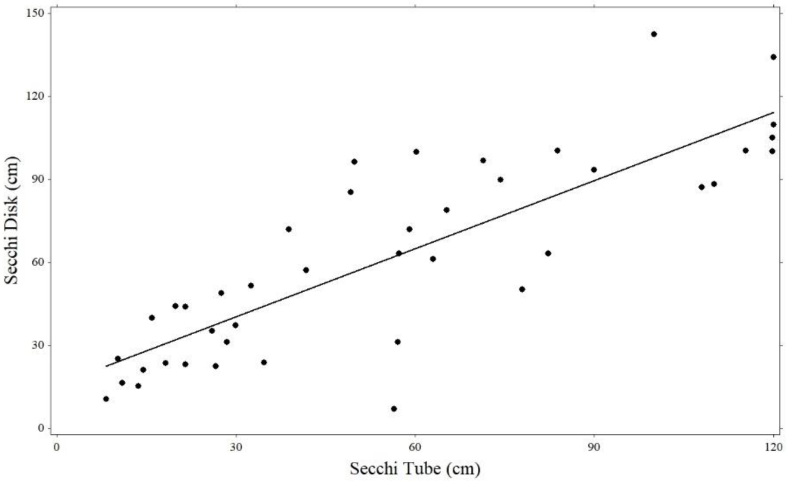

Figure 1. Linear regression relationship of paired Secchi tube and Secchi disk readings (n=42).

$$Secchi\ Disk = 15.68\ \times\ 0.82(Secchi\ Tube)$$

Age and Growth

Up to ten *P. grandis* specimens were collected at random from each lake basin site containing live specimens and returned to the laboratory for aging and growth measurements. Measured live and dead shells of *P. grandis* not collected for age determinations were used to predict age-at-length. To determine age structure we created thin sections following the procedure described by Neves and Moyer (1988). A cut from the umbo towards the ventral margin of the shell was made using a wet tile saw with a diamond studded blade. The cut shell was bonded to a Plexiglass slide (4.25 in. X 7.25 in.) with epoxy and a second cut was made after a minimum of a 24-hour drying period to create a thin 2 mm section. Fine sandpaper was used to polish the thin section.

Age and growth measurements were determined using an OLYMPUS model SZX12 zoom dissecting microscope and OLYMPUS CellSens Dimension 1.16 imaging software. True annuli were counted and measured from the umbo to the shell margin along each thin section (Rypel et al. 2008). A second reader checked 25% of the aged shells for accuracy. Growth of each mussel within a lake or reservoir was modeled using the von Bertalanffy growth curve (VBGC) (Appendix 3-1) (von Bertalanffy 1938, Haag and Rypel 2011).

$$L_t = L_{inf}(1 - e^{-k(t-t_0)})$$

L_t represents length (cm) at time t (age in years). The estimated length (cm) at time infinity is represented by L_{inf}. The growth coefficient (K) provides a measure of how quickly the specimen will reach L_{inf} (Bauer 1992). Growth increments for each age were measured using imaging software, which then allowed estimates of growth for each age using the VBGC (Anthony et al. 2001). Back-calculated length-at-age for each specimen was required to calculate average length-at-age and standard deviation for each age class within each lake basin (Jones and Neves 2011).

Length-At-Age Analysis

Measured live and dead shells of *P. grandis* not collected for age determination were used to predict length-at-age. The dorsal-ventral dimension was used in these calculations to coincide with thin sections used for aging. We used ages derived from our thin section analysis to construct age-length keys following Ogle (2016). Mean length-at-age was calculated and 1-cm length bins were assigned which allowed us to group unaged specimens to a class. Ages were assigned to all unaged alive and dead *P. grandis* specimens based on those lakes where live *P. grandis* were collected (n=21).

Catch-Curve Analysis

Using VBGC and length-at-age keys we are able to construct catch-curves to predict mortality rates. Instantaneous total mortality rate (Z) follows a linear trendline:

$$Z = \log(C_t) - \log(C_{t+1})$$

This metric provides a measure of mussel mortality at any given time. This instantaneous rate can then be converted into a total annual mortality rate (A) using the equation below (Jones and Neves 2011):

$$A = 1 - e^{-Z}$$

Assumptions of catch-curve analysis include: constant recruitment, equal survival among age classes, steady survival from year to year, natural consistent mortality in a given year, and fitted catch-curves that are not bias to a certain age class (Jones and Neves 2011, Ogle 2016).

Basin Type Differences

Each lake served as an experimental unit within our study. Thus, means of maximum age (A_{max}), growth coefficient (K), estimated length (L_{inf}), instantaneous mortality rate (Z), and annual mortality (A) for natural lakes and reservoirs were compared using a two-sample t-test. We used the Satterthwaite t-test for comparison of means as variances of the two groups were unequal.

Relationships with Lake Trophic State

To evaluate relationships with lake trophic state, we regressed maximum age (A_{max}), growth coefficient (K), estimated length (L_{inf}), instantaneous mortality rate (Z), and annual mortality (A) of *P. grandis* against each lake's trophic state index. A significant slope coefficient was used to evaluate our prediction of significant relationships with lake trophic state.

RESULTS

Data from our 2017 survey revealed that 13 natural lakes (19% of all natural lakes) and 8 reservoir sites (16% of all reservoirs) contained live and dead shells of *Pyganodon grandis* (Chapter 2). These sites were distributed in the Big Sioux, James, Minnesota and Missouri river basins, no lakes within the Red river basin during our survey contained evidence of mussels (Figure 2). Trophic State Index values ranged from 55.8 to 98.3 across all lakes containing *P. grandis* (Table 1). Mean TSI for natural lakes was 68.9, while reservoirs had a mean of 68.7 (Table 1).

Age and Growth

A total of 1,178 live and dead *Pyganodon grandis* were utilized to calculate age and growth curves. Ages in natural lakes ranged from 4 to 9 years, while the range from reservoirs was 6 to 11 years. Natural lakes had a mean age of 6.1 years, while *P. grandis* found in reservoirs had a mean age of 7.8 years (Table 2). A marginal significant difference in age was observed when comparing age means of natural lakes and reservoirs (t-test, p=0.054).

A total of 178 *P. grandis* from 21 lakes were aged to estimate length-at-age keys of unaged specimens. Mean estimated length (L_{inf}) of natural lakes was 9.71 cm, while reservoirs had a mean of 12.90 cm (Table 2). Mean growth coefficients (K) for natural lakes and reservoirs were 0.27 and 0.23 cm $\cdot$ year^{-1}, respectively (Table 2). There were no statistical differences observed in estimated lengths (L_{inf}) (t-test, p=0.115) or growth coefficients (K) (t-test, p=0.406) between lake types.

Mortality Rates

Instantaneous mortality (Z) and total mortality (A) rates were compared between lake trophic states. The first three years were not included in the analysis, because *P. grandis* is not fully mature until the age of 4 or 5 and recruited to the population (Cummings and Graf 2010, Thorp et al. 2014). Reservoirs displayed a higher mean instantaneous mortality rate than natural lakes, but there was no significant difference (t-test, p=0.207) (Table 2). Mean annual mortality rate across all basin types was of 36.7% and slightly higher in reservoirs compared to natural lakes, but there was no significant difference between lake types (t-test, p=0.208) (Table 2).

Relationships with Lake Trophic State

Age, growth and mortality parameters were all regressed against the calculated trophic state index for each basin. Maximum age regressed was found to vary negatively with natural lake trophic state (R^2= 0.394, p= 0.022) but no significant relationship was observed for reservoir *P. grandis* (R^2=0.099, p=0.447) (Figure 3). Growth, estimated length, instantaneous mortality and annual mortality did not vary significantly with lake trophic state for natural lakes or reservoirs (Figures 4-7).

DISCUSSION

Pyganodon grandis is a widely distributed generalist unionid in North America, found from the Gulf of Mexico to central Alberta, Canada (Kesler and Van Tol 2000). We chose *P. grandis* as our model species due to its wide distribution, high occurrence and high abundance relative to other species. *P. grandis* was also the most frequently encountered and abundant species during a recent statewide stream survey (Faltys 2016) and eastern South Dakota lake basins (Chapter 2). *P. grandis* has been used as a test organism to evaluate environmental disturbances (Grabarkiewicz and Davis 2008). Their growth trends have been compared in two different borrow pits (Kesler and Van Tol 2000). *P. grandis* also served as a test organism to evaluate uptake methyl mercury and its biological effects within lake systems (Malley et al. 1996).

We observed maximum age of *P. grandis* from natural lake basins to be negatively correlated with lake trophic state. Increased food quantity within a system can increase mussel growth rate (Strayer 2014), but our findings support those of others that faster growth rates corresponded to shorter life spans in more culturally enriched systems

(Bauer 1992, Patzner and Muller 2001, Haag and Rypel 2011, Haag 2012). Studies have found *P. grandis* to have a maximum age of 9 to 12 years, similar to our findings, and age of maturity ranges from 4 to 5 years (Haag and Rypel 2011, Thorp et al. 2014). It has been common for freshwater mussels to be labeled as long-lived, slow-growing species, but as Haag and Rypel (2011) found this is not the most representative description for this species. Tolerant, generalists such as *P. grandis* tend to have faster growth rates and shorter life spans (Haag and Rypel 2011). In a similar study, Bauer (1992) found the maximum life span of *Margaritifera margaritifera* (Pearl Mussel) was reduced in habitats with elevated nitrate and increased habitat productivity. Thus, our findings and those documented by others suggests that mussel age is likely to get shorter in response to cultural eutrophication.

We expected to see a positive correlation between *P. grandis* growth rate and lake trophic state in natural lakes and reservoirs. However, our results instead showed no significant relationship. Increased productivity of a system allows for more food availability to freshwater mussels (Strayer 2014). Age and growth have an inverse relationship, as one variable increases, the other decreases (Bauer 1992, Patzner and Muller 2001, Haag and Rypel 2011). Cultural eutrophication presents trade-offs of enhanced food production but altered or reduced food quality. Eastern South Dakota lakes are plagued by seasonal blooms of blue-green bacteria, some of which are capable of producing cyanotoxins. Thus, growth responses may be balanced not only be availability of food mass but also changing quality. Bauer (1992) looked at variation in growth of *Margaritifera margaritifera* (Pearl Mussel) and found there to be a negative correlation with eutrophication, stating the results to this relationship is open to question.

In contrast, multiple studies have noted increased growth in response to nutrient enrichment and productivity (Arter 1989, Ostrovsky et al. 1993, Dunca et al. 2005, Strayer 2014, Fritts et al. 2017). Although we expected similar results, *P. grandis* growth appears conservative relative to the range of trophic states represented within our study.

Our results displayed no significances between mortality parameters of *P. grandis* and lake trophic state. Bauer (1992) found that elevated levels of nitrate led to increased mortality of *Margaritifera margaritifera* (Pearl Mussel). It is to be expected that longer-lived mussels would have lower mortality, compared to shorter-lived mussels such as *P. grandis* (Bauer and Wachtler 2001, Haag and Rypel 2011). Bauer and Wachtler (2001) also point out that mortality relates of mussels are typically highest prior to reaching sexual maturity. Our estimates of mortality were derived from catch curve analysis of sexually mature individuals. While not statistically significant, mortality of sexually mature *P. grandis* in this study displayed a negative relationship with increasing trophic state.

Our results suggested a marginal significant difference in age between natural lakes and reservoirs. This could be due to differences in basin morphology. Reservoirs commonly act as sediment traps due to decreased water velocity and silt causing reduced light penetration and algae abundance (Watters 2000). It has been documented that *P. grandis* found in deep natural lake basins grow slower relative to populations in shallower waters (Hanson et al. 1988), and in return, slower growth can be linked to longer-lived specimens (Haag and Rypel 2011). Our findings and others findings suggest that *P. grandis* population dynamics are different between natural lake basins and reservoirs.

In South Dakota, we know shorter-lived *P. grandis* have adapted well to the Great Plains region (Chapter 2). Our findings suggest that *P*. grandis live shorter lives with increasing intensity of cultural eutrophication. However, we observed no significant relationship between growth or mortality and lake trophic state in either natural lakes or reservoirs. This leads to question how eutrophication affects the age of other native mussels within this region, since there is documentation of more sensitive species such as *Amblema plicata* and *Fusconaia flava* (Stein 1973, Perkins et al. 1995, Perkins and Backlund 2003, Minnesota Department of Natural Resources 2004). Cultural eutrophication is a major impact to lakes in this region, and our results display complex relationships between these population parameters and cultural eutrophication. Experimental manipulations in laboratory controlled environments and using species with different sensitivities might be warranted to gain improved insight.

Table 1. Listing of natural lakes and reservoirs containing three or more live *P. grandis* (n=21). Lake information provided is type, trophic state, TSI. Age and growth parameters were used with only live specimens for estimated length (cm) (L_{inf}), growth coefficient (cm) (K), maximum age (years) (A_{max}) and number of aged shells (N). Mortality parameters were used with live and dead specimens collected for instantaneous rate (Z), annual mortality rate (A) and number of specimens used (N). Trophic state: E= eutrophic and H= hypereutrophic. TSI value was calculated on a 0-100 scale.

Lake Name	**County**	**Type**	**Trophic State**	**TSI**	**Age and Growth**				**Mortality**		
					L_{inf}	K	A_{max}	N	**Z**	**A**	N
Natural Lakes											
Pierpont	Day	Natural	E	55.8	8.76	0.45	7	10	0.23	20.4%	91
Enemy Swim	Day	Natural	E	59.6	10.74	0.19	8	10	0.38	31.5%	78
Six Mile	Marshall	Natural	E	59.6	8.39	0.31	7	10	0.32	27%	97
Clear	Marshall	Natural	E	60	8.36	0.23	7	9	0.47	37.5%	108
Mud	Marshall	Natural	E	64.7	11.14	0.15	5	10	0.45	36.4%	82
Roy	Marshall	Natural	E	65.8	7.73	0.29	9	8	0.12	11%	71
Florence	Hamlin	Natural	H	67.6	11.81	0.15	8	10	0.25	22%	121
Oakwood West	Brookings	Natural	H	68.2	14.47	0.17	5	3	0.65	47.8%	28
Dry	Codington	Natural	H	69.7	9.29	0.39	5	10	0.32	27.3%	59
Oak	Brookings	Natural	H	71.9	8.29	0.34	4	3	-0.13	-13.5%	167
Peno	Hyde	Natural	H	73.6	12.18	0.21	5	10	0.69	50%	79
Greys	Marshall	Natural	H	80.6	6.79	0.28	5	10	0.13	11.8%	80
Dry	Hamlin	Natural	H	98.7	8.33	0.31	4	6	0.14	13.4%	28
Reservoirs											
Dakotah	Hand	Reservoir	E	59.6	13.85	0.19	9	7	0.37	30.9%	94
Dudley	Spink	Reservoir	E	60	7.75	0.28	6	10	0.47	37.4%	86
Straum	Beadle	Reservoir	E	62	16.52	0.15	6	10	1.13	67.7%	229
Wagner	Charles Mix	Reservoir	E	64.4	10.82	0.34	9	10	0.21	18.6%	105
Tyndall C.F.P.	Bon Homme	Reservoir	H	70.8	12.70	0.21	8	3	0.25	22%	47
Hiddenwood	Walworth	Reservoir	H	74	22.09	0.09	6	9	1.18	69.1%	140
Wolff	McPherson	Reservoir	H	78.2	6.90	0.36	7	10	0.12	11.5%	129
Elm #1	Brown	Reservoir	H	80.9	12.58	0.23	11	10	0.45	36.4%	334

Table 2. Calculated means of age, estimated length (L_{inf}) (cm) and growth coefficient (*K*) (cm) for grouped natural lakes and reservoirs with live *P. grandis*. Calculated means of instantaneous mortality (Z) and annual mortality rate (A) for grouped natural lakes and reservoirs with live *P. grandis*.

	Age and Growth				**Mortality**		
Site Type	**Age**	L_{inf}	***K***	***N***	**Z**	**A**	***N***
Natural	6.08	9.71	0.27	13	0.31%	24.8%	13
Reservoir	7.75	12.90	0.23	8	0.52%	36.7%	8

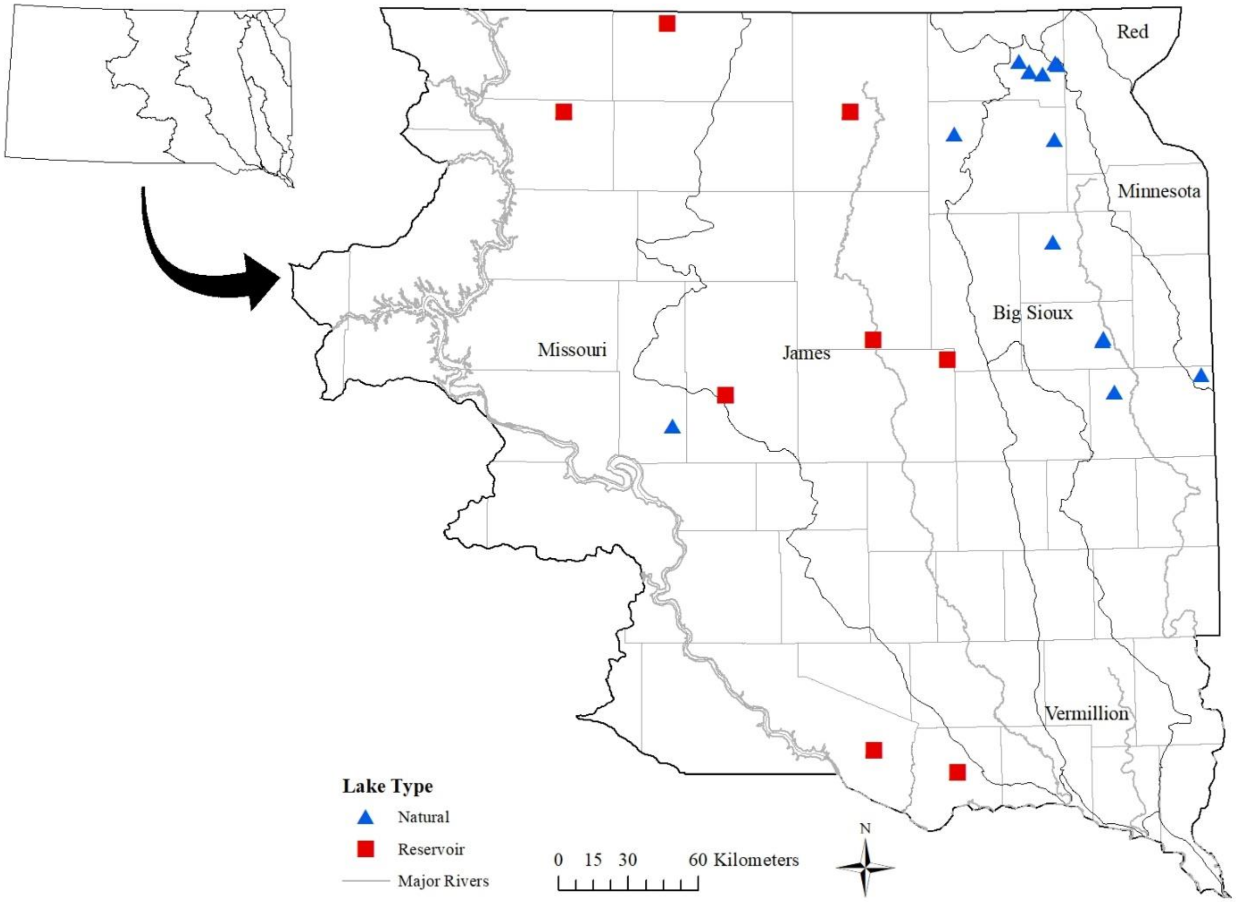

Figure 2. Site locations with evidence of *Pyganodon grandis* (n=21). Sites are labeled by their corresponding lake types: natural and reservoir.

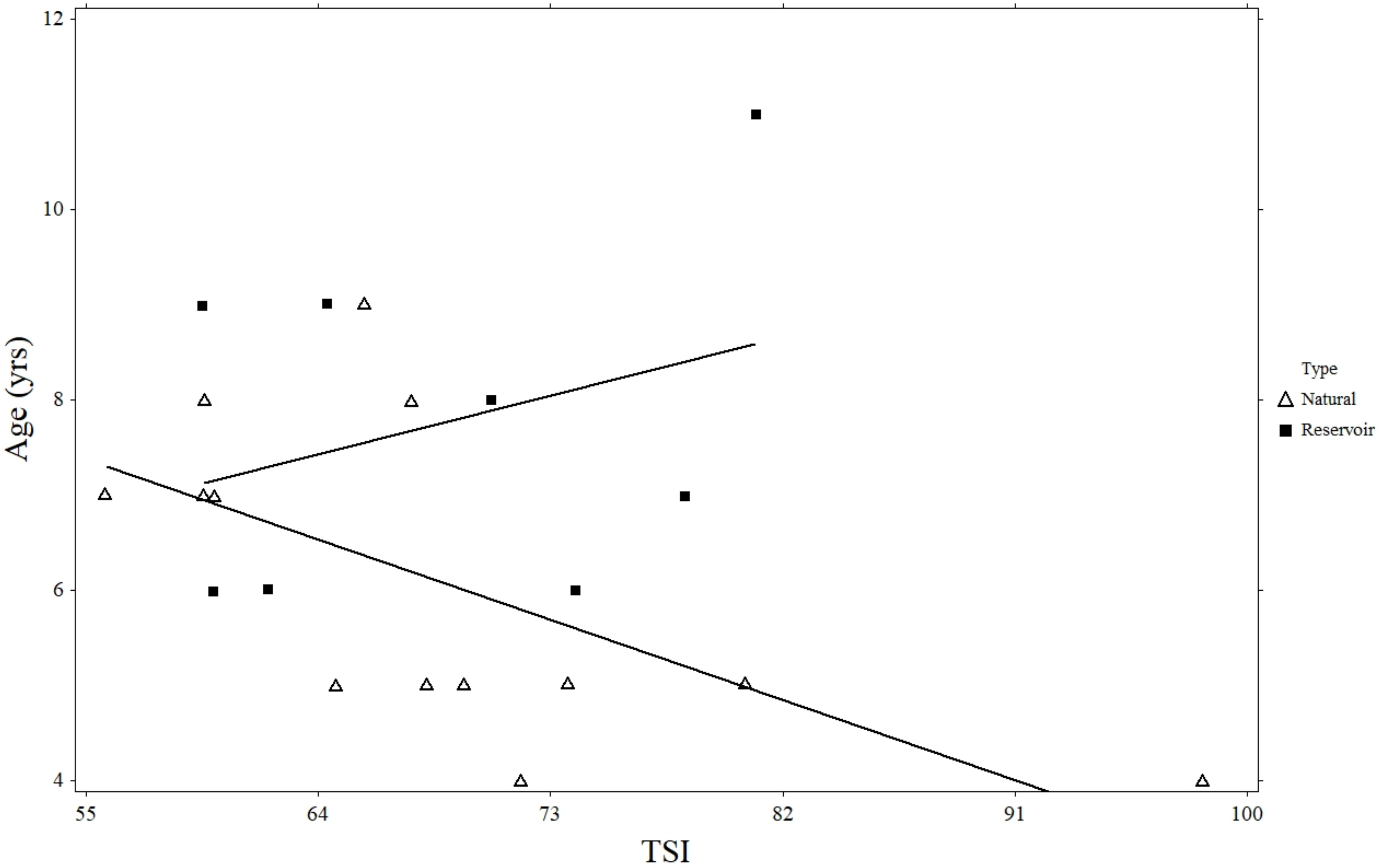

Figure 3. Relationship between maximum age of *P. grandis* and lake trophic state based on lake basin type.

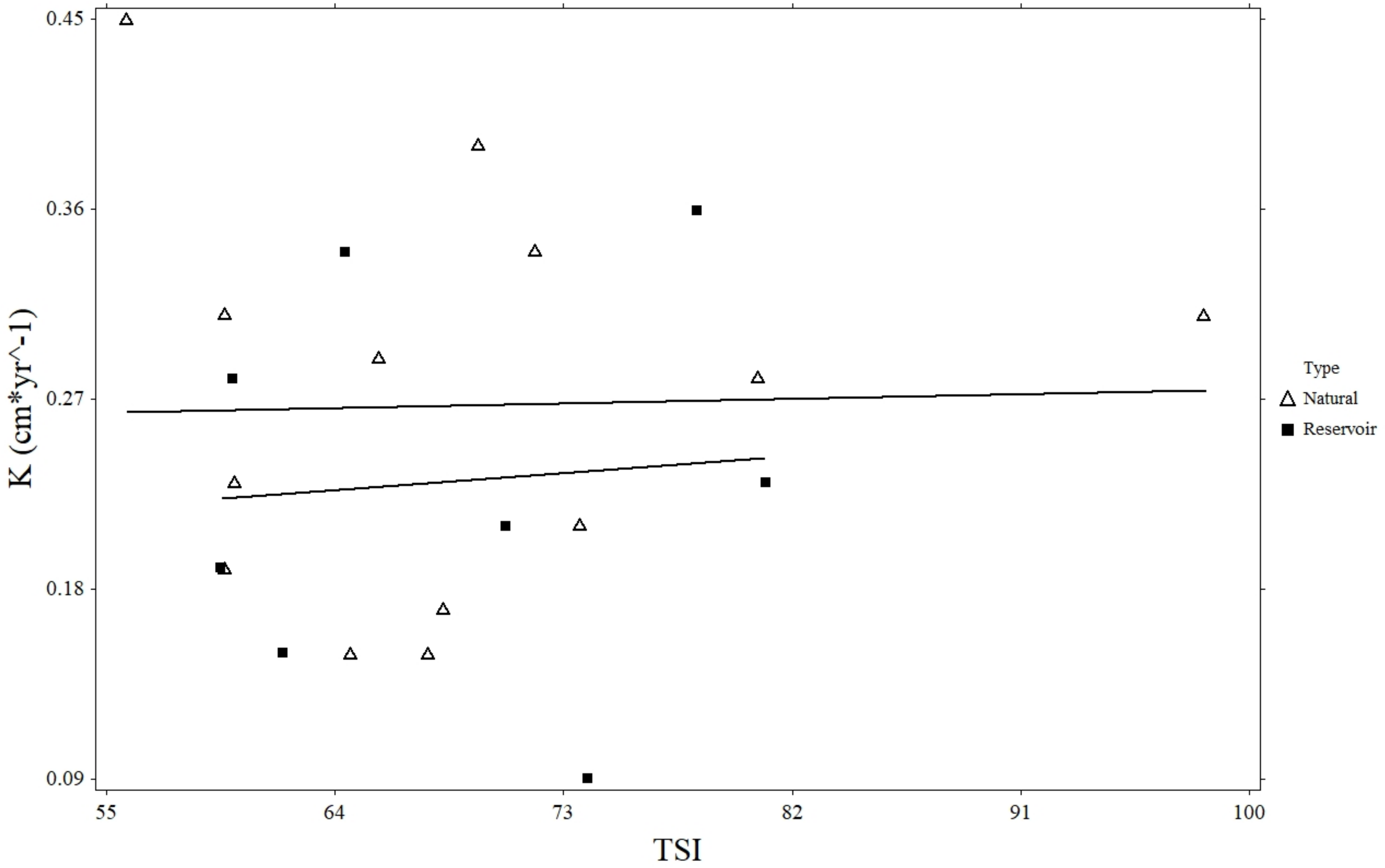

Figure 4. Relationship between growth coefficient (*K*) of *P. grandis* and lake trophic state based on lake basin type.

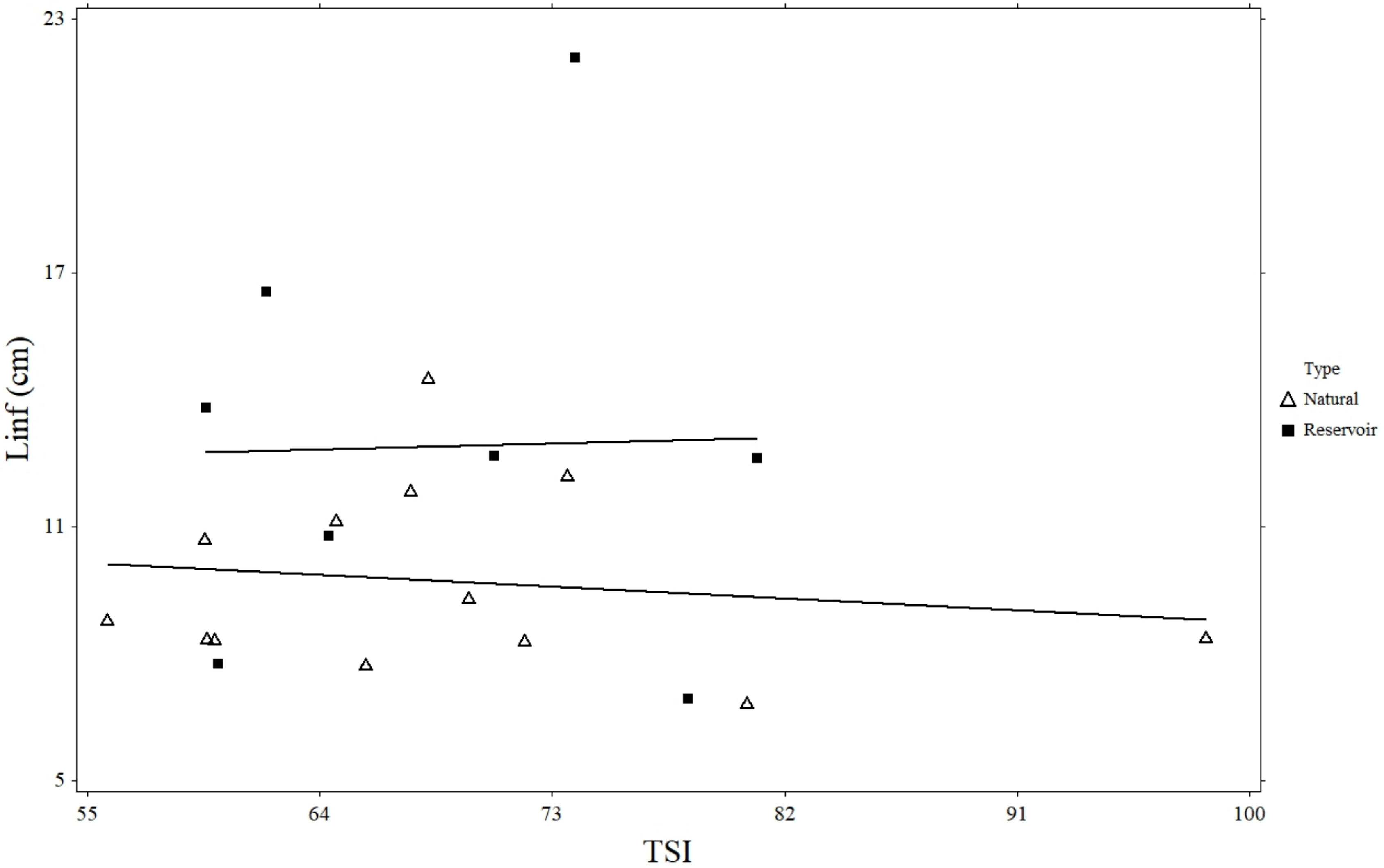

Figure 5. Relationship between estimated length (L_{inf}) of *P. grandis* and lake trophic state based on lake basin type.

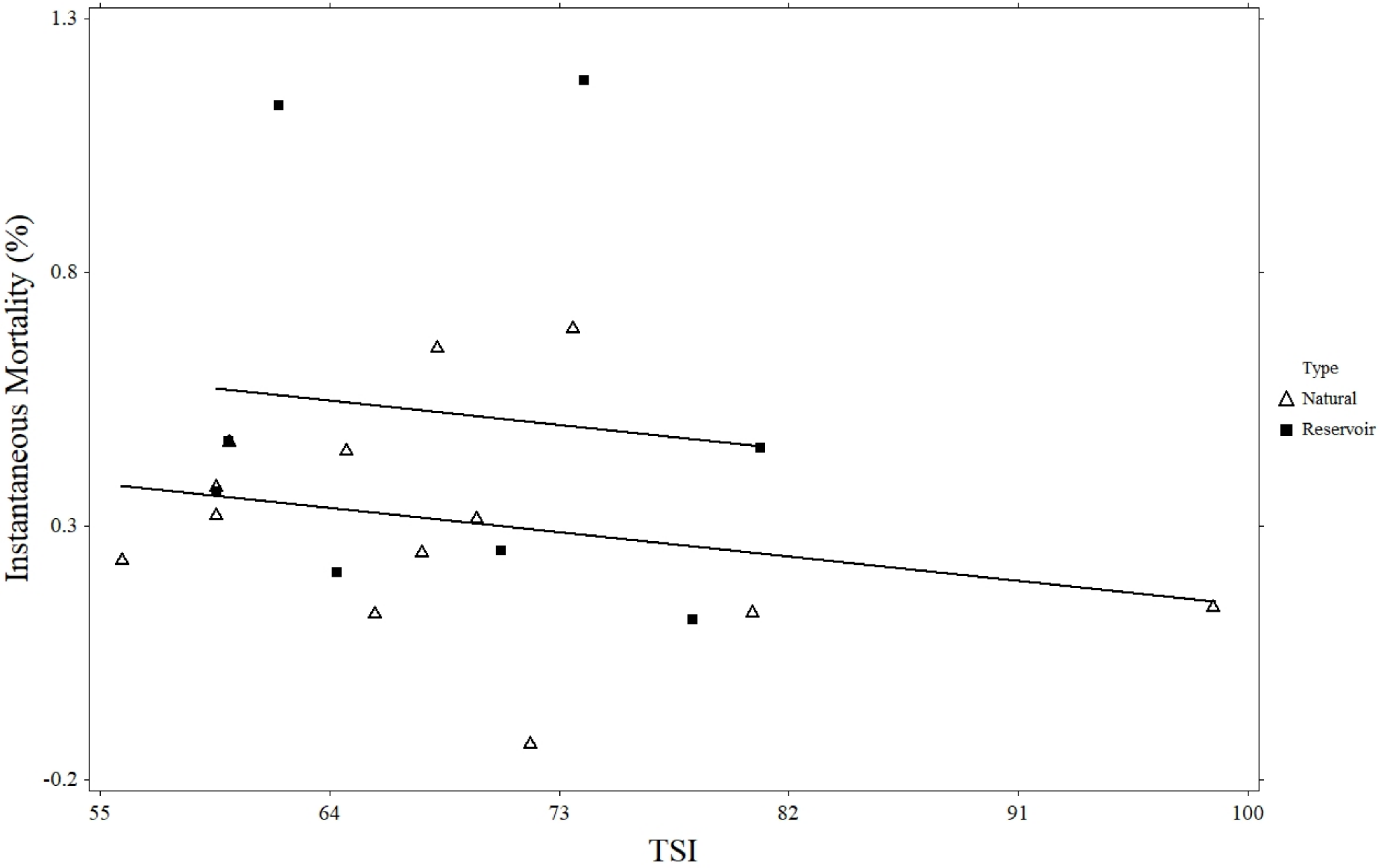

Figure 6. Relationship between instantaneous mortality (Z) of *P. grandis* and lake trophic state based on lake basin type.

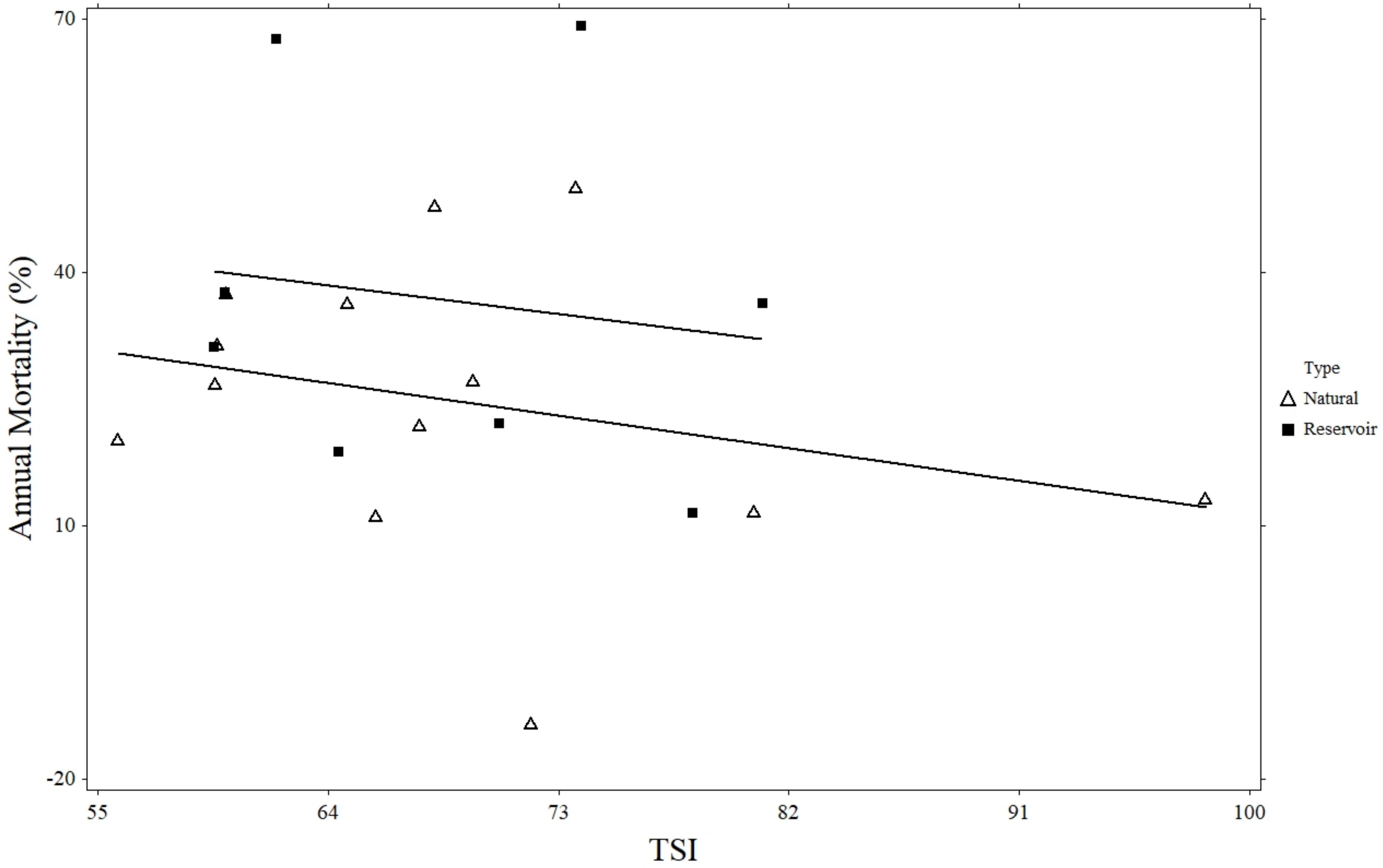

Figure 7. Relationship between total mortality rate (A) of *P. grandis* and lake trophic state based on lake basin type.

CHAPTER 4: CONCLUSIONS

Freshwater mussels in North America and globally are the most threatened and imperiled freshwater fauna (Bogan 1993, Strayer et al. 2004, Strayer 2008, Lopes-Lima et al. 2014). Their filter-feeding ability provides water clarity, substrate stabilization, sequestration of nutrients and they serve as a food source to other animals; mussels are a critical part of the freshwater ecosystem (Downing and Downing 1992, Grabarkiewicz and Davis 2008, Strayer 2008, Vaughn 2018). Mussels are sensitive to the effects of increased urbanization, agricultural practices, impoundments and invasive species (Bogan 1993, Haag et al. 1993, Baker and Hornbach 1997, Schneider et al. 1998, Lydeard et al. 2004, Strayer 2008). Cultural eutrophication is an impairment of many northern plains lakes, but there is little research and much debate as to mussel responses to increased nutrient enrichment (Sawyer 1966, Patzner and Muller 2001, Smith and Schindler 2009, Strayer 2014, South Dakota Department of Environment and Natural Resources 2018). The overall objectives of this study were to provide documentation of unionid occurrence, abundance and status within the lakes of eastern South Dakota, and to enhance our understanding of unionid responses to cultural eutrophication within South Dakota and the midwestern region.

The first objective for this study was to document freshwater mussel abundance, distribution and occurrence across lakes of eastern South Dakota based on river basin and basin type (Chapter 2). Previous work on freshwater mussels within South Dakota focused only on rivers and tributaries (Coker and Southall 1915, Perkins et al. 1995, Skadsen 1998, Perkins and Backlund 2000, Skadsen and Perkins 2000, Hoke 2003, Wall and Thomson 2004, Ecological Specialists 2005, Shearer et al. 2005, Perkins 2007, Faltys

2016). There has been no documentation of freshwater mussels in lakes of eastern South Dakota prior to this study. We found nine different species from two different orders across 50 of the 116 sampled lakes. We documented the occurrence of *Dreissena polymorpha* (zebra mussel) from McCook Lake (Union Co.) and *Corbicula fluminea* (Asian clam) from Yankton Lake (Yankton Co.) and Westside Community Fishing Pond (Yankton Co.). We found the most abundant and frequently occurring species to be *Pyganodon grandis*, a tolerant generalist species to habitat and fish host (Vanleeuwen and Arruda 2001, Grabarkiewicz and Davis 2008, Haag 2012), representing 75.9% of the total assemblage across all lakes. Less abundant and occurring species such as, *Amblema plicata*, *Fusconaia flava* and *Truncilla truncata,* were highly sought out during intensive harvesting (Coker and Southall 1915) and prefer more stable substrates (Tyrrell and Hornbach 2006, Grabarkiewicz and Davis 2008). According to the IUCN red list of threatened species, all those documented from our survey were listed as species of least concern with populations considered to be stable (IUCN 2019). This fauna still remains in a critical state within the United States due to habitat destruction, invasive species and changes in water quality (Bogan 1993, Lydeard et al. 2004, Strayer 2008).

Results of our survey led us to use *P. grandis* as our focus species for age and growth studies since it was the most frequently occurring and abundant species. This allowed us to examine the relationship between *P. grandis* age, growth and mortality versus lake trophic state for natural lakes and reservoirs (Chapter 3). We predicted that *P. grandis* would have shorter life spans, increased growth and higher mortality with increasing trophic state. Our survey found 13 natural lakes and 8 reservoir sites with live and dead *P. grandis,* which we used to answer our objective questions. *P. grandis* found in natural lakes had a mean age of 6.1 years, while reservoirs had a mean age of 7.8 years. *P. grandis* becomes fully mature around 4-5 years (Cummings and Graf 2010, Thorp et al. 2014). Our results supported our hypothesis of a negative relationship between age and lake trophic state and this result is consistent with reports from other culturally enriched bodies of water (Bauer 1992, Haag and Rypel 2011, Haag 2012). Having younger age structures brings to question if the populations are healthy or declining and not reaching sexual maturity. If populations have a lower number of younger individuals, that indicates the population is in decline or there is poor reproductive success (Bauer and Wachtler 2001, Outeiro et al. 2008). With higher frequencies of younger year classes, this can indicate successful recruitment occurring (Hastie et al. 2000).

We predicted increased growth of *P. grandis* with increased nutrient enrichment. Our results indicated no significant correlations between growth coefficients or estimated length and lake trophic state. Many studies suggest that there are faster growth rates with increasing trophic state (Arter 1989, Ostrovsky et al. 1993, Dunca et al. 2005, Strayer 2014, Fritts et al. 2017). *P. grandis* found in deeper waters had slower growth rates compared to shallow waters, similar to our findings (Hanson et al. 1988). Lower growth rates can be observed in basins with diminished food quality, when lakes become highly eutrophic (Strayer 2014). This could explain why our growth rates were lower in lakes having increased eutrophication. Within South Dakota we could see lower growth rates in different mussel species due to basins being highly eutrophic, causing poor food quality.

Higher mortality of *P. grandis* with increased trophic state was predicted, but not supported from our results. Bauer (1992) found higher mortality of *Margaritifera margaritifera* (Pearl Mussel) in response to elevated nitrate concentrations. Our results failed to document higher mussel mortality of *P. grandis* from more culturally eutrophic lake basins. Increased siltation could be an impact on unionid mortality as it has been documented that increased sedimentation has led to 90% mortality in mussels (Ellis 1936). This mortality could also be linked to decreased light penetration and algae abundance (Watters 2000). In addition, juvenile mussels are generally more sensitive to sedimentation. Our analysis generated mortality estimates from sexually mature age classes and may have missed the more sensitive juvenile period. Mortality observed in adult unionids is generally low across species (Nalepa et al. 1991).

This study documented that *P. grandis* was the most frequently occurring and abundant unionid mussel in eastern South Dakota lakes. From our analysis of *P. grandis* we were able to establish a negative relationship between average age and lake trophic state. As *P. grandis* is known as a tolerant generalist species (Grabarkiewicz and Davis 2008, Haag 2012), it seems likely that more sensitive, habitat and host specialist mussel species might be more responsive to cultural eutrophication (Du et al. 2011). This leads to the question of how eutrophication affects the lifespans of other native mussels within this region, such as *Amblema plicata, Fusconaia flava* and *Truncilla truncata*.

Our study provided the first regional survey of lake dwelling unionid mussels in South Dakota. Paired with a recently completed survey of wadable streams which was also the first of its kind, these studies contribute valuable information regarding the occurrence, distribution and relative abundance of this critically imperiled group.

Knowledge of the freshwater mussel species found in South Dakota lakes is beneficial because there is now a baseline of species presence. Surveying more lakes can help establish knowledge on population presence and absence, document rare or endangered species, and help aid in management strategies (Downing and Downing 1992, Williams et al. 1993, Metcalfe-Smith et al. 2000, Smith et al. 2001). Many states have developed standardized unionid surveys and protocols for streams and rivers used as collection and monitoring data (Clayton et al. 2018, Hanshue et al. 2018, Ohio Department of Natural Resources et al. 2018). Their goals are all very similar, wanting to provide standardized guidance and to document the presence and absence of state or federally endangered unionids.

Educational programs and public outreach are needed to increase public awareness of this imperiled organism group, as there is a lack of general knowledge of freshwater mussels (Strayer 2017). Expressing why we do not want invasive species, like zebra mussels, is important but there is currently minimal effort expended to provide information regarding species we are trying to protect (Strayer 2017). Groups such as the Minnesota Zoo and Mollusk Conservation Society provide exhibits and resources to educate the public about these native species (Freshwater Mollusk Conservation Society 2017, Minnesota Zoo 2019). Texas Parks and Wildlife have also successfully recruited the public and implemented a mussel watch volunteer program (Texas Parks & Wildlife 2019). Since 2012 volunteers have been able to upload photos, identifications and observation locations onto an interactive website iNaturalist (Texas Parks & Wildlife 2012). Developing a state outreach program in the form of campaigns, classroom programs or interactive websites would be valuable to facilitate education regarding species occurrence in South Dakota and the roles played by these species in supporting aquatic ecosystems.

These considerations for future unionid work in South Dakota can help facilitate unionid conservation and public awareness. Creation of a state unionid protocol for surveys would facilitate examination of assemblage changes within our lakes and streams. Future work could also include assessment of impacts and spread of Zebra mussels (*Dreissena polymorpha*) and Asian clams (*Corbicula fluminea*) on native unionid populations.

APPENDIX 2-1

Individual species distribution maps for all 9 species found throughout the 116 lake sites for the 2017 freshwater mussel survey in eastern South Dakota. Locations are labeled based on lake type: natural and reservoir.

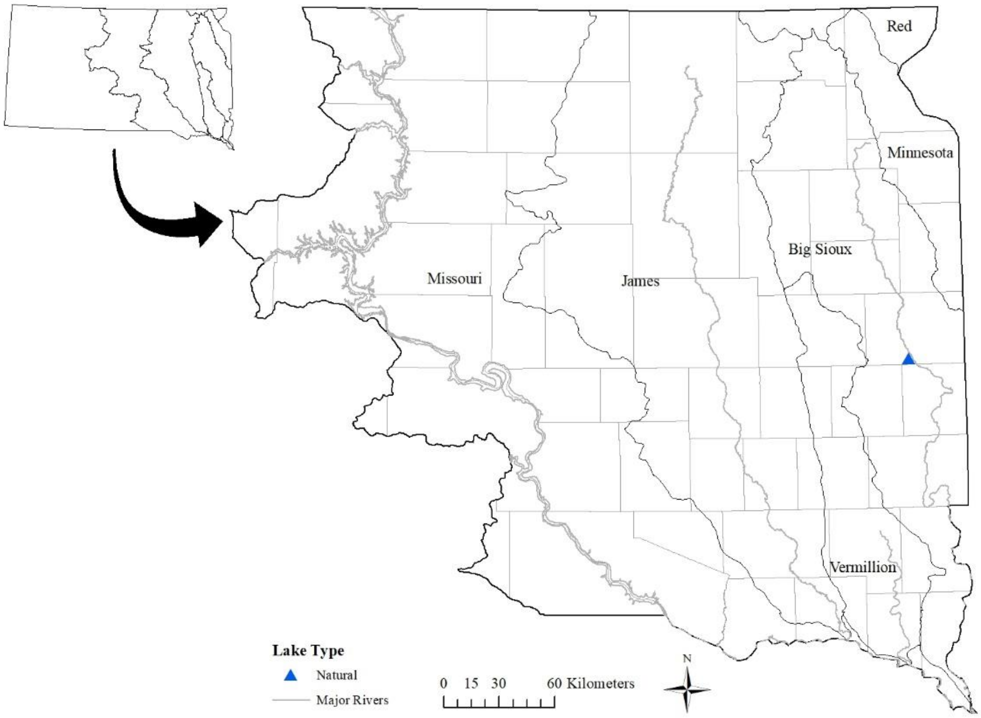

Figure 1: Distribution of *Amblema plicata* from the 2017 lake survey.

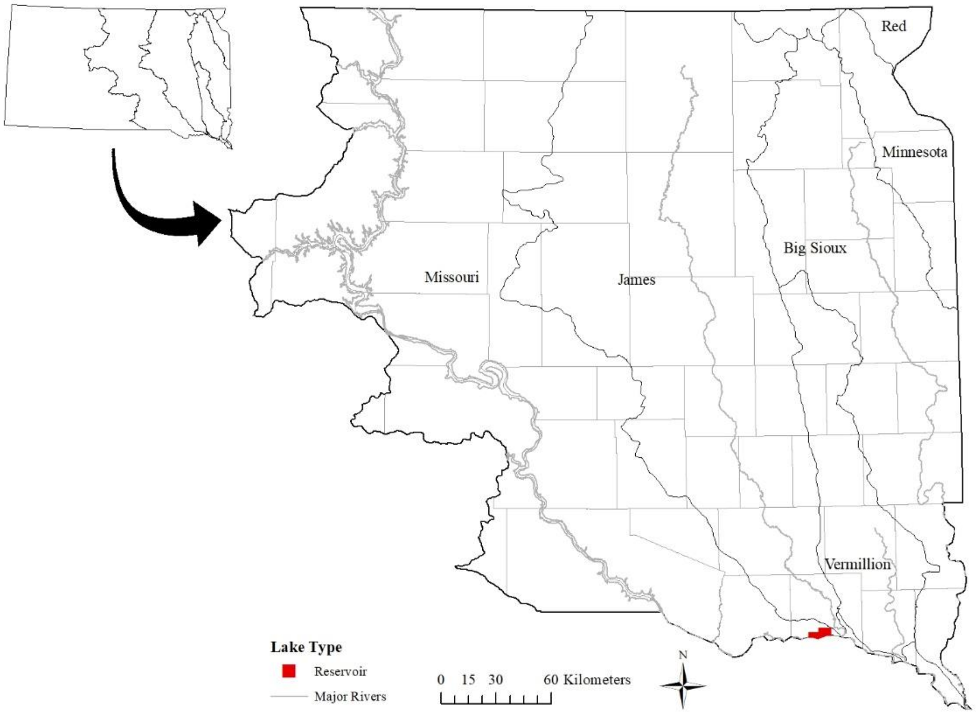

Figure 2: Distribution of *Corbicula fluminea* from the 2017 lake survey.

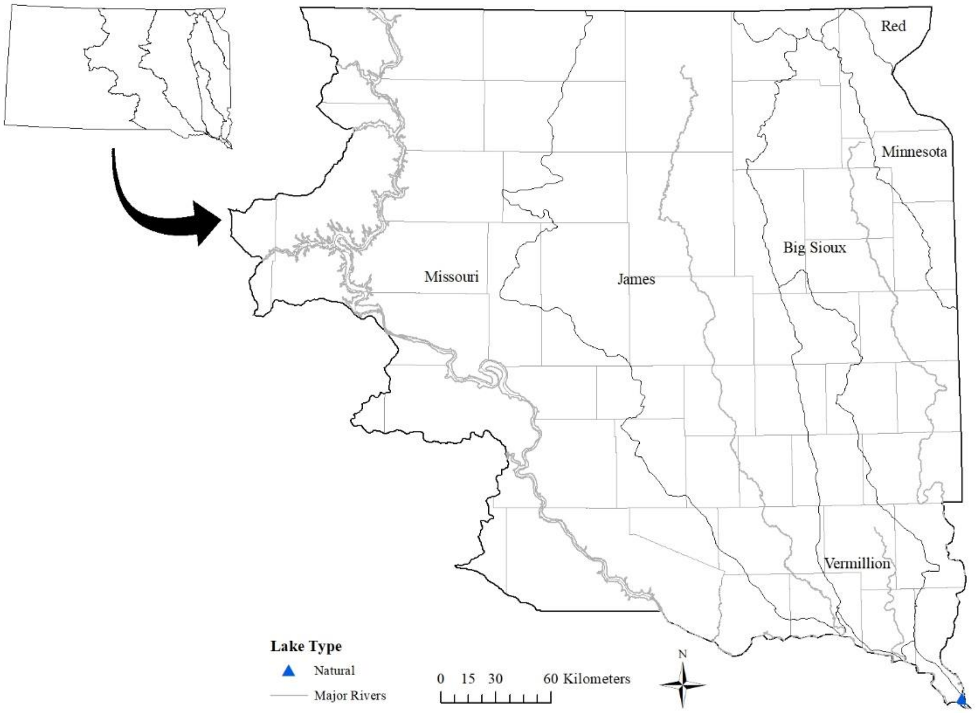

Figure 3: Distribution of *Dreissena polymorpha* from the 2017 lake survey.

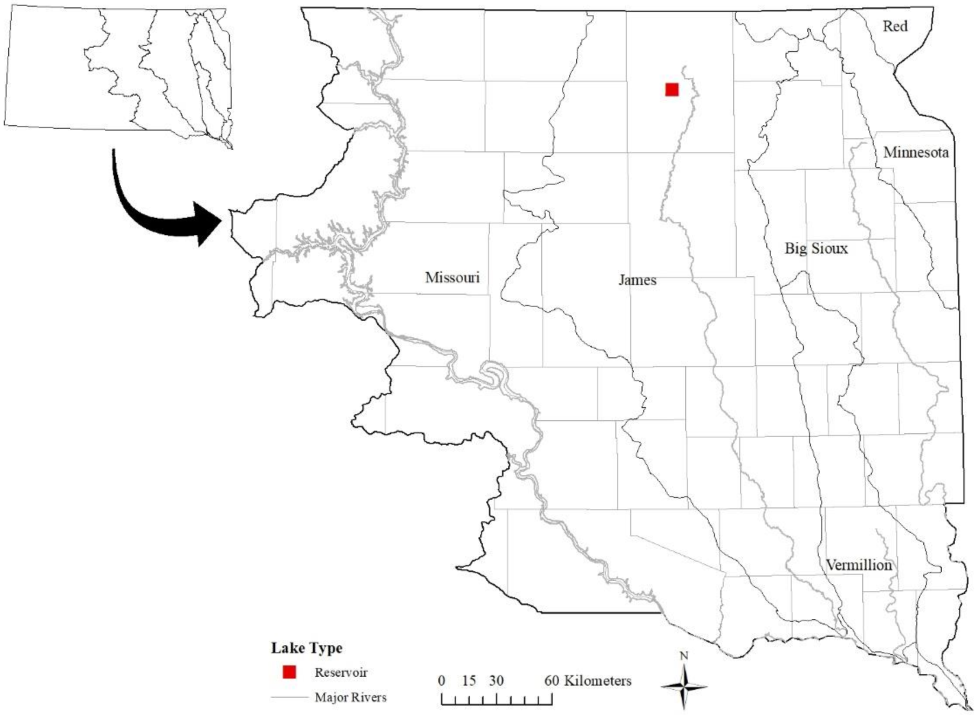

Figure 4: Distribution of *Fusconaia flava* from the 2017 lake survey.

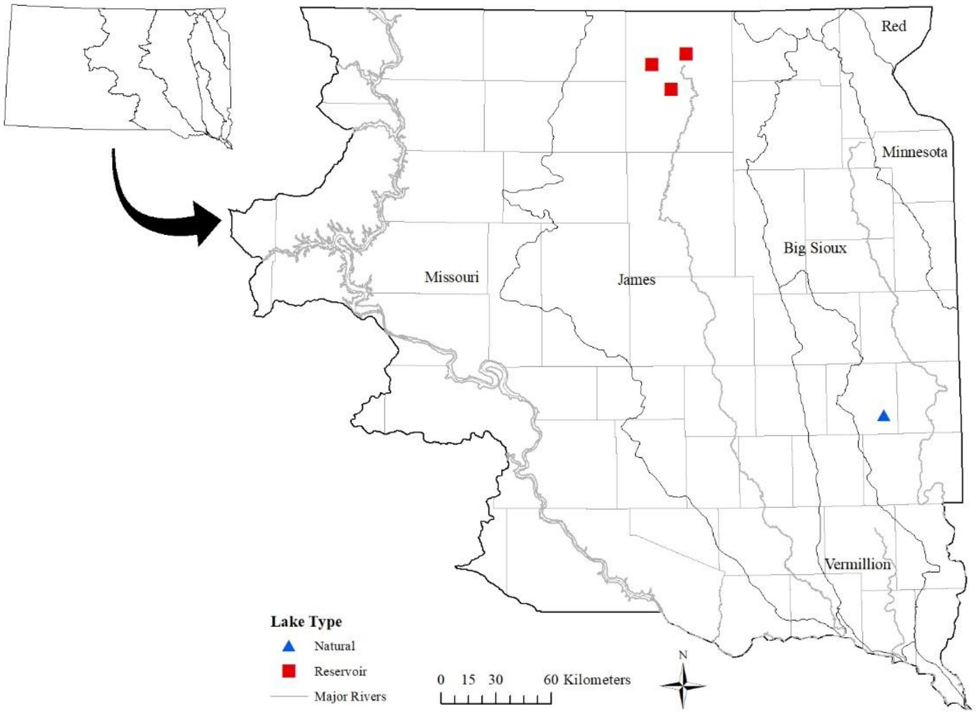

Figure 5: Distribution of *Lasmigona complanata* from the 2017 lake survey.

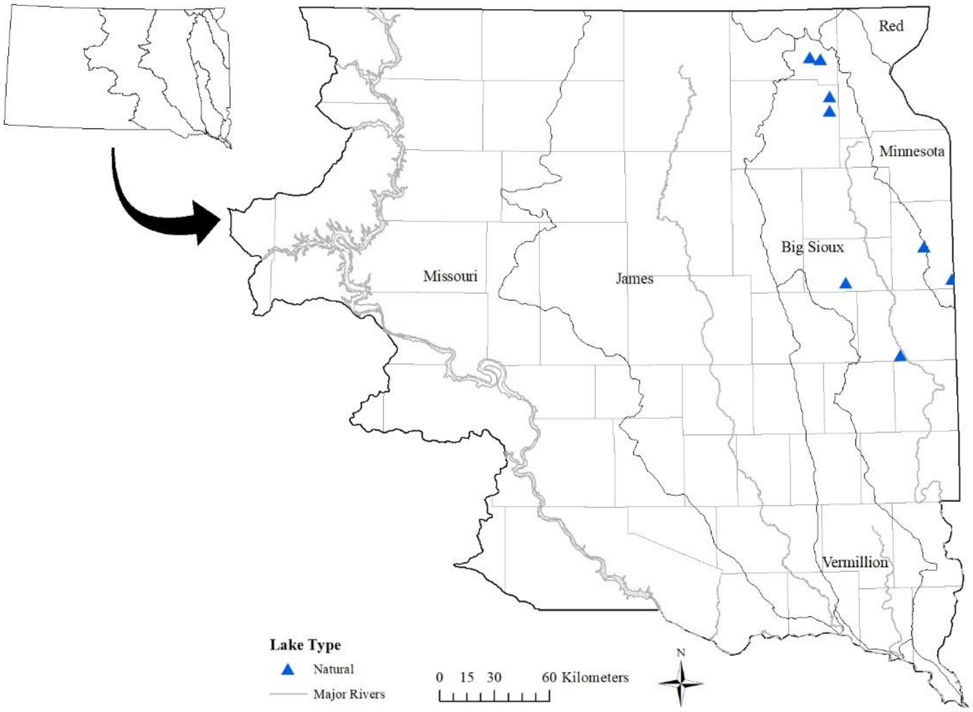

Figure 6: Distribution of *Lampsilis siliquoidea* from the 2017 lake survey.

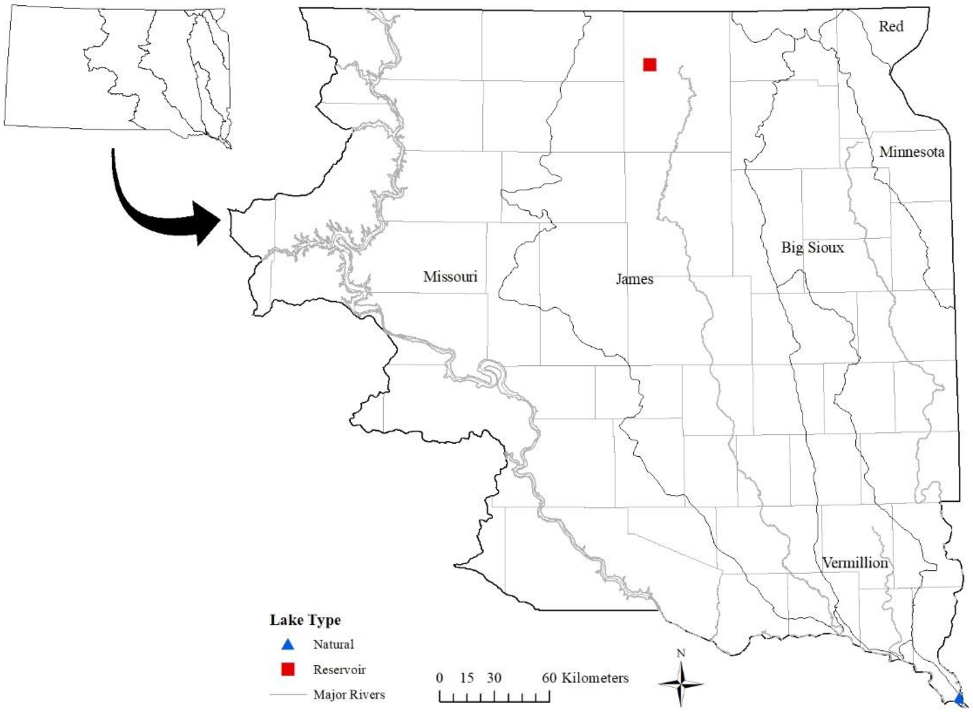

Figure 7: Distribution of *Potamilus alatus* from the 2017 lake survey.

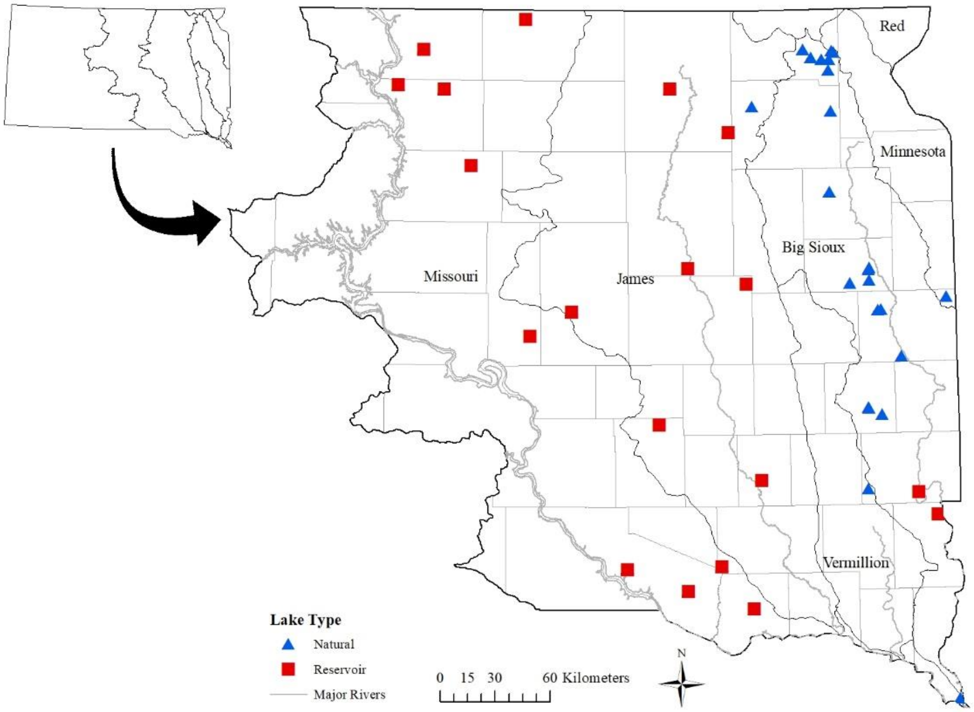

Figure 8: Distribution of *Pyganodon grandis* from the 2017 lake survey.

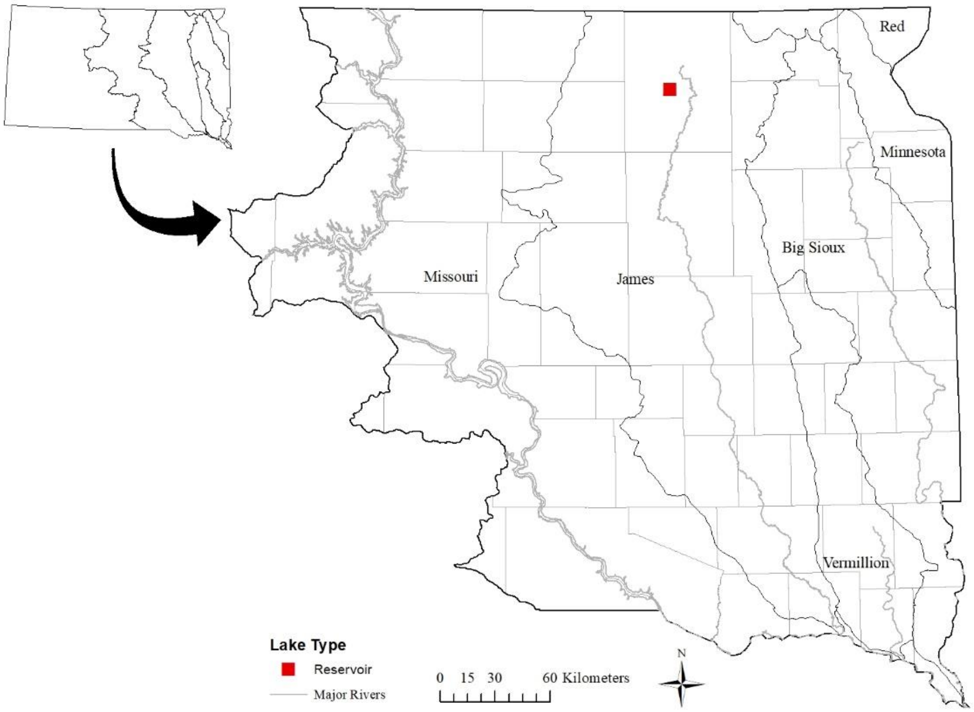

Figure 9: Distribution of *Truncilla truncata* from the 2017 lake survey.

APPENDIX 2-2

All lakes with freshwater mussels found (n=50). Individual lake information provides species counts, species richness and species abundance. Species: PG= *Pyganodon grandis*, LS= *Lasmigona siliquoidea*, AP= *Amblema plicata*, LC= *Lasmigona complanate*, FF= *Fusconaia flava*, TT= *Truncilla truncata*, PA= *Potamilus alatus*, DP= *Dreissena polymorpha*, and CF= *Corbicula fluminea.*

Lake Name	County	River Basin	Type	Species									Species Richness	Species Abundance
				PG	LS	AP	LC	FF	TT	PA	DP	CF		
Natural Lakes														
Bourne Slough	Lake	Big Sioux	Natural	1									1	1
Buffalo North	Marshall	James	Natural	2									1	2
Campbell	Brookings	Big Sioux	Natural	2	6	1							3	9
Clear	Deuel	James	Natural	2	24								2	26
Clear	Marshall	Missouri	Natural	53	16								2	69
Dry	Codington	Big Sioux	Natural	12									1	12
Dry	Hamlin	Big Sioux	Natural	6									1	6
Enemy Swim	Day	Big Sioux	Natural	10	1								2	11
Fish	Deuel	Minnesota	Natural		17								1	17
Florence	Hamlin	Big Sioux	Natural	45									1	45
Greys	Marshall	James	Natural	35									1	35
Lost	Minnehaha	Vermillion	Natural	1									1	1
Madison	Lake	Big Sioux	Natural	1									1	1
Mary	Hamlin	Big Sioux	Natural	1									1	1
McCook	Union	Missouri	Natural	1						2	9		3	12
Mud	Marshall	James	Natural	37									1	37
Norden	Hamlin	Big Sioux	Natural		3								1	3
Oak	Brookings	Minnesota	Natural	155									1	155
Oakwood East	Brookings	Big Sioux	Natural	3									1	3
Oakwood West	Brookings	Big Sioux	Natural	13									1	13
Pickerel	Day	Big Sioux	Natural		3								1	3
Pierpont	Day	James	Natural	29									1	29
Poinsett	Hamlin	Big Sioux	Natural	1									1	1
Round	Lake	Minnesota	Natural	3			2						2	5

Appendix 2-2 continued

Lake Name	County	River Basin	Type	Species									Species Richness	Species Abundance
				PG	LS	AP	LC	FF	TT	PA	DP	CF		
Roy	Marshall	James	Natural	8	281								2	289
Sarah	Marshall	James	Natural	24									1	24
Six Mile	Marshall	James	Natural	35									1	35
Reservoirs														
Alvin	Lincoln	Big Sioux	Reservoir	32									1	32
Campbell	Campbell	Missouri	Reservoir	66									1	66
Columbia Res.	Brown	James	Reservoir				1						1	1
Covell U.F.P.	Minnehaha	Big Sioux	Reservoir	1									1	1
Dakotah	Hand	James	Reservoir	39									1	39
Dudley	Spink	James	Reservoir	33									1	33
Elm #1	Brown	James	Reservoir	238			11	2	4				4	255
Elm #4	Brown	James	Reservoir				2			2			2	4
Fraser Dam	Aurora	James	Reservoir	1									1	1
Geddes	Charles Mix	Missouri	Reservoir	9									1	9
Hanson	Hanson	James	Reservoir	3									1	3
Hiddenwood	Walworth	Missouri	Reservoir	100									1	100
Molstad	Walworth	Missouri	Reservoir	1									1	1
Peno	Hyde	Missouri	Reservoir	35									1	35
Pigors	Brown	James	Reservoir	6									1	6
Simon	Potter	Missouri	Reservoir	8									1	8
Straum	Beadle	James	Reservoir	181									1	181
Tripp	Hutchinson	Missouri	Reservoir	10									1	10
Tyndall C.F.P.	Bon Homme	Missouri	Reservoir	23									1	23
Wagner	Charles Mix	Missouri	Reservoir	25									1	25
Westside C.F.P.	Yankton	Missouri	Reservoir									8	1	8
Wolff	McPherson	Missouri	Reservoir	66									1	66
Yankton	Yankton	Missouri	Reservoir									37	1	37

APPENDIX 2-3

All lakes containing freshwater mussels (n=50). Individual lake information on: DO= dissolved oxygen, Cond= conductivity, pH, Sub= substrate average, Stube= Secchi tube, distance searched during timed sampling, and average depth at which mussels were found.

Lake Name	County	River Basin	Type	DO (mg/L)	Cond (uS/cm)	pH (s.u.)	Sub (mm)	Stube (cm)	Temp (C)	Distance (m)	Depth (cm)
Natural Lakes											
Bourne Slough	Lake	Big Sioux	Natural	16.62	1883.33	8.91	2	18.2	20.56	214.36	60
Buffalo North	Marshall	James	Natural	11.23	590.33	8.76	2	56.8	26.13	160.48	75
Campbell	Brookings	Big Sioux	Natural	12.72	1858	8.46	2	39	14.4	114.3	100
Clear	Deuel	James	Natural	11.65	698	7.77	2	80	11.47	99.27	120.87
Clear	Marshall	Missouri	Natural	8.09	570.33	8.6	5.7	83.8	24.15	161.28	37.25
Dry	Codington	Big Sioux	Natural	6.14	2886.67	8.89	2	32.4	26.89	246.61	92.08
Dry	Hamlin	Big Sioux	Natural	13.2	917.33	8.7	2	56.4	22.93	123.38	108.34
Enemy Swim	Day	Big Sioux	Natural	8.99	352	8.65	2.18	120	21.03	186.65	101.36
Fish	Deuel	Minnesota	Natural	7.83	759	8.31	2	29.9	24.6	220	83
Florence	Hamlin	Big Sioux	Natural	7.62	689.33	8.11	2	68.6	20.61	101.54	62.72
Greys	Marshall	James	Natural	8.33	520	8.26	1	34.6	26.83	75.3	40.28
Lost	Minnehaha	Vermillion	Natural	11.99	1619.67	10.03	17.79	36.8	13.78	295.08	88.33
Madison	Lake	Big Sioux	Natural	11.95	1814.67	8.85	2	20	22.02	350.14	75
Mary	Hamlin	Big Sioux	Natural	10.21	2090.67	8.46	2	49.2	27.38	235.72	90
McCook	Union	Missouri	Natural	9.28	919.67	8.25	2	39	26.23	149.36	150
Mud	Marshall	James	Natural	11.84	418.33	9.5	1	84.2	25.64	227.46	68.02
Norden	Hamlin	Big Sioux	Natural	12.76	2056.33	8.81	2	63	22.14	439.08	85
Oak	Brookings	Minnesota	Natural	13.21	550.67	7.81	5.39	51	10.65	24.33	125.85
Oakwood East	Brookings	Big Sioux	Natural	12.15	1354.67	8.4	2	54.8	17.2	209.6	90
Oakwood West	Brookings	Big Sioux	Natural	5.26	1442.33	8.07	3.61	66	16.06	226.41	135
Pickerel	Day	Big Sioux	Natural	8.89	471.67	8.52	7.82	120	21.01	221.96	90
Pierpont	Day	James	Natural	10.09	1295	9.41	4.01	120	25.87	62.39	78.65
Poinsett	Hamlin	Big Sioux	Natural	13.34	1633.67	8.96	2	100.2	21.98	288.49	50
Round	Lake	Minnesota	Natural	6.36	1475	8.72	2	28.4	23.07	175.28	69
Roy	Mashall	James	Natural	8.18	768.33	8.48	2	78	22.99	71.15	62.11

Appendix 2-3 continued

Lake Name	County	River Basin	Type	DO (mg/L)	Cond (uS/cm)	pH (s.u.)	Sub (mm)	Stube (cm)	Temp (C)	Distance (m)	Depth (cm)
Sarah	Marshall	James	Natural	8.63	440.33	10.05	1	81.8	31.69	61.68	32.41
Six Mile	Marshall	James	Natural	7.83	975.67	8.79	4.16	120	23.93	70.71	83.29
Reservoirs											
Alvin	Lincoln	Big Sioux	Reservoir	14.47	1572	8.98	2	37.5	14.01	101.14	120.92
Campbell	Campbell	Missouri	Reservoir	9.61	4096	8.3	6.63	57.4	24.92	68.03	133.92
Columbia Res.	Brown	James	Reservoir	21.13	1230.67	8.72	1	26.2	26.65	159.81	90
Covell U.F.P.	Minnehaha	Big Sioux	Reservoir	11.69	655	9.05	2	31.8	21.45	89.21	70
Dakotah	Hand	James	Reservoir	11.57	1335.67	8.09	2	120	19.13	29.25	93.32
Dudley	Spink	James	Reservoir	11.49	1186	8.24	2	120	18.65	88.33	80.91
Elm #1	Brown	James	Reservoir	18.03	2052	8.06	2	27.3	26.01	34.99	54.82
Elm #4	Brown	James	Reservoir	11.33	1883.67	8.35	1	16	26.43	108.63	116.25
Fraser Dam	Aurora	James	Reservoir	17.32	876.67	8.91	2	52	22.79	104.82	102.5
Geddes	Charles Mix	Missouri	Reservoir	9.72	2586	8.37	6	37.4	25.6	123.1	137
Hanson	Hanson	James	Reservoir	12.68	2496	8.07	2	41.8	23.44	223.82	135
Hiddenwood	Walworth	Missouri	Reservoir	12.8	1579.33	8.44	2.91	44.2	29.03	77.73	114.26
Molstad	Walworth	Missouri	Reservoir	18.27	3107.67	8.58	1	65.2	26.42	125.37	17.67
Peno	Hyde	Missouri	Reservoir	10.26	2646.67	8.23	2	45.4	17.49	63.3	112.57
Pigors	Brown	James	Reservoir	6.57	1737.33	9.1	1	120	24.32	137	49.28
Simon	Potter	Missouri	Reservoir	11.91	1580.67	9.13	6.49	78	24.42	80.28	118.5
Straum	Beadle	James	Reservoir	12.96	2093	8.96	1	108	24.42	86.58	70.34
Tripp	Hutchinson	Missouri	Reservoir	6.96	2563.67	8.21	2	90.2	24.5	62.43	146.78
Tyndall C.F.P.	Bon Homme	Missouri	Reservoir	9.23	1497.33	8.27	1	55.2	28.19	134.47	135.09
Wagner	Charles Mix	Missouri	Reservoir	7.74	2012	8.07	2	86	28.71	88.2	116.38
Westside C.F.P.	Yankton	Missouri	Reservoir	6.19	1741.67	7.66	9.8	61.4	23.09	117.76	30.91
Wolff	McPherson	Missouri	Reservoir	10.24	1023.33	9.01	2	32.9	22.63	48.44	85.69
Yankton	Yankton	Missouri	Reservoir	12.62	848.33	8.84	2.15	120	28.57	289.06	41.37

APPENDIX 3-1

von Bertalanffy growth curves amount lakes based on trophic status with live *Pyganodon grandis*. For clarity, observed lengths are not shown on the graphs.

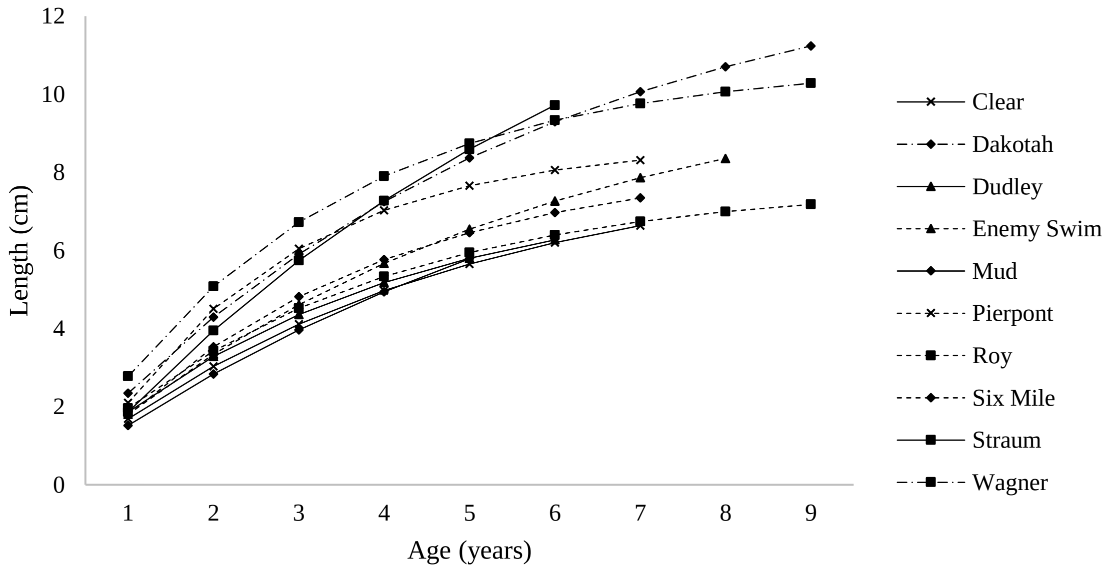

Figure 1: von Bertalanffy growth curves of eutrophic lakes and reservoirs in eastern South Dakota.

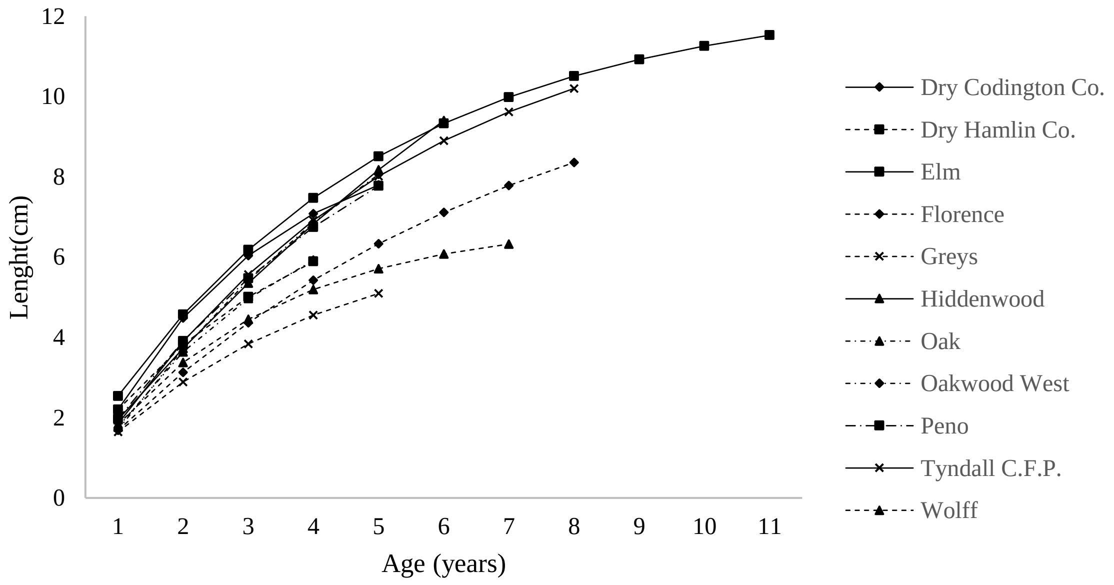

Figure 2: von Bertalanffy growth curves of hypereutrophic lakes and reservoirs in eastern South Dakota.

APPENDIX 3-2

Histograms of age frequencies of *Pyganodon grandis*.

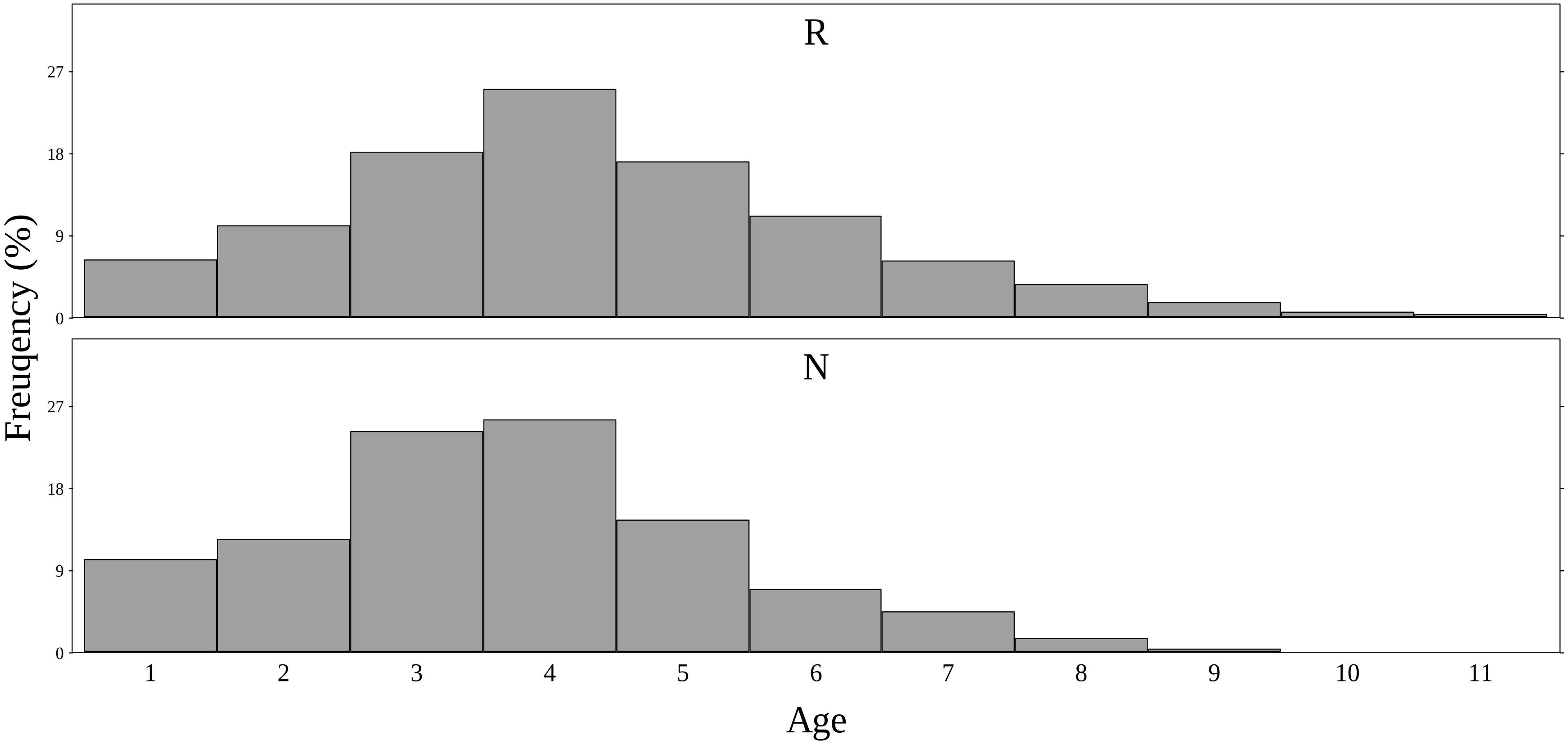

Figure 1: Age frequency histograms of *P. grandis* found in reservoirs (R) and natural lakes (N).

LITERATURE CITED

Anthony, J. L., D. H. Kesler, W. L. Downing, and J. A. Downing. 2001. Length-specific growth rates in freshwater mussels (Bivalvia: Unionidae): Extreme longevity or generalized growth cessation? Freshwater Biology 46:1349–1359.

Arter, H. E. 1989. Effect of eutrophication on species composition and growth of freshwater mussels (Mollusca, Unionidae) in Lake Hallwil (Aargau, Switzerland). Aquatic Sciences 51:87–99.

Auch, R. F. 2015. Northern glaciated plains ecoregion. Pages 69–76 *in* J. L. Taylor, W. Acevedo, R. F. Auch, and M. A. Drummond, editors. Status and Trends of Land Change in the Great Plains of the United States- 1973 to 2000. U.S. Geological Survey. Professionl Paper 1794-B.

Baker, S. M., and D. J. Hornbach. 1997. Acute physiological effects of zebra mussel (Dreissena polymorpha) infestation on two unionid mussels, Actinonaias ligamentina and Amblema plicata. Canadian Journal of Fisheries and Aquatic Sciences 54:512–519.

Bauer, G. 1992. Variation in the life span and size of the freshwater pearl mussel. The Journal of Animal Ecology 61:425–436.

Bauer, G., and K. Wachtler. 2001. Ecology and Evolution of the Freshwater Mussels Unionoida. Page Ecology and Evolution of the Freshwater Mussels Unionoida.

Begley, M. T. 2013. Assessment of the freshwater mussel community of the upper Mahoning river watershed and factors influencing diversity and abundance in small streams. Cleveland State University.

Bogan, A. E. 1993. Freshwater bivalve extinctions (Mollusca: Unionoida): A search for causes. American Zoologist 33:599–609.

Callisto, M., J. Molozzi, and J. L. E. Barbosa. 2014. Eutrophication of lakes. Pages 55-71. Eutrophication: Causes, Consequences and Control: Volume 2.

Carell, B., S. Forberg, E. Grundelius, L. Henrikson, A. Johnels, U. Lindh, H. Mutvei, M. Olsson, K. Svardstrom, and T. Westermark. 1987. Can mussel shells reveal environmental history? AMBIO: A Journal of the Human Environment 16:2–10.

Carlson, R. E. 1977. A trophic state index for lakes. Limnology and Oceanography 22:361–369.

Clayton, J. L., B. Douglas, and P. Morrison. 2018. West Virginia mussel survey protocols.

Coker, R. E., and J. B. Southall. 1915. Mussel resources in tributaries of the upper Missouri river. Bureau of Fisheries:17.

Cummings, K. S., and D. L. Graf. 2010. Mollusca: Bivalvia. Page 309 Ecology and Classification of North American Freshwater Invertebrates.

Cummings, K. S., and C. A. Mayer. 1992. Field guide to freshwater mussels of the midwest. Illinois Natural History Survey Manual 5, Champaign.

DeLorme, A. 2011. A two-phase population survey of mussels in North Dakota rivers. Final Report, North Dakota Game and Fish Department. Bismarck, ND.

Dolloff, A. C., C. Krause, and C. Roghair. 2013. Initial implementation of a long-term freshwater mussel monitoring program for the Chattooga River. Blacksburg, VA.

Downing, J. A., and W. L. Downing. 1992. Spatial aggregation, precision, and power in surveys of freshwater mussel populations. Canadian Journal of Fisheries and Aquatic Sciences 49:985–991.

Downing, J. A., P. Van Meter, and D. A. Woolnough. 2010. Suspects and evidence: a review of the causes of extirpation and decline in freshwater mussels. Animal Biodiversity and Conservation 33:151–185.

Du, L. N., Y. Li, X. Y. Chen, and J. X. Yang. 2011. Effect of eutrophication on molluscan community composition in the Lake Dianchi (China, Yunnan). Limnologica 41:213–219.

Dunca, E., B. R. Schöne, and H. Mutvei. 2005. Freshwater bivalves tell of past climates: But how clearly do shells from polluted rivers speak? Palaeogeography, Palaeoclimatology, Palaeoecology 228:43–57.

Ecological Specialists. 2005. Characterization of unionid communities at three sites in the Missouri River at river miles 810.0, 769.8, and 761.5. Final report submitted to the U.S. Army Corps of Engineers- Omaha District. Omaha, NE. 15 p.

Edgar, L., and K. Schilling. 2009, August 14. U.S. fish and wildlife service uses caution after discovery of Asian clams above Gavins Point National Fish Hatchery. News Release. USFWS Mountain-Prairie Region:1. Lakewood, CO.

Ellis, M. M. 1936. Erosion silt as a factor in aquatic environments. Ecology 17:29–42.

Faltys, K. L. 2016. Assessing freshwater mussels (Bivalvia:Unionidae) in South Dakota and indentifying drivers of assemblage variation. South Dakota State University.

Freshwater Mollusk Conservation Society. 2017. Freshwater mussels are important. https://molluskconservation.org/Links.html.

Fritts, A. K., M. W. Fritts, W. R. Haag, J. A. DeBoer, and A. F. Casper. 2017. Freshwater mussel shells (Unionidae) chronicle changes in a North American river over the past 1000 years. Science of the Total Environment 575:199–206.

Galbraith, H. S., D. E. Spooner, and C. C. Vaughn. 2010. Synergistic effects of regional climate patterns and local water management on freshwater mussel communities. Biological Conservation 143:1175–1183.

Gewertz, D., and F. Errington. 2015. Doing good and doing well: Prairie wetlands, private property, and the public trust. American Anthropologist 117:17–31.

Grabarkiewicz, J. D., and W. S. Davis. 2008. An introduction to freshwater mussels as biological indicators. Environmental Protection 260:1–108.

Haag, W. R. 2012. North American Freshwater Mussels: Natural History, Ecology, and Conservation. Page Cambridge University Press.

Haag, W. R., D. J. Berg, D. W. Garton, and J. L. Farris. 1993. Reduced survival and fitness in native bivalves in response to fouling by the introduced zebra mussel (Dreissena polymorpha) in western Lake Erie. Canadian Journal of Fisheries and Aquatic Sciences 50:13–19.

Haag, W. R., and A. L. Rypel. 2011. Growth and longevity in freshwater mussels: Evolutionary and conservation implications. Biological Reviews 86:225–247.

Haag, W. R., and J. D. Williams. 2014. Biodiversity on the brink: An assessment of conservation strategies for North American freshwater mussels. Hydrobiologia 735:45–60.

Hall, R. I., P. R. Leavitt, R. Quinlan, A. S. Dixit, and J. P. Smol. 1999. Effects of agriculture, urbanization, and climate on water quality in the northern Great Plains. Limnology and Oceanography 44:739–756.

Hanshue, S., J. Rathburn, P. Badra, J. Bettaso, B. Holser, J. Pruden, and J. Grabarkiewicz. 2018. Michigan freshwater mussel survey protocols and relocation procedures.

Hanson, J. M., W. C. Mackay, and E. E. Prepas. 1988. The effects of water depth and density on the growth of a unionid clam. Freshwater Biology 19:345–355.

Harper, D. 1992. Eutrophication of freshwaters principles problems and restoration. Page Chapman and Hall: London, England, Uk; New York, New York, USA.

Hastie, L. C., M. R. Young, P. J. Boon, P. J. Cosgrove, and B. Henninger. 2000. Sizes, densities and age structures of Scottish Margaritifera margaritifera (L.) populations. Aquatic Conservation: Marine and Freshwater Ecosystems 10:229–247.

Hau, D. 2005. Biology, captive propagation, and feasibility of pearl culture in the pink heelsplitter (Potamilus alatus) (Say, 1871) (Bivalvia:Unionidae). Virginia Polytechnic Institute and State University.

Hoke, E. 2003. Investigations on the distribution of freshwater mussels in the Missouri River reservoirs of South Dakota. Final report submitted to South Dakota Game, Fish and Parks. Pierre, SD. 26 p.

Hoke, E. 2011. The Freshwater Mussels (Mollusca: Bivalvia: Unionoida) Of Nebraska. Transactions of the Nebraska Academy of Sciences & Affiliated Societies 32:1–46.

Hult, J. 2015, September 21. Zebra mussels spread through South Dakota dam. Argus Leader. Sioux Falls, SD.

IUCN. 2019. The IUCN red list of threatened species. https://www.iucnredlist.org/.

Johnson, R. R., K. F. Higgins, M. L. Kjellsen, and C. R. Elliott. 1997. Formation of eastern South Dakota basins, Appendix A, in Wetland resources of eastern South Dakota. Brookings, South Dakota State University.

Jones, J. W., and R. J. Neves. 2011. Influence of life-history variation on demographic responses of three freshwater mussel species (Bivalvia: Unionidae) in the Clinch River, USA. Aquatic Conservation: Marine and Freshwater Ecosystems 21:57–73.

Kesler, D. H., and N. Van Tol. 2000. Growth of the freshwater mussel Pyganodon grandis (Unionidae) in two west Tennessee borrow pits. Journal of the Tennessee Academy of Science 75:1–5.

Levine, T. D., H. B. Hansen, and G. W. Gerald. 2014. Effects of shell shape, size, and sculpture in burrowing and anchoring abilities in the freshwater mussel Potamilus alatus (Unionidae). Biological Journal of the Linnean Society 111:136–144.

Lind, O. T. 1979. Handbook of common methods in limnology. C.V. Mosby Co., St. Louis.

Lopes-Lima, M., A. Teixeira, E. Froufe, A. Lopes, S. Varandas, and R. Sousa. 2014. Biology and conservation of freshwater bivalves: Past, present and future perspectives. Hydrobiologia 735:1–13.

Lydeard, C., R. H. Cowie, W. F. Ponder, A. E. Bogan, P. Bouchet, S. A. Clark, K. S. Cummings, T. J. Frest, O. Gargominy, D. G. Herbert, R. Herchler, K. E. Perez, B. Roth, M. Seddon, E. E. Strong, and F. G. Thompson. 2004. The global decline of nonmarine mollusks. BioScience 54:321–330.

Mackie, G. L. 1991. Biology of the exotic zebra mussel, Dreissena polymorpha, in relation to native bivalves and its potential impact in Lake St. Clair. Hydrobiologia 219:251–268.

Malley, D. F., A. Robin Stewart, and B. D. Hall. 1996. Uptake of methyl mercury by the floater mussel, Pyganodon grandis (bivalvia, unionidae), caged in a flooded wetland. Environmental Toxicology and Chemistry 15:928–936.

Metcalfe-Smith, J. L., J. Di Maio, S. K. Staton, and G. L. Mackie. 2000. Effect of sampling effort on the efficiency of the timed search method for sampling freshwater mussel communities. Journal of the North American Benthological Society 19:725–732.

Metcalfe-Smith, J. L., S. K. Staton, G. L. Mackie, and N. M. Lane. 1998. Changes in the biodiversity of freshwater mussels in the Canadian waters of the lower Great Lakes drainage basin over the past 140 years. Journal of Great Lakes Research 24:845–858.

Minnesota Department of Natural Resources. 2004. Minnesota statewide mussel (Bivalvia: Unionidae) survey: 2003-04. Prepared for U.S.Fish and Wildlife Serivce. Ecological Serices Division Report, Minnesota Deparment of Natural Resources, St.

Paul, MN.

Minnesota Zoo. 2019. Restoring freshwater mussels. http://mnzoo.org/conservation/minnesota/freshwater-mussels/.

Moorkens, E. A. 1999. Conservation management of the freshwater pearl mussel Margaritifera margaritifera Part 1: Biology of the species and its present situation in Ierland. Irish Wildlife Manuals 8.

Motew, M., X. Chen, E. G. Booth, S. R. Carpenter, P. Pinkas, S. C. Zipper, S. P. Loheide, S. D. Donner, K. Tsuruta, P. A. Vadas, and C. J. Kucharik. 2017. The influence of legacy P on lake water quality in a midwestern agricultural watershed. Ecosystems 20:1468–1482.

Nalepa, T. F., W. S. Gardner, and J. M. Malczyk. 1991. Phosphorus cycling by mussels (Unionidae: Bivalvia) in lake St. Clair. Hydrobiologia 219:239–250.

Neves, R. J., and S. N. Moyer. 1988. Evalutation of techniques for age determination of freshwater mussels (Unionidae). American Malacological Bulletin 6:179–188.

Oesch, R. D. 1984. Missouri naiades a guide to the mussels of Missouri. Missouri Department of Conservation.

Ogle, D. H. 2016. Introductory fisheries analysis with R. CRC Press, Boca Raton.

Ohio Department of Natural Resources, Division of Wildlife and U.S. Fish and Wildlife Service, and Ohio Ecological Services Field Office. 2018. Ohio mussel survey protocol.

Ostrovsky, I., M. Gophen, and I. Kalikhman. 1993. Distribution, growth, production, and ecological significance of the clam Unio terminalis in Lake Kinneret, Israel. Hydrobiologia 271:49–63.

Outeiro, A., P. Ondina, C. Fernandez, R. Amaro, and E. San Miguel. 2008. Population density and age structure of the freshwater pearl mussel, Margaritifera margaritigera, in two Iberian rivers. Freshwater Biology 53:485–496.

Patzner, R. A., and D. Muller. 2001. Effects of eutrophication on Unionids. In Bauer, G. & K. Wachtler (eds), Ecology and Evolution of the Freshwater Mussels Unionoida. Springer, Berlin.

Perkins, K. I. 2007. Final report: Unionid mussels- species distribution and response to changes in discharge along the fifty nine mile reach of the Missouri National Recreational River from Gavin's Point Dam to Ponca, NE. Final report submitted to the National Park Service. Yankton, SD. 85 p.

Perkins, K. I., and D. C. Backlund. 2000. Freshwater mussels of the Missouri National Recreational River below Gavins Point Dam, South Dakota and Nebraska. Page US Army Corps of Engineers. SD GFP Report 2000-1. South Dakota Game, Fish and Parks. Pierre, SD. 24 p.

Perkins, K. I., and D. C. Backlund. 2003. A survey for winged mapleleaf (Quadrula fragosa) and scaleshell (Leptodea leptodon) in the James River, South Dakota. GFP Report 2003-17, South Dakota Department of Game, Fish and Parks. Pierre, SD. 22 p.

Perkins, K. I., D. R. Skadsen, and D. Backlund. 1995. A survey for unionid mussels in Day, Deuel, Grant, and Roberts Counties, South Dakota. Final report submitted to

South Dakota Game, Fish and Parks. Pierre, SD. 62 p.

Ricciardi, A., R. J. Neves, and J. B. Rasmussen. 1998. Impending extinctions of North American freshwater mussels (Unionoida) following the zebra mussel (Dreissena polymorpha) invasion. Journal of Animal Ecology 67:613–619.

Ricciardi, A., and J. B. Rasmussen. 1999. Extinction rates of North American freshwater fauna. Conservation Biology 13:1220–1222.

Rypel, A. L., W. R. Haag, and R. H. Findlay. 2008. Validation of annual growth rings in freshwater mussel shells using cross dating. Canadian Journal of Fisheries and Aquatic Sciences 65:2224–2232.

Sawyer, C. N. 1966. Basic concepts of eutrophication. Journal Water Pollution Control Federation 38:737–744.

Schneider, D. W., C. D. Ellis, and K. S. Cummings. 1998. A transportation model assessment of the risk to native mussel communities from zebra mussel spread. Conservation Biology 12:788–800.

Shearer, J. D., D. Backlund, and S. K. Wilson. 2005. Freshwater mussel survey of the 39-mile district- Missouri National Recreational River, South Dakota and Nebraska. Final report submitted to the National Park Service. O’Neill, NE. 16 p.

Sietman, B. E. 2003. Field guide to the freshwater mussels of Minnesota. Minnesota Department of Natural Resources.

Skadsen, D. R. 1998. A report on the results of a survey for unionid mussels on the upper and middle Big Sioux River and tributaries: Grant, Codington, Hamlin, Brookings, and Moody Counties, South Dakota. Report submitted to the South Dakota Department of Game, Fish and Parks. Pierre, SD. 42 p.

Skadsen, D. R., and K. I. Perkins. 2000. Unionid mussels of the Big Sioux River and tributaries Moody, Minnehaha, Lincoln, and Union counties South Dakota. Final report submitted to the South Dakota Department of Game, Fish and Parks. Pierre, SD. 57 p.

Skinner, A., M. Young, and L. Hastie. 2000. Ecology of the freshwater pearl mussel. Page Conserving Natura.

Smith, D. R., R. F. Villella, and D. P. Lemarié. 2001. Survey protocol for assessment of endangered freshwater mussels in the Allegheny River, Pennsylvania. Journal of the North American Benthological Society 20:118–132.

Smith, V. H., and D. W. Schindler. 2009. Eutrophication science: where do we go from here? Trends in Ecology and Evolution 24:201–207.

Sousa, R., C. Antunes, and L. Guilhermino. 2009. Ecology of the invasive Asian clam Corbicula fluminea (Müller, 1774) in aquatic ecosystems: an overview. Annales de Limnologie - International Journal of Limnology 44:85–94.

South Dakota Department of Environment and Natural Resources. 2016. The 2016 South Dakota integrated report for surface water quality assessment. Pierre, South Dakota, USA.

South Dakota Department of Environment and Natural Resources. 2018. The 2018 South Dakota integrated report for surface water quality assessment. Pierre, South Dakota, USA.

Sparks, B. L., and D. L. Strayer. 1998. Effects of low dissolved oxygen on juvenile Elliptio complanata (Bivalvia:Unionidae). Journal of the North American Benthological Society 17:129–134.

Stangel, P., and A. Shambaugh. 2005. Lake Champlain 2004 zebra mussel monitoring program. Waterbury, Vermont.

Stein, C. B. 1973. The life history of Amblema plicata (Say, 1817), the three-ridge naiad (Mollusca:Bivalvia). Ohio State University.

Strayer, D. L. 2008. Freshwater mussel ecology: A multifactor approach to distribution and abundance. 1st edition. University of California Press.

Strayer, D. L. 2014. Understanding how nutrient cycles and freshwater mussels (Unionoida) affect one another. Hydrobiologia 735:277–292.

Strayer, D. L. 2017. What are freshwater mussels worth? Freshwater Mollusk Biology and Conservation 20:103–113.

Strayer, D. L., J. A. Downing, W. R. Haag, T. L. King, J. B. Layzer, T. J. Newton, and J. S. Nichols. 2004. Changing perspectives on pearly mussels, North American’s most imperiled animals. BioScience Vol. 54:429–439.

Taylor, J. 2015. Northwestern glaciated plains ecoregion. Pages 77–86 *in* J. L. Taylor, W. Acevedo, R. F. Auch, and M. A. Drummond, editors. Status and Trends of Land Change in the Great Plains of the United States- 1973 to 2000. U.S. Geological Survey. Professionl Paper 1794-B.

Texas Parks & Wildlife. 2012. Freshwater mussels of Texas. https://www.inaturalist.org/projects/freshwater-mussels-of-texas.

Texas Parks & Wildlife. 2019. Texas mussel watch: Become a Texas mussel watch volunteer. https://tpwd.texas.gov/huntwild/wild/wildlife_diversity/texas_nature_trackers/mussel/volunteer/.

Thorp, J. H., D. C. Rogers, and W. W. Dimmick. 2014. Thorp and Covich's Freshwater Invertebrates: Ecology and General Biology: Fourth Edition. Page Thorp and Covich's Freshwater Invertebrates: Ecology and General Biology: Fourth Edition.

Tyrrell, M., and D. J. Hornbach. 2006. Selective predation by muskrats on freshwater mussels in 2 Minnesota rivers. Journal of the North American Benthological Society 17:301–310.

U.S. Environmental Protection Agency. 2013. Level III ecoregions of the continental United States. https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states.

Vander Laan, J. J., C. P. Hawkins, J. R. Olson, and R. A. Hill. 2013. Linking land use, in-stream stressors, and biological condition to infer causes of regional ecological impairment in streams. Freshwater Science 32:801–820.

Vanleeuwen, D. J., and J. A. Arruda. 2001. A survey of the unionid mussels in six tributaries of the lower Neosho river (Kansas). Transactions of the Kansas Academy of Science.

Vaughn, C. C. 2018. Ecosystem services provided by freshwater mussels. Hydrobiologia 810:15–27.

Vaughn, C. C., S. J. Nichols, and D. E. Spooner. 2008. Community and foodweb ecology of freshwater mussels. Journal of the North American Benthological Society 27:409–423.

von Bertalanffy, L. 1938. A quantitative theory of organic growth (Inquiries on growth laws II). Human Biology 10:181–213.

Wall, S. S., and S. K. Thomson. 2004. Freshwater mussels of the James River tributaries, South Dakota. Final report submitted to South Dakota Game, Fish and Parks. Pierre, SD. 8 p.

Watters, G. T. 2000. Freshwater mussels and water quality : A review of the effects of hydrologic and instream habitat alterations. Society:261–274.

Weinzinger, J. 2018. Wisconsin mussel mointoring program training manual.

Williams, J. D., M. L. Warren, Jr., K. S. Cummings, J. L. Harris, and R. J. Neves. 1993. Conservation Status of Freshwater Mussels of the United States and Canada. Fisheries 18:6–22.

Wisconsin Department of Natural Resources. 2003. Freshwater mussels of the upper Mississippi river. Wisconsin Department of Natural Resources.

Zieritz, A., M. Lopes-Lima, A. E. Bogan, R. Sousa, S. Walton, K. A. A. Rahim, J. J. Wilson, P. Y. Ng, E. Froufe, and S. McGowan. 2016. Factors driving changes in freshwater mussel (Bivalvia, Unionida) diversity and distribution in Peninsular

Malaysia. Science of the Total Environment 571:1069–1078.