QUANTIFYING HUMAN AND ECOLOGICAL DIMENSIONS TO ADVANCE
HOLISTIC UNDERSTANDING OF PRAIRIE LAKE ECOSYSTEMS

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By
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Lushani Chaya Nanayakkara, candidate for the degree of Doctor of Philosophy in Biology, has presented a thesis titled, *Quantifying Human and Ecological Dimensions to Advance Holistic Understanding of Prairie Lake Ecosystems*, in an oral examination held on April 26, 2018. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

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ABSTRACT

Successfully managing the impacts of changing environmental conditions on complex socio-ecological systems (SES) requires identifying, quantifying, and understanding the multitude of threats facing such systems. Research that transcends disciplinary boundaries is the best means of accomplishing this task. Therefore, in this study, I combined multiple methods from the social sciences and natural sciences to quantify the human and ecological dimensions of prairie lakes in Saskatchewan, Canada.

Firstly, to advance understanding of lake-use patterns and users’ perceptions of these systems, I designed and distributed a stakeholder survey. Results indicate primary lake-uses in this region are recreational, particularly fishing. Walleye (*Sander vitreus*) are targeted more than native fishes such as northern pike (*Esox lucius*) or yellow perch (*Perca flavescens*). Overall, respondents expressed concerns about pollution and urbanization, but invasive species and climate change were of minimal concern. Next, I quantified the current status and potential resilience of the aforementioned game fish species to changing environmental conditions using three parameters. I used Bayesian mixing models (MixSIAR) to evaluate resource-use, while body condition was expressed as relative weight indices (*W_r*), and parasite loads were enumerated via gut analyses. Based on the results, stocked walleye appear to be less resilient to environmental variability compared to naturally occurring species. This suggests that walleye will need to be continuously stocked in the future, particularly under climate change scenarios. Finally, because invasive species are expected to significantly impact game fish populations in temperate regions, and humans being key vectors in the spread and
establishment of invasive species, I examined stakeholder knowledge about aquatic invasive species (AIS). Results from a survey questionnaire indicated low education and communication success, as respondents exhibited substantial knowledge gaps regarding non-native mussels and key preventative behaviours. Furthermore, I identified correlates of AIS knowledge and recommend exploitation of these predictors to improve effectiveness of education, outreach, and communication efforts. Based on the collated results from this interdisciplinary study, I recommend development of management strategies that focus on ensuring the long-term sustainability of recreational angling, improving AIS knowledge through re-structured education campaigns, and enhancing efforts for detecting AIS transfer. Overall, utilizing an interdisciplinary approach to examine the human and ecosystem dimensions of prairie lakes advanced comprehensive understanding of these complex SES.
**PREFACE**

This dissertation consists of five chapters. Chapter One is a general introduction to the research project, Chapters Two-Four are research chapters, and Chapter Five is a synthesis chapter that contains general takeaways and management recommendations that are of interest to the larger research community. Chapters Two-Four were written as manuscripts. At the time of submission to the Faculty of Graduate Studies and Research, Chapters Two and Four were published in the peer-reviewed journals Lake and Reservoir Management, and Biological Invasions, respectively. Chapter Three was in review at the Canadian Journal of Fisheries and Aquatic Sciences. Citations are as follows:


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# TABLE OF CONTENTS

ABSTRACT........................................................................................................................................i-ii

PREFACE.........................................................................................................................................iii

ACKNOWLEDGEMENTS..............................................................................................................iv

TABLE OF CONTENTS................................................................................................................v-vii

LIST OF TABLES..........................................................................................................................viii-xi

LIST OF FIGURES........................................................................................................................xii-xv

LIST OF APPENDICES................................................................................................................xvi

CHAPTER 1: GENERAL INTRODUCTION.........................................................................................1

1.1 Threats facing lake ecosystems.........................................................................................1

1.2 Previous research on prairie lakes..................................................................................3

1.3 Human dimensions of complex socio-ecological systems...........................................5

1.4 Objectives and relevance...............................................................................................6

CHAPTER 2: PRELIMINARY INVESTIGATION OF LAKE-USE PATTERNS IN
PRAIRIE LAKES, STAKEHOLDER PERCEPTIONS AND RESULTING
MANAGEMENT IMPLICATIONS......................................................................................................10

2.1 Abstract..........................................................................................................................10

2.2 Introduction...................................................................................................................11
CHAPTER 3: RESOURCE-USE, HEALTH, AND SUSTAINABILITY OF POPULATIONS OF STOCKED AND NATIVE FISHES IN CANADIAN PRAIRIE LAKES.

3.1 Abstract........................................................................................................40
3.2 Introduction....................................................................................................40
3.3 Methods.........................................................................................................43
3.4 Results...........................................................................................................54
3.5 Discussion......................................................................................................66
3.6 Conclusions...................................................................................................73
3.7 Acknowledgements.......................................................................................73

CHAPTER 4: IN LAKES BUT NOT IN MINDS: STAKEHOLDER KNOWLEDGE OF INVASIVE SPECIES IN PRAIRIE LAKES

4.1 Abstract........................................................................................................74
4.2 Introduction....................................................................................................75
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3</td>
<td>Methods</td>
<td>79</td>
</tr>
<tr>
<td>4.4</td>
<td>Results</td>
<td>87</td>
</tr>
<tr>
<td>4.5</td>
<td>Discussion</td>
<td>101</td>
</tr>
<tr>
<td>4.6</td>
<td>Conclusions</td>
<td>109</td>
</tr>
<tr>
<td>4.7</td>
<td>Acknowledgements</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td><strong>CHAPTER 5: CONCLUSIONS</strong></td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>Synthesis and management relevance of results</td>
<td>111</td>
</tr>
<tr>
<td>5.2</td>
<td>Management recommendations</td>
<td>114</td>
</tr>
<tr>
<td>5.3</td>
<td>Future work</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td><strong>REFERENCES</strong></td>
<td>121</td>
</tr>
<tr>
<td></td>
<td><strong>APPENDIX</strong></td>
<td>154-160</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 2.1 Fish complexity, infrastructure and population characteristics of lakes in a long-term ecosystem survey in Saskatchewan, Canada. All lakes are in the grassland ecotone, experience a semi-arid climate, and are located in endorheic basins. Size ranges from 1-60 km$^2$, depth from 3-30 m, Chl a from 5-90 µg l$^{-1}$, salinity 0.5-60 g l$^{-1}$, DIC 30-350 mg l$^{-1}$, and trophic status varies from mesotrophic to hypertrophic. Population information from Statistics Canada 2011 Census of Population and camp site information from Tourism Saskatchewan. Fish complexity is noted due to the popularity of recreational fishing in the area. *lakes that were part of this stakeholder survey.................................................................17-19

Table 2.2 Percentage representation of concerns for each lake user group. $n$ represents number of respondents, CO = conservation officer and empty cells denote no concern for the given lake user group.................................................................28

Table 2.3 Two main clusters of lake user involvement in a community monitoring group (CMG), different roles involvement are denoted as categories within clusters, along with the number of respondents interested in participating in various roles. $n = 34$ but do not sum to 34 because users were interested in multiple roles.................................................................32

Table 3.1 Environmental and limnological parameters of the 13 lakes included in the study. Complexity refers to fish community complexity; low = (only forage fishes) and high = (forage fishes, benthivores and game fishes). Mean and ±SD for recorded values

viii
of maximum depth ($Z_{\text{max}}$) in meters, total dissolved solids (salinity as TDS) in g L$^{-1}$, chlorophyll a (Chla) in µ L$^{-1}$, total Kjedahl nitrogen (TKN) in µg L$^{-1}$, total phosphorous (TP) in µg L$^{-1}$ and dissolved organic carbon (DOC) in mg L$^{-1}$. “46-47

Table 3.2 Comparison of the ratios of amphipod: fish remains found in the stomachs of walleye (*Sander vitreus*), northern pike (*Esox lucius*) and a comparison between amphipod: fish: caldoceran consumption for yellow perch (*Perca flavescens*). Data collected bi-annually from 2008-2014 in all study lakes with game fish species. NA = no data were collected based on foraging patterns reported in the literature (Hartman and Margraf 1992, Sammons et al. 1994, Lott et al. 1996). “61

Table 3.3 Body condition (Wr) data for the three main game fishes; walleye (*Sander vitreus*), northern pike (*Esox lucius*) and yellow perch (*Perca flavescens*). All fishes used in this analyses exceeded minimum total lengths (walleye >150mm, pike >100mm, perch >100mm). Intercept and slope parameters for the Wr equations for each species from the following sources: (Murphy et al. 1990) (walleye), (Willis 1989) (pike), (Willis et al. 1991) (perch). Target range for Wr is 95 – 105. “62

Table 3.4 Climate conditions from 2008 to 2014. Temperature records obtained from the Saskatoon weather station and ice cover data (ice-on, ice-off) were taken from the Buffalo Pound water treatment facility. Mean highs and lows are recorded for the full ice off period. Optimal temperature ($T_{\text{OPT}}$) for all three game fish species are between 10 to 22-

Bioenergetic thermal maxima for walleye is 27 °C (Bozek et al. 2011).

Table 4.1 Presence/absence and impact knowledge for each species, PLUMS 2015-2016. Valid percent (% first row) and frequency (n, second row). All fishes and plants are present in SK, mussels are absent. All AIS listed are associated with negative impacts.

Table 4.2 Crosstabulations with chi-square tests for associations between correctly identifying presence/absence of a group of AIS and correctly identifying negative impacts of a group of AIS, PLUMS 2015-2016. *p<0.001.

Table 4.3 Stepwise multiple linear regression for predictor variables associated with correctly identifying presence/absence of fish, plant and mussel organisms, PLUMS 2015-2016. 1Reference category = Medium-to-large population center: population of 30,000 or more; 2 Reference category = Diefenbaker – Qu’Appelle system; (−) = Predictor variable did not enter the model. In each model, we entered the following predictors: respondent’s sex, age, race, highest educational level, self-perceived SES, city/town/RM of residence, lake’s region, purpose: fishing, purpose: swimming, purpose: boating, purpose: recreation, purpose: work, purpose: cabining, awareness of eutrophication, awareness of winterkill and awareness of water extraction. Dummy coded variables (no. of categories -1) were created for categorical predictors.
Table 4.4 Stepwise multiple linear regression for predictor variables associated with correctly identifying negative impact of fish, plant and mussel organisms, PLUMS 2015-2016. ¹Reference category = Female; ²Reference category = Diefenbaker – Qu’Appelle system; (−) = Predictor variable did not enter the model. In each model, we entered the following predictors: respondent’s sex, age, race, highest educational level, self-perceived SES, city/town/RM of residence, lake’s region, purpose: fishing, purpose: swimming, purpose: boating, purpose: recreation, purpose: work, purpose: cabining, awareness of eutrophication, awareness of winterkill and awareness of water extraction. Dummy coded variables (no. of categories -1) were created for categorical predictors………………………………………………………………………………………………………………………………………………..96-97

Table 4.5 Forward conditional stepwise logistic regression of awareness of zebra and quagga mussels, PLUMS 2015-2016. ¹Reference category = Female; (−) = Predictor variable did not enter the model. In each model, we entered the following predictors: respondent’s sex, age, race, highest educational level, self-perceived SES, city/town/RM of residence, lake’s region, purpose: fishing, purpose: swimming, purpose: boating, purpose: recreation, purpose: work, purpose: cabining, awareness of eutrophication, awareness of winterkill and awareness of water extraction. Dummy coded variables (no. of categories -1) were created for categorical predictors…………………………………..100
LIST OF FIGURES

Figure 2.1  Study lakes in southern Saskatchewan. Study lakes are shown as circles and lakes where the surveys were distributed are shown as solid black circles. Please refer to Table 1 for additional site information. Major urban centers as open squares. All lakes are part of the long-term ecosystem survey……………………………………………………………………………………………………16

Figure 2.2  Percent of lake users’ various activities as determined from lake use surveys in summer 2013. The values do not sum to 100% as users often engage in more than one use……………………………………………………………………………………………………………………………………………25

Figure 2.3  Percent of lake users’ concern on various issues with regard to the lakes they utilize as determined from lake management surveys in summer 2013. The values do not sum to 100% as users cited multiple issues of concern………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………
solid line represents the grassland transition zone and dashes lines represent annual precipitation deficits. Boxes indicate the major urban centers in SK.

Figure 3.2 Comparison of benthic contribution to whole-lake production (x-axis) to mean whole-lake benthic contribution to fish diets (y-axis). Open circles = high complexity lakes (includes forage fishes, benthivores and game fishes) and closed circles = low complexity lakes (only forage fishes). Line indicates 1:1 for benthic contribution for whole-lake production and fish reliance on benthic carbon. f(BP) values estimated from the Vadeboncoeur et al. (2008) productivity model and mean benthic contribution estimated from Bayesian mixing models (MixSIAR).

Figure 3.3 Mean benthic reliance for each fish group. Vertically compared by season (Early vs. Late) and horizontally compared by complexity (High vs. Low). Mean benthic reliance for each group estimated from Bayesian mixing models (MixSIAR). Black circles indicate outliers.

Figure 3.4 Species level reliance on benthic carbon for forage fishes. All species except spottail shiners (*Notropis hudsonius*) were found in both low and high complexity lakes. Vertically divided by lake complexity (High vs. Low). Mean estimates of benthic reliance obtained from Bayesian mixing models (MixSIAR). Black circles indicate outliers.

Figure 3.5 Species level reliance on benthic carbon for game fishes. Walleye (*Sander vitreus*) and northern pike (*Esox lucius*) exhibited significantly higher reliance on benthos.
than did yellow perch (*Perca flavescens*). Whitefish (*Coregonus clupeaformis*), cisco (*Coregonus artedi*) are not discussed in the manuscript because of low sample sizes. Mean benthic reliance estimates were obtained from Bayesian mixing models (MixSIAR).

Figure 3.6 Body condition values are vertically divided by the three dominant game fishes; walleye (*Sander vitreus*), northern pike (*Esox lucius*), and yellow perch (*Perca flavescens*). All fishes used in this analyses exceeded minimum total lengths (walleye >150mm, pike >100mm, perch >100mm). Intercept and slope parameters for the $W_t$ equations for each species from the following sources: Murphy et al. 1990 (walleye), Willis 1989 (pike), Willis et al. 1991 (perch). Target range for $W_t$ is 95 – 105. Closed triangles = June and closed circles = August values.

Figure 3.7 Comparison of the mean benthic reliance results from the two methods utilized in this study. Closed circles = gut content analysis and closed triangles = Bayesian mixing model (MixSIAR) result values for the three species of game fishes.

Figure 4.1 Map of study lakes in Saskatchewan, Canada. Inset identifies the location of the study area within the province. The Qu’Appelle River catchment consists of the following lakes: Pasqua, Echo, Katepwa, Crooked and Round. Surveys were distributed at Redberry, Wakaw, Lenore, Kipabiskau, Little Manitou, Fishing, Buffalo Pound, Last Mountain, and Echo lakes. Regina and Saskatoon are the major urban centers in Saskatchewan.
Figure 4.2 Conceptual framework of influence of trans-situational, situational, and lake-related knowledge predictors on presence/absence and impact of AIS.................85

Figure 4.3 Findings-based layout of the impact of trans-situational, situational, and lake-related knowledge predictors on presence/absence of AIS. Unless otherwise specified, the predictor impacts all three groups (fish, pant, mussel) of organisms. (+) and (-) indicates the direction of the relationship. For example, older respondents are less knowledgeable about presence of non-native fishes but more knowledgeable about plants.................................................................................................................................95

Figure 4.4 Findings-based layout of the impact of trans-situational, situational, and lake-related knowledge predictors on negative impact of AIS. Unless otherwise specified, the predictor impacts all three groups (fish, pant, mussel) of organisms. (+) and (-) indicates the direction of the relationship. For example, older respondents are less knowledgeable about the impact of non-native fishes.................................................................98

Figure 5.1 Conceptual diagram of threats facing game fish, especially walleye, in Saskatchewan, Canada. The left column describes the most imminent threats facing these fish populations and the right column notes the primary impacts of these threats. Threats may act synergistically and impacts may be attributed to more than one threat........113
LIST OF APPENDICES

Appendix 1. Operational definitions and explanations of concepts in ‘invasive species’, PLUMS 2015-2016. *List of organisms was provided by the Saskatchewan Ministry of Environment.................................................................156-157

Appendix 2. Operational definitions of predictor variables considered in the regression analyses, PLUMS 2015-2016.................................................................158

Appendix 3. Frequency and percent of lake-use by region, PLUMS 2015-2016……159

Appendix 4. Profiles for the respondents’ lake-use by region, including significant chi-squared results for region differences, PLUMS 2015-2016. Valid percent (%, first row) and frequency (n, second row). *p<0.05; **p<0.01; +few cases..............................160

Appendix 5. Frequency and percent results for awareness of non-native mussels, PLUMS 2015-2016. +4 respondents did not answer; ++8 respondents did not answer.............................................................161

Appendix 6. Copy of ethics approval (File #87S1213) issued by the University of Regina Research Ethics Board.................................................................162
1. GENERAL INTRODUCTION

1.1 Threats facing lake ecosystems

Evidence is mounting that the synergistic effects of climate change, intensive land-use, urbanization, and invasive species, combined with fishing pressure may ultimately lead to declines in recreational fisheries (Post et al. 2002) and threaten the adaptive capacity of lake ecosystems (Cooke and Murchie 2015, McMeans et al. 2016). As lake temperatures increase in response to climate change, there may be notable changes in lake trophic assemblages. Species-specific variations in abundance of important game fish will likely be observed, along with concurrent range shifts (Ficke et al. 2007, Lynch et al. 2016). However, because fish are reliant on ambient temperatures to maintain homeostasis, temperate (cold- and cool- water species) fishes will likely experience disproportionate impacts on their physiology, growth, and reproduction (Quist et al. 2002, Ficke et al. 2007, Pankhurst and Munday 2011). In addition to increased temperatures, climate change will also decrease the amount of dissolved oxygen (DO) in the water column, potentially increasing the frequency of summerkill events (Ficke et al. 2007). Increased evaporation rates as a result of higher temperatures may also yield higher solute concentrations in the ice-off season leading to osmotic stress, especially in prairie lakes (Starks et al. 2014, Mosley 2015, Whitney et al. 2016). Additionally, as temperatures shift away from the optimal range for cool- and cold- water species, their immune systems will not function at full capacity, making them more vulnerable to diseases and parasites (Marcogliese 2002, Wegner et al. 2008, Bowden 2008).
Runoff from intensive land-use and point-source pollution from urbanization often results in increased nutrient inputs to lentic systems, thereby stimulating prolific phytoplankton productivity and cultural eutrophication of lakes (Smith 2003). As phytoplankton die-off over the course of the ice-off season and sink to the bottom of the lake, bacterial decomposition and respiration can drive oxygen levels below the requirements of certain fish species (Barica and Mathias 1979, Babin and Prepas 1985). Therefore, if there is a substantial biomass of phytoplankton decomposing under ice (with limited to no photosynthesis), the oxygen pool may become completely depleted and cause winterkill (Barica and Mathias 1979). At the same time, elevated air temperatures in spring can reduce the extent of the ice-on period, possibly reducing the risk of winterkill even in productive lakes (Fang and Stefan 2009). Alternatively, higher temperatures can also increase thermal stratification in the ice-off season and lead to substantial decreases of DO in the hypolimnion (Foley et al. 2012). Given the complexity of potential climate effects, more information is needed on the status of susceptible lakes, including those in the Canadian Prairies.

As lentic systems continue to experience the impacts of climate change and other anthropogenic influences of land-use, they will likely become more vulnerable to invasions by non-native organisms (Ehrenfeld 2010, Strayer 2010). Once established, non-native species have been shown to dramatically alter food webs (Kreps et al. 2016). For example, one of the most recognizable aquatic invasive species, zebra mussels (*Dreissena polymorpha*), have dramatically altered the food-webs in invaded lakes and shifted production away from pelagic phytoplankton to benthic production dominated systems (Strayer, 2010). The arrival of warm-water invasive fish species such as small
mouth bass also significantly decreased the occurrence of cool-water species such as walleye (*Sander vitreus*), by as much as three times (Van Zuiden and Sharma 2016). At present, it is unknown how climate change, intensified land use practises, and invasive species may interact, or even if managers and the public are aware of the multifaceted threats to inland waters.

1.2 **Previous research on prairie lakes**

Lakes are a common landscape feature in the northern Great Plains. In southern Saskatchewan (SK), lakes exhibit a diverse array of chemical, morphometric, and physical parameters (Rawson and Moore 1944b, Hammer 1986, Last and Ginn 2005). For example, salinity in these lakes range from freshwater (<0.5 gL\(^{-1}\)) to hyper saline (>50 gL\(^{-1}\)) and depth can vary several orders of magnitude (Pham et al. 2008, 2009, Wissel et al. 2011). This large gradient in physical (e.g., depth) and limnological (e.g., nutrients) parameters is mainly attributed to lakes being located in endorheic basins and climate variability. Endorheic or interior basins lack permanent surface inflow and outflow, and experience net evaporative loss (Rawson and Moore 1944a, Hammer 1986, Laird et al. 1996). Therefore, even though the majority (~70%) of precipitation in this region falls as rain, due to intense summer evaporation, many closed-basin prairie lakes are largely sustained through winter precipitation (Pham et al. 2009). Additionally, temperature extremes (-40 °C to +30 °C) and hydrologic variability (precipitation can range from <250 to >600 mm yr\(^{-1}\)) can result in lakes experiencing drought and deluge conditions over relatively brief periods (< 10 years) of time (Pham et al. 2008, Starks et al. 2014).
As climate change exacerbates environmental variability, region-specific increases in evaporation rates and frequency of extreme precipitation events, may increase the occurrence of drought and deluge events and alter lake trophic assemblages (Starks et al. 2014). Overall, trophic complexity in prairie lakes is correlated with salinity, fish community complexity, and proxies of lake productivity (e.g., nutrients) (Cooper and Wissel 2012b). Analyses of food-webs in these lacustrine environments reveal that the response of major taxonomic groups to chemical, biological, and climate variability is taxon specific. For example, although species richness in these lakes is strongly associated with salinity (Hammer, 1986), fish community richness often exhibits an upper limit of ~8 gL⁻¹ (Hammer, 1986) while zooplankton assemblages change predictably along a salinity gradient and benthic macroinvertebrates communities remained static up to 20 g L⁻¹ (Hammer 1986, Hammer et al. 1990, Cooper and Wissel 2012b). Wissel et al. (2011) identified salinity as the primary predictor of changes in pelagic invertebrate community composition, while mineral nutrients (e.g., Ca²⁺) and lake depth exerted secondary and tertiary control mechanisms, respectively. However, zooplankton communities appear to be robust to short-term climatic variability (Starks et al. 2014, Wissel et al. 2011). In lakes with low salinity (<3 g TDS L⁻¹), pelagic invertebrate community composition is positively associated with predation pressure (Cooper and Wissel 2012a, Starks et al. 2014). The salinity threshold of <3 g L⁻¹ for present-day fish communities identified by Cooper and Wissel (2012a) is considerably lower than the 5-8 g L⁻¹ threshold identified in the past (Hammer, 1986). This lower threshold may be indicative of the importance of winterkill as a determinant of fish assemblages (Cooper and Wissel 2012a). Winterkill in these lakes has been characterized
as an interaction between depth and productivity (Barica and Mathias 1979) and varies with climate conditions (Robarts et al. 2005).

Prairie lakes have been directly impacted by anthropogenic activities such as agriculture and urbanization since the late 1800’s (Rawson and Moore 1944a, Smith et al. 1999, Leavitt et al. 2006). Catchment areas of lakes are often subject to intensive agricultural (both cereal crops and livestock production) practices that increase soil erosion and nutrient inputs into lakes, with adverse impacts on water quality (Hall et al. 1999). Previous studies observed increased nutrient inputs from agricultural lands and corresponding increases in algal abundance (Hall et al. 1999, Soranno et al. 1999). Similarly, urban effluent has resulted in a 300% increase in lake production downstream from major urban centers in southern SK, however each lake basin sequestered up to 80% of nitrogen, diminishing the downstream impacts of nutrient inputs on water quality (Leavitt et al. 2006). Unlike algal communities, benthic invertebrate assemblages are significantly correlated with both climate variability and land-use, suggesting differential trophic responses to environmental changes in prairie lakes (Quinlan et al. 2002). Overall, freshwater (<0.5 g/L) and mesosaline (20-50 g/L) lakes have been identified as the most vulnerable to impacts of long-term climate variability and anthropogenic activities (Cooper and Wissel 2012a and 2012b).

1.3 Human dimensions of complex socio-ecological systems

Previous studies of prairie lakes have identified key chemical, biological, climatic, and anthropogenic controls of food-web diversity; however, the human
dimensions of these complex socio-ecological systems (SES) are not as well understood. The absence of recognition of human dimensions can lead to an incomplete understanding of the coupling between biophysical and human systems and a failure to meet management objectives (Bennett 2016, Echeverri et al. 2017), which are dependent on public support and modification of human behaviours (Christie et al. 2017). Despite recent efforts to incorporate the social dimensions of human systems into ecosystem management, governance of natural resources still overlooks the importance of stakeholder values and perceptions (Bennett 2016) thereby obscuring the role of human behaviour in the SES being studied (Adams and Sandbrook 2013). Stakeholder perceptions may not be accurate or factual, but it is important to understand their values, knowledge, and opinions regarding an SES. In particular, because stakeholder perceptions inform opinions on management objectives and identify how likely the public is to comply with regulatory measures (Brown et al. 2015, Bennett 2016, Christie et al. 2017). Successfully integrating human and ecological dimensions of SES often requires an interdisciplinary research approach to both advance scientific knowledge and develop effective management solutions (Cook et al. 2013). Interdisciplinary research involves the integration of different disciplinary ideas to understand a phenomenon, compared to multidisciplinary research where disciplinary boundaries are not challenged, and transdisciplinary research which transcends disciplinary boundaries and includes non-academic actors in the research process (Holm et al. 2013).

1.4 Objectives and relevance
Chapter Two presents the initial attempt at quantifying the human dimensions of management of prairie lakes. Compared to the ecological dynamics of prairie lakes, human dimensions are not as well understood. Given the cultural services provided (e.g., recreational fishing), the societal aspects of these lakes are likely essential to a holistic understanding of these systems. This survey provided several important insights on primary lake-uses, stakeholder concerns and perceptions about these systems, and interest in citizen science. Additionally, attempts to manage heavily-utilized systems such as prairie lakes are largely dependent on changing human behaviour. Therefore, understanding lake users’ perceptions, values, opinions, and concerns are an instrumental first-step in identifying behaviours that must be altered and knowledge gaps that must be closed to successfully manage these systems.

Chapter Three focuses on the ecology of prairie lake foodwebs, and compares the status of artificially stocked, recreationally desired, and economically valuable game fish (walleye; *Sander vitreus*) to naturally occurring species. Game fish populations were evaluated along three parameters: resource-use, body condition health, and parasite load. These parameters encompass components of general fish ecology that are important because of their role as proxy measurements of prey availability, population stability, and possible changes to community structure. Combined, they also allow assessments of the ability of prairie lakes to support desired fish species as impacts of multiple stressors exacerbate over time. In this chapter, I compared spatial and temporal trends and the influence of limnological variables (e.g., morphometric and chemical) on these parameters. As the magnitude of environmental changes in SK is expected to increase
over time, information gleaned from this chapter may help anticipate impacts to the lakes and the recreational fishing industry from changing fish community compositions.

The primary goals of Chapter Four were to understand lake users’ knowledge and perceptions about time-sensitive threats to prairie lakes. Specifically, I evaluated knowledge about aquatic invasive species (AIS), awareness of their presence/absence, and impacts (positive or negative). Additionally, I assessed knowledge about protocols essential to preventing AIS ‘hitchhiking’ on transient vessels that were in contaminated waterbodies and the point of contact in case AIS are discovered on a vessel. Following this, I examined the role of parameters identified in the literature and their influence on AIS knowledge and perceptions. Given that humans are key vectors in transporting AIS from one location to another, understanding lake users’ knowledge regarding this time-sensitive threat is a critical component of AIS prevention because once established, certain AIS (e.g., zebra mussels) are virtually impossible to eradicate. Therefore, this information is a key step towards analyzing the risks SK water bodies face regarding AIS and assessing the success/failure of educational and outreach efforts to disseminate AIS knowledge.

Finally, Chapter Five provides a synthesis of the previous research chapters and recommendations for future work in prairie lake SESs. Based on the results of the previous chapters, I proposed several management recommendations focused on maintaining the recreational fishing industry and closing critical knowledge gaps. This study helps advance the relatively new discipline of interdisciplinary SES research (which is focused on integrating human and ecological dimensions of these complex
systems) by providing an empirical example of how to carry out an interdisciplinary research study and link the different components of the system together. Currently, there is no universally accepted methodology for conducting interdisciplinary SES research. Therefore, successful examples such as this study are an important addition to a growing body of research that helps advance the field, provides guidance to the interdisciplinary research community, and ultimately aids both researchers and policy practitioners holistically manage ‘wicked problems’ currently facing many ecosystems.
2. PRELIMINARY INVESTIGATION OF LAKE-USE PATTERNS IN PRAIRIE LAKES, STAKEHOLDER PERCEPTIONS AND RESULTING MANAGEMENT IMPLICATIONS

2.1 Abstract

To better understand use and perception of lakes in the prairie region of North America, we distributed 200 lake-use and management surveys at 9 lakes in southern Saskatchewan, Canada during 2013 and received 65 responses. Survey results indicate recreational uses such as angling, swimming and boating were most common. Anglers targeted walleye approximately 3 times more than other taxa such as northern pike and yellow perch, and consumption or catch-and-release was based on species and size. Overall, pollution of water bodies (76% of responses) and overfishing (60% of responses) were stated as issues of highest concern in response to an open-ended question, but results varied among user groups. When asked to rank a set of issues potentially related to lake health, urbanization ranked above both agriculture and climate change. Only about half of respondents had a general understanding of eutrophication and food-web composition, anglers were unconcerned about overfishing, and critical matters such as climate change and invasive species were of little concern. These results indicate a possible decoupling between science and public perception about anthropogenic influences on lake ecosystems in southern Saskatchewan prairie lakes. Importantly, 60% of respondents stated their interest in lake management involvement. Monitoring and committee participation garnered the most interest. Based on our results, scientific findings and future threats to lakes need to be better communicated to the public to
successfully adapt to and mitigate the effects of important issues. Ultimately, enhanced science communication with stakeholders may increase citizen science involvement in lake monitoring and management.

2.2 Introduction

Management strategies benefit from incorporating stakeholder knowledge, perceived value and feedback on willingness to protect socio-ecological systems. In the social sciences, importance of personal beliefs and/or values, and its impact on knowledge and behavior has been established through theories like Value-Belief-Norm (VBN) (Stern et al. 1999). VBN considers personal beliefs and/or values integral to environmental knowledge and the likelihood an individual engages in environmentally responsible behavior (Stern et al. 1999). Relevance of VBN and similar social science theories have been documented through various studies. For example, an analysis of water security in agriculture recognized personal beliefs, perceptions, identities and values as foundations of individual behaviors and interactions with common resources, such as water (Morton 2015). Further, research into farmer perceptions about climate change in Iowa revealed the importance of belief and perception in supporting adaptive efforts over mitigation (Arbuckle et al. 2015). Accordingly, management efforts focused on adaptation were more likely to succeed, while better engagement was needed to educate the farming community about the importance of mitigation (Arbuckle et al. 2015). Stakeholder feedback about potential management efforts also provide valuable information that help guide and increase the success of such efforts. A meta-analysis of the public’s willingness-to-pay (WTP) to protect unimpaired waters and forest
conservation across the United States suggests increased WTP depends on several factors, including program type, scale and target resource (Kreye et al. 2014). Such practical applications of knowing perceptions and biases of stakeholders may extend to lake monitoring and management objectives as well.

Inland aquatic ecosystems such as lakes are ubiquitous across the global landscape and provide important ecosystem services including provisioning services (clean water, commercial fisheries), cultural services (tourism, recreational angling), and regulating services (climate regulation, nutrient cycling) (Downing et al. 2006, Lapointe et al. 2014, Voora and Venema 2008). Despite their significance in multiple aspects of both natural and social sciences, inland aquatic ecosystems and related recreational and angling activities receive far less attention than warranted compared to ocean systems (Post 2013, Lapointe et al. 2014).

In particular, lake cultural services like recreational angling have important ecosystem and economic impacts. From a biological standpoint angling can impact the health of aquatic ecosystems in multiple ways, including selective exploitation of desirable fish species, alteration of trophic cascades, increased fish mortality, pollutants from boat traffic, nutrient input modifications, and substantially altering food-webs (Lewin et al. 2006). Therefore, direct and indirect impacts of recreational angling create an important ecological relationship between predator (anglers) and prey (fish) (Post 2013). From an economic perspective recreational angling is a significant income generator for many regions, especially for local communities (Beard et al. 2011).

Together with the aforementioned ecological and economic impacts of recreational uses, the personal beliefs, values and norms of users result in behaviors and
attitudes that have management implications. Post et al. (2008) and Post and Parkinson (2012) noted pronounced spatial patterns in lake utilization, with angling density being highest near urban centers and lowest in rural areas, resulting in disproportionate angling pressures among regions. With respect to recreational fisheries in Germany, Arlinghaus and Mehner (2005) found the tendency of anglers was to support fish stocking rather than habitat restoration when given a choice. Overall, previous studies indicate that human behavior with regards to lake utilization, is complex and should be an integral part of any management strategy.

Therefore, to improve lake management frameworks in the Canadian prairie region, and advance understanding of lake-use habits, stakeholder perceptions and concerns, we conducted a survey to assess stakeholders’ 1) use and understanding of prairie lakes, 2) perception of threats to prairie lakes, and 3) disposition for management involvement.

2.3 Study site

Lakes are a common landscape feature across the Northern Great Plains (Waite 1986, Last and Ginn 2005) and many of them are located in endorheic (interior) basins that lack surface inflow or outflow, with evaporation exceeding precipitation by 40-60 cm/y (Laird et al. 1996). Features such as salinity, depth, area, and trophic complexity in these lakes vary several orders of magnitude aggregating many natural lake conditions found in varied locations throughout the globe (Hammer and Haynes 1978, Waite 1986, Last and Ginn 2005). These factors combined make them ideal model systems to evaluate ecosystem processes and the biotic and abiotic factors that drive them in different lakes.
For this study we selected a subset of 20 lakes located in the prairie region of southern SK that have been monitored since 2002 as part of a long-term ecosystem survey (Figure 1, Table 1). Water chemistry, zooplankton, littoral macroinvertebrate and fish have been evaluated annually (May – August) to quantify food-web and ecosystem dynamics (Wissel et al. 2011, Cooper and Wissel 2012a, 2012b).

Long-term monitoring has increased understanding of ecosystem processes and anthropogenic influences on these lakes (Leavitt et al. 2006, Wissel et al. 2011, Cooper and Wissel 2012a, 2012b). Intensive land-use practices in areas surrounding prairie lakes have led to runoff containing increased nutrient quantities (Cade-Menun et al. 2013). Since long-term hydrologic characteristics of these lakes are maintained by spring runoff, increased nutrient inputs and non-point pollution lead to decreased water quality (Pham et al. 2009). Large-scale, noxious algal blooms resulting from increased nutrients increase organic content in the water column and sediments, further impairing these naturally productive lakes (Wissel et al. 2011). This, coupled with extended ice-cover over winter, may lead to accelerated oxygen depletion, resulting in fish winterkill (Rawson and Moore 1944a, Barica and Mathias 1979). Furthermore, recent analysis of chemical and biological factors that determine trophic assemblages in these lakes suggests that winterkill may now play a more significant role than salinity (Cooper and Wissel 2012b). Such impacts of decreased water quality will undoubtedly influence recreational activities at these lakes, but stakeholder opinions remain poorly understood. Therefore, we carried out a preliminary investigation to obtain relevant stakeholder information about these lakes. This study was ultimately limited to lake users of 9 out of the 20 lakes that are part of the long-term ecosystem study (Figure 1, Table 1). The remaining 11 lakes are too
remote and receive little to no visitors, therefore we were unable to distribute any surveys at these locations.

2.4 Materials and methods

Literature reviews and consultation with Ministry of Environment officials yielded no estimate of the population of interest (lake users) for lakes in this study, possibly due to lakes in North America being largely open access. Considering these limitations we utilized a non-probabilistic convenience sampling framework. This type of sampling scheme involves choosing settings and individuals that are conveniently located and willing to participate in the study (Onwuegbuzie and Collins 2007). While convenience sampling generally has more limitations than probabilistic sampling, this technique is still widely used in research surveys and questionnaires (Onwuegbuzi and Collins 2007). Given the sampling framework employed, caution is advised when generalizing the results of this study as the representativeness of the sample is unknown. Yet, we believe that an unknown population size also signifies the novelty and importance of our study. Clearly, valuable information of lake-use in this region has been undocumented and this study was an attempt to rectify this.

In July and August 2013 we distributed “Saskatchewan lake-use and management” survey packets; due to resource constraints we limited distribution to 200 surveys. Prior to distribution, the survey was reviewed and approved by the Research Ethics Board at the University of Regina (file 87S1213). A survey packet consisted of a cover letter explaining the purpose of the survey, the questionnaire and a
Figure 2.1 Study lakes in southern Saskatchewan. Study lakes are shown as circles and lakes where the surveys were distributed are shown as solid black circles. Please refer to Table 1 for additional site information. Major urban centers as open squares. All lakes are part of the long-term ecosystem survey.
Table 2.1 Fish complexity, infrastructure and population characteristics of lakes in a long-term ecosystem survey in Saskatchewan, Canada. All lakes are in the grassland ecotone, experience a semi-arid climate, and are located in endorheic basins. Size ranges from 1-60 km², depth from 3-30 m, Chl \( a \) from 5-90 μgl\(^{-1}\), salinity 0.5-60 gl\(^{-1}\), DIC 30-350 mg{l}^{-1}, and trophic status varies from mesotrophic to hypertrophic. Population information from Statistics Canada 2011 Census of Population and camp site information from Tourism Saskatchewan. Fish complexity is noted due to the popularity of recreational fishing in the area. *lakes that were part of this stakeholder survey.

<table>
<thead>
<tr>
<th>Lake name</th>
<th>Fish complexity</th>
<th>Accessibility, infrastructure, facilities and campsite capacity (where available) information</th>
<th>Population of nearest First Nation (FN), rural municipality (RM), town or village</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fishing</strong>*</td>
<td>Piscivores</td>
<td>This lake is home to Leslie Beach Regional park and has an official park entrance. Situated inside Fishing First Nations reserve. Lake has undergone flooding several times, residents have constructed a ‘sea-wall’ from sand bags and rocks to protect their cabins and the shoreline. Many cabins, pull-through RV sites, (51 electric and water sites) and fishing amenities (including easily accessible boat launch and fish cleaning room) at this park.</td>
<td>Fishing Lake FN: 489</td>
</tr>
<tr>
<td><strong>Humboldt</strong>*</td>
<td>Piscivores</td>
<td>Relatively well maintained access road. Easy access to boat launch and plenty of parking but no public park (therefore no official park entrance), only permanent homes.</td>
<td>Humboldt: 5,678</td>
</tr>
<tr>
<td><strong>Kipabiskau</strong>*</td>
<td>Piscivores</td>
<td>Regional park with official park entrance, located partially inside Kinistin First Nations reserve. Access road is a grid road through the reserve. Easily accessible boat launch, beach area, amenities, plenty of parking and some cabins.</td>
<td>Full-time residents at lake: 15 800 park passes sold on average/annum Kinistin FN: 365</td>
</tr>
<tr>
<td><strong>Lac Pelletier</strong>*</td>
<td>Piscivores</td>
<td>Regional park that has a well-maintained, paved access road and official park entrance. Many cabins, pull-through RV and tenting sites, 262 (50 non-electric, 204 electric and water, 8 full hook-up) sites at this park. Easily accessible boat launch and parking area.</td>
<td>Lac Pelletier: 607</td>
</tr>
<tr>
<td>Location</td>
<td>Species</td>
<td>Description</td>
<td>Distance/Address</td>
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</tr>
<tr>
<td>Lenore/St. Brieux*</td>
<td>Piscivores</td>
<td>Regional park with official park entrance. Well-developed beach, boat launch, and many cabins. Pull-through RV and tenting sites, 76 (12 non-electric and 64 electric only) sites at this park.</td>
<td>St. Brieux: 590</td>
</tr>
<tr>
<td>Little Manitou*</td>
<td>Fishless</td>
<td>Easily accessible from main road but no official entrance. Well-developed resort area and spa, semi-developed boat launch, amenities. Lake is a unique tourist attraction because of high salinity.</td>
<td>Manitou Beach resort village: 256</td>
</tr>
<tr>
<td>Redberry*</td>
<td>Planktivores</td>
<td>Regional park, grid road leading to the lake accessible from a highway. There is an official park entrance but generally unmanned. Boat launch, beach and camping space available. Pull-through RV and tenting sites, 125 (25 non-electric and 100 electric-only) campsites at this park. Home of the Redberry Lake Biosphere Reserve.</td>
<td>Redberry RM: 372</td>
</tr>
</tbody>
</table>
| Wakaw*            | Piscivores| Regional park with boat launch, cabins and beach area for recreation. No official park entrance, it is also a resort village. Pull-through RV and tenting sites, 125 (46 electric-only and 79 full hook-up) campsites at this park. | Wakaw (nearest town): 985  
Wakaw Lake resort village: 30          |
| Shannon*          | Piscivores| Access road is a little hidden from the main road and no official entrance. Have seen a few boats on the lake. Privately owned campground with 22 campsites.                    | Wakaw: 985                        |
| Arthur            | Fishless  | On the side of a grid road, no real access point to launch boat. Have not seen anyone use this lake.                                                                                                            | St Benedict: 82              |
| Antelope          | Planktivores/Fishless| Regional park but official park entrance is unmanned. Lake experienced flooding and access road leading to water quality sampling point has been washed out. Have seen people on a boat on only one occasion, no other users were spotted. RV and tenting (52 electric only and 11 non-electric) sites available at park. | Gull Lake: 201                   |
| Charron           | Fishless  | Road flooded out recently, bathrooms and shower facilities were also infiltrated. Beach, recreational area and boat launch under water. Park entrance is unmanned and park in general is in dis-repair, haven’t seen anyone except the park manager (who refused to participate in the survey). 73 (6 non-electric and 67 electric only) campsites at this park. | Naicam: 686                      |
| Clair             | Planktivores| Access road off highway and lake is off the side of road. Have not seen anyone use this lake.                                                                                                             | Lake between Quill Lake: 409 and Lakeview RM: 336 |
| Deadmoose         | Planktivores/Fishless| Lake is on side of the highway. Access through small road between fields. Have not seen anyone use this lake.                                                                                             | Humboldt: 5,678                  |
| Edouard           | Planktivores| Adjacent to a private property, lake is accessed through road that leads to the property.                                                                                                                | Naicam: 686                      |
| Middle            | Planktivores| Access road has been flooded out several times and lake has spilled over to neighboring                                                                                                                    | Middle Lake: 242                 |
fields. Have not seen anyone use this lake.

<table>
<thead>
<tr>
<th>Location</th>
<th>Status</th>
<th>Description</th>
<th>RM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rabbit</td>
<td>Fishless</td>
<td>Access road is remote and was recently flooded out (difficult to access even for water quality sampling). Have not seen anyone use this lake.</td>
<td>Redberry: 372</td>
</tr>
<tr>
<td>Snakehole</td>
<td>Fishless</td>
<td>Abandoned salt mine, access through private property therefore, no public access.</td>
<td>Lake between Pennant:120 and Cabri:399</td>
</tr>
<tr>
<td>Success</td>
<td>Fishless</td>
<td>Inside private property therefore no public access. Property owner refused to participate in survey.</td>
<td>Success: 40</td>
</tr>
<tr>
<td>Waldsea</td>
<td>Planktivores</td>
<td>Lake underwent substantial flooding in 2011, all cabins flooded out. Therefore no cabins, nor people around since. Access road was also washed out in flood and now goes right into the lake.</td>
<td>Humboldt: 5,678</td>
</tr>
</tbody>
</table>
stamped/addressed return envelope. At lakes Pelletier, Redberry, Lenore (at St Brieux), Kipabiskau and Fishing, which have park entrances, survey packets were left with park entrance attendants who distributed the surveys to visitors as they entered the park. At lakes Wakaw, Lenore (main basin), Humboldt and Little Manitou which do not have park entrances, members of the public were approached directly and handed survey packets to complete and mail back. Additionally, survey packets were distributed at the SK Ministry of Environment and mailed to the following compliance area offices: Saskatoon, Swift Current, Humboldt, Melfort, Wadena, Regina, Rowan’s Ravine/Strasbour and Moose Jaw as we wanted to evaluate the opinion of Conservation Officers, who are often directly involved in resource management, and public information and education. Conservation Officers were included in this survey because they are important stakeholders in these lakes. They are often ‘the face’ of lake management, actively participating in enforcement and resource management. Additionally, if Conservation Officers are willing to participate in a citizen management group in a volunteer capacity they may be an excellent liaison between universities/scientists/policy makers and the general public. Respondents mailed back the surveys over the following months and survey returns ceased by the end of October 2013.

Survey description

The survey was structured as a detailed questionnaire and separated into four main categories: demographic information, resource-use information, knowledge of aquatic systems and resource-management. Demographic information included age, gender, postal code and education level. These variables were included to identify factors such as gender bias in respondent answers, influence of education on knowledge of lake
ecosystems and perceived issues, and geographic origin of lake users. This was followed by the lake-use section where participants were asked in an open-ended question to list all the activities they engaged in at these lakes. If they engaged in recreational angling, they were asked to report 1) how many times they fished/year, 2) what fish taxa were targeted, 3) whether fish were consumed or released, 4) whether they caught fish with lesions, parasites or generally off-putting appearance. To determine the respondents’ awareness and knowledge of lake ecosystems, they indicated awareness (check “yes” or “no”) of following terms, 1) eutrophication, 2) phytoplankton, 3) zooplankton, 4) macroinvertebrate, and then asked to explain/define the meaning of each term and place the terms phytoplankton, zooplankton, macroinvertebrate, and fish in a food-web hierarchy. They were then asked in an open-ended question to list all concerns they have regarding lakes they use. Next, they were given a list of factors potentially related to water quality in the region: agriculture, urbanization, animal husbandry, climate change and ‘other’ to rank from 1 (most important) to 5 (least important) according to its influence and impact on lakes they use. Animal husbandry was listed as a separate category from agriculture because it is less pervasive than crop production in SK and to allow respondents to consider impacts that may be specific to livestock, such as manure infiltrating lakes and lakes possibly being used as watering holes for animals. To assess their perceptions about lake management, in an open-ended question, respondents were asked to list the level of government/authority they think manages the lakes they use and who should manage these lakes. Finally, survey participants noted their willingness to get involved in lake monitoring and management through participation in a citizen monitoring group (CMG) and listed preferred capacities of involvement. From the data
we were able to determine what the most common lake-uses were, recreational angling habits, user knowledge of aquatic systems, lake users’ concerns, and their willingness to participate in lake monitoring and management.

Data analyses

All qualitative analyses were done using QSR International’s NVivo 10 qualitative data analysis software. Since the responses to ‘lake-use’ were wide and varied, answers were carefully screened, general categories determined from common themes after all the responses were received. Since many respondents listed multiple uses, each use was coded according to the category that best represented the answer. Answers were placed into the following categories: angling, swimming, boating (includes canoeing, kayaking, paddle boating), conservation officer (CO), recreation (includes wildlife viewing, walking along shore, winter sports such as skiing), farming (includes irrigation, animal husbandry, aquaculture), work (not specified), and residence (includes residing adjacent to lake or getting water supply from lake). Responses to ‘lake concern’ were also numerous, thus, they were coded and placed in the following categories using the same aforementioned process as for ‘lake-use’ answers: overfishing, pollution, development (of shoreline), misuse (includes drainage, inappropriate use of recreational aquatic vehicles, disregard for environment), no/lack of regulation, climate change, and invasive species. Utilizing the same process, responses to ‘level of government/authority’ were coded and placed in the following categories: Saskatchewan Environment, Water Security Agency, Ministry of Environment (only), Municipal government, Provincial government, First Nations, Federal government, and non-governmental organization.
Responses to participation in a CMG were coded and placed in two clusters 1) CMG development, and 2) maintain CMG network.

Quantitative analyses were conducted in R cran statistical package (RStudio 0.98.1091; R Development Core Team 2014). We conducted chi-square test for independence to determine influence of education level on knowledge of eutrophication, because given the prevalence of eutrophication in some lakes it is important to understand what factors contribute to stakeholder awareness. Citizen scientists are valuable lake monitoring and managing resources, therefore, it is important to understand factors that may encourage or discourage participation in a CMG. We also conducted chi-square tests for independence to determine 1) if type of lake-use influences willingness for getting involved in a CMG, 2) if perceived level of government/authority in charge of lake management influences disposition for CMG participation (R cran packages ‘MASS’: Venables and Ripley 2002, ‘gmodels’, version 2.15.4.1: Warnes et al. 2013). Chi-square analyses was limited to categories with more than 5 responses. A non-parametric Friedman’s ANOVA was conducted to test differences in ranks assigned to urbanization, animal husbandry, agriculture and climate change. The ranking question was selected for Friedman’s ANOVA since the open-ended ‘lake concern’ question required no indication of the relative importance of each issue making it unsuitable for this analysis. Ranks assigned to ‘other’ category were excluded from this analysis because most respondents left it empty. Multiple comparisons between groups after Friedman test with Bonferroni correction (α<.05) were conducted to identify differences between rankings. (R cran packages ‘pgirmess’, version 1.5.9: Giraudoux 2014).
Study limitations

The sampling framework employed, due to limited knowledge of lake-use population, confines the general extrapolation and broad-scale application of the findings from the study. Yet, there is no evidence in the literature for similar prairie regions that contradicts our findings; for instance, other sources also indicate that recreational angling is the most prevalent type of lake-use. This was a preliminary investigation and future studies should address these methodological limitations. A follow-up angler diary survey or creel cards may help gather additional information about angling habits. Angler diary surveys are the traditional assessment method for determining recreational angling patterns (Kerr 2007). Given the ecosystem services provided by lakes (Downing et al. 2006), a short survey to determine public perception about prairie lakes that may not support fish, may also prove useful for managers. A potential follow up survey hopes to address these issues and expand the geographic coverage to regions where lakes are heavily utilized.

2.5 Results

Of the 200 questionnaires that were distributed, 65 (33%) were returned. This response rate is consistent with other studies that employed mail surveys (Kanuk and Berenson 1975, Cobanoglu et al. 2001, Kaplowitz et al. 2004). From the questionnaires returned, 63 (97%) indicated they use lakes for various activities. Lake users (Figure 2) participated in recreational angling (76%), swimming (73%), boating (37%), recreation (37%), CO (Conservation Officer, 23%), residence (3%), farming (2%), and work (2%). Users engaged in recreational angling elaborated on their activities: anglers preferred
Figure 2.2 Percent of lake users’ various activities as determined from lake use surveys in summer 2013. The values do not sum to 100% as users often engage in more than one use. CO = Conservation Officer.
walleye (*Sander vitreus*) almost 3:1 over the second most desired fish taxa, northern pike (*Esox lucius*), followed by trout (unspecified), yellow perch (*Perca flavescens*), rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), and tiger trout (*Salmo trutta X Salvelinus fontinalis*). Most fished over both seasons (75%) and others exclusively in the summer (16%) or winter (9%), but seasonality results are unlikely to be representative as survey data were only collected in the summer. About 45% of anglers sometimes released what they caught and consumed it at other times, while 40% exclusively harvested what they caught and 15% exclusively released what they caught.

Approximately half of lake users, 49% (*n* = 31) were aware of the term ‘eutrophication’ and correctly identified this phenomenon. No significant relationship was observed between awareness of eutrophication and level of education. Most respondents were aware of the terms: phytoplankton (79.4%, *n* = 50), zooplankton (84.1%, *n* = 53), macroinvertebrate (90.5%, *n* = 57), food-web (84.1%, *n* = 53); but not all correctly defined them: phytoplankton identified as primary producers and/or microscopic plants (46%, *n* = 29), zooplankton identified as primary consumers and/or microscopic animals (44.4%, *n* = 28), macroinvertebrates identified as large insects and/or other spineless organisms (68.2%, *n* = 43); or correctly placed them in a food-web hierarchy (68.2%, *n* = 43).

Lake users were concerned about multiple issues regarding lakes they utilize (Figure 3): pollution (76%), overfishing (60%), misuse (26%), shoreline development (21%), climate change (5%), no regulation (5%) and invasive species (3%). Main concerns for each user group varied (Table 2). Anglers, boaters and swimmers were mainly concerned about pollution and misuse. Most COs were concerned about pollution
Figure 2.3  Percent of lake users’ concern on various issues with regard to the lakes they utilize as determined from lake management surveys in summer 2013. The values do not sum to 100% as users cited multiple issues of concern.
Table 2.2 Percentage representation of concerns for each lake user group. $n$ represents number of respondents, CO = conservation officer and empty cells denote no concern for the given lake user group.

<table>
<thead>
<tr>
<th></th>
<th>Overfishing</th>
<th>Pollution</th>
<th>Development</th>
<th>Misuse</th>
<th>Climate Change</th>
<th>Regulation</th>
<th>Invasive Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fishing</td>
<td>21.28% ($n = 10$)</td>
<td>74.47% ($n = 35$)</td>
<td>25.53% ($n = 12$)</td>
<td>31.91% ($n = 15$)</td>
<td>4.25% ($n = 2$)</td>
<td>6.38% ($n = 3$)</td>
<td>4.25% ($n = 2$)</td>
</tr>
<tr>
<td>Swimming</td>
<td>15.91% ($n = 7$)</td>
<td>72.73% ($n = 32$)</td>
<td>15.91% ($n = 7$)</td>
<td>27.27% ($n = 12$)</td>
<td>2.27% ($n = 1$)</td>
<td>4.54% ($n = 2$)</td>
<td></td>
</tr>
<tr>
<td>Boating</td>
<td>13.79% ($n = 4$)</td>
<td>75.86% ($n = 22$)</td>
<td>27.59% ($n = 8$)</td>
<td>34.82% ($n = 10$)</td>
<td>3.45% ($n = 1$)</td>
<td>3.45% ($n = 1$)</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>33.33% ($n = 6$)</td>
<td>66.66% ($n = 12$)</td>
<td>38.88% ($n = 7$)</td>
<td>22.22% ($n = 4$)</td>
<td></td>
<td>5.55% ($n = 1$)</td>
<td>11.11% ($n = 2$)</td>
</tr>
<tr>
<td>Recreation</td>
<td>9.09% ($n = 1$)</td>
<td>81.82% ($n = 9$)</td>
<td></td>
<td>36.36% ($n = 4$)</td>
<td>9.09% ($n = 1$)</td>
<td>9.09% ($n = 1$)</td>
<td></td>
</tr>
<tr>
<td>Farming</td>
<td>100% ($n = 1$)</td>
<td>100% ($n = 1$)</td>
<td>100% ($n = 1$)</td>
<td>100% ($n = 1$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work</td>
<td>100% ($n = 1$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residence</td>
<td>100% ($n = 2$)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
and shoreline development. Recreational and residential users were mostly concerned about pollution and misuse. Farmers and work users were both primarily concerned about pollution, in addition farmers were also concerned about shoreline development and misuse. The number of responses to farming, work and residence categories were all less than 5.

Most respondents ranked urbanization (45%) or agriculture (40%) as their highest concern (Figure 4). The difference in overall ranking of the four categories was statistically significant, $X^2(3) = 36.61, P < .01$. Post-hoc multiple comparisons between groups following the Friedman’s ANOVA identified where significant differences occurred between groups. Groups were significantly different from each other when observed difference of mean rank sum is larger than or equal to the critical difference. Observed difference of mean rank sum below the critical difference indicate groups not significantly different from each other where difference can be attributed to chance. Ranks differed significantly between urbanization and animal husbandry ($observed\ difference = 63$), urbanization and climate change ($observed\ difference = 65$), animal husbandry and agriculture ($observed\ difference = 53$), and climate change and agriculture ($observed\ difference = 55$), but did not differ significantly between urbanization and agriculture ($observed\ difference = 10$), and animal husbandry and climate change ($observed\ difference = 2$). In all cases, the critical difference ($\alpha = .05$ corrected for the number of tests) was 37.93.

Of the respondents, 40 (60%) expressed interest in participating in a CMG initiative. COs ($P = 0.01$) were less likely to participate in a CMG compared to other lake users. If provincial ($P = 0.01$) and/or municipal ($P = 0.10$) governments were perceived
Figure 2.4 Percent of lake users that ranked various issues listed in lake management surveys in summer 2013. Survey respondents were asked to rank the listed issues from 1 (most important) to 5 (least important). Percent rankings for each issue (except ‘other’) sum to 100%.
to be in charge of lake management instead of other listed levels of government/authorities, lake users were more likely to participate in a CMG. Most users interested in participating in a CMG \( (n = 34) \) elaborated on the capacity in which they would like to be involved (Table 3). Specified roles were placed in two main clusters, ‘CMG development’ and ‘maintain CMG network’. Users’ answers were categorized as follows: for CMG development, committee members \( (n = 12) \), strategy development \( (n = 9) \), experts (provide knowledge, \( n = 2 \)), and unsure \( (n = 3) \); for maintain CMG network, monitor \( (n = 19) \), staff (issue reporting network, \( n = 2 \)), experts (provide knowledge, \( n = 2 \)), data analysis (with collaborators, \( n = 2 \)), management input \( (n = 5) \), and unsure \( (n = 3) \).

2.6 Discussion

Lake-use patterns

Our lake-use and management survey indicates that lakes in southern SK are largely utilized for recreational activities, primarily angling. This is consistent with findings of a previous study commissioned by the SK Ministry of Environment which examined the importance of recreational angling at both the provincial and local level (Derek Murray Consulting Associates 2006), as well as studies investigating recreational angling trends on a national and global scale (Cooke and Cowx 2004). Additionally, the recreational angling industry is intricately tied to the tourism industry. Anglers travel from other Canadian provinces as well as the United States to take advantage of fishery resources in SK (Derek Murray Consulting Associates 2006). While tourism on the
Table 2.3 Two main clusters of lake user involvement in a community monitoring group (CMG), different roles involvement are denoted as categories within clusters, along with the number of respondents interested in participating in various roles. \( n = 34 \) but do not sum to 34 because users were interested in multiple roles.

<table>
<thead>
<tr>
<th>CLUSTERS</th>
<th>CATEGORIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMG development</td>
<td>1. Committee member (12)</td>
</tr>
<tr>
<td></td>
<td>2. Strategy development (9)</td>
</tr>
<tr>
<td></td>
<td>3. Provide expert knowledge (2)</td>
</tr>
<tr>
<td></td>
<td>4. Unsure (3)</td>
</tr>
<tr>
<td>Maintain CMG network</td>
<td>1. Monitor (19)</td>
</tr>
<tr>
<td></td>
<td>2. Staff issue reporting network (2)</td>
</tr>
<tr>
<td></td>
<td>3. Provide expert knowledge (2)</td>
</tr>
<tr>
<td></td>
<td>4. Analyze data with collaborators (2)</td>
</tr>
<tr>
<td></td>
<td>5. Provide management input (5)</td>
</tr>
<tr>
<td></td>
<td>6. Unsure (3)</td>
</tr>
</tbody>
</table>
whole provides substantial income province-wide ($156.7 million, annually), intra-provincial tourism (where SK residents travel from major urban centers to lakes) is especially important to the small communities where these lakes are located (Derek Murray Consulting Associates 2006, Sauchyn et al. 2009). The rural communities of Wakaw, Humboldt, Watrous, Cabri and Wadena, and even the larger Swift Current, experience the economic benefits (including income generated through equipment rentals, motels/hotels and restaurants) of fishery and lake resources (Waite 1986).

Responses to angling-specific questions revealed additional details about angling habits. Catch-and-release rates of ~60% in our study are consistent with a previous analysis of Canadian and global recreational angling habits (Cooke and Cowx 2004). Releasing fish caught has become increasingly prevalent given the general perception that catch-and-release angling has less impacts on fish populations compared to harvest angling. We are unsure about the specific impact each angling method is having on the fish populations in these lakes, in terms of mortality and population changes. Generally, while catch-and-release methods reduce direct fish mortality, it can negatively affect fish fitness through sub-lethal effects such as increased stress levels, feeding and growth impacts, loss of reproductive output and increased vulnerability to predation, which may lead to population changes similar to harvest fishing (Cooke and Schramm 2007). Consistent with other settings, anglers exhibit species and size preference, and for our study lakes the taxon of choice is walleye. It should be noted that walleye are non-native to this region and regularly stocked (“Stocked Waters Guide 2013” 2013). Therefore the overall impact of recreational angling on their populations may deviate from the norm.
Additionally, anglers participate in multiple angling trips a year, both in summer and winter. Even though seasonal angling habit data may not be representative, multiple lake interactions over a season and/or year may contribute to ‘place meaning’ and ‘place attachment’ relationships developing between users and lakes. The complex social science concepts ‘place meaning’ and ‘place attachment’, which commonly refer to the attachment a visitor or user has with a place, can also play a role in knowledge and behavior relevant to natural resource management (Simoni and Floress 2015). These relationships typically develop from repeated interactions between users and places, and may result in users becoming more involved in issues that concern the place (Williams and Roggenbuck 1989). The meaning and attachment to a place may be functional (example: lake supports good angling) or emotional (example: emotional connection or value of the lake for its aesthetic appeal) (Simoni and Floress 2015). Therefore, even though we did not specifically examine the dynamics of these phenomena for our lake users, ‘place meaning’ and ‘place attachment’ may play a role in the users’ concern about pollution and development of the shoreline, and inclination for getting involved in managing these lakes.

Perception of threats to lakes

Heightened concern of all recreational users about the impact of agriculture, runoff and eutrophication (pollution) in these lakes is consistent with ecosystem studies of the region. This result is supplemented by anecdotal evidence: on numerous occasions lake users have approached us while conducting water sampling, to inquire about the deteriorating water quality they have observed over the years. Additional anecdotal evidence emerged from a summer fish kill in 2013 at St Brieux/Lenore lake, during
which lake users expressed concern about the safety of the water to fish, swim and do boating related activities such as wake-boarding. Specifically, given the intimate relationship between swimmers and the water body, we were not surprised that most swimmers were concerned about pollution, which included water quality issues such as noxious algal blooms. Due to the relatively low number of responses in the farming, work and residence lake-use categories, a larger sample may be needed to correctly understand their perceptions of threats to lakes despite overall concern about pollution.

Nearly 40% of COs were concerned about shoreline development and this may be related to their official duties, which in SK include enforcement, resource management and education outreach. Enforcement and management objectives may become more challenging to realize as more people visit lakes due to improved facilities and accessibility resulting from shoreline development. While shoreline development was a top concern for farmers, we are hesitant to infer a relationship given the low response in this category. Anglers (26%), boaters (27%) and, particularly swimmers (16%), were concerned to a lesser degree about shoreline development. Generally, angling, boater and swimming activities are dependent on facilities and accessibility (Reed-Andersen et al. 2000), which would be expected to improve with shoreline development. Therefore, given the possible benefits of shoreline development, these users may be less concerned about changing the façade of lakes.

Although statistically insignificant, respondents unexpectedly ranked urbanization higher than agriculture. Possibly due to the perceived notion that, as large urban centers Regina and Saskatoon expand because of the current economic and population boom, lakes and surrounding rural areas may become more congested. Furthermore, respondents
were considerably less concerned about climate change compared to pollution and shoreline development, which will certainly be the most important factor determining the long-term fate of these lakes. Canadian prairies have warmed at higher rates than the global average and will experience conditions outside of the climate norm as early as the 2020s (Sauchyn et al. 2009). Daily temperature minimums in southern SK are projected to increase along with the frequency and intensity of extreme weather events, and winters are expected to become warmer and wetter (Sauchyn et al. 2009). Comparatively, the increase in urban vs. rural population was less dramatic, increasing slightly from 2006 (65%) to 2011 (67%) (Sauchyn et al. 2009, Statistics Canada 2011). Therefore, considering the importance of climate, especially winter precipitation, in maintaining the hydrologic balance of prairie lakes, projected climate change impacts may outweigh potential impacts of urban development.

Management implications

Our results indicate a possible decoupling between science and stakeholder perceptions and values. While most recreational anglers were concerned about pollution impacting fish populations, less than a quarter were concerned about overfishing. Further, only about 5% were concerned about invasive species, while the most desired species in these waters, walleye, is non-native and artificially stocked. Decision-makers could develop outreach efforts and education campaigns about non-native species and increased vulnerability to aquatic invaders due to a changing climate. These campaigns can take place regularly at lakes between May and August when visitor levels are highest. Additionally, most users expressed concern about pollution including agricultural runoff, but only (approximately) half of the respondents had an understanding of eutrophication.
Therefore, outreach and education campaigns should be cognizant of minimizing technical terms and use engaging, accessible language to ensure maximal impact of these efforts. Jargon-heavy material may make the public more wary and be less effective in getting the message across and achieving management goals. Finally, there was an overall lack of concern about climate change despite strong scientific concerns.

Therefore, to successfully manage these lakes in changing climate conditions, education campaigns may be necessary to inform the public about projected climate change scenarios and facilitate a collaborative approach to successfully monitor and manage this resource. Such misconceptions may serve as a larger commentary as to the value and need for conducting regular surveys (such as this study) to identify knowledge gaps and user biases that exist in the community.

Interest of respondents in participating in a CMG and providing management input may be a valuable resource in effectively monitoring and managing lakes.

Significance of citizen-science initiatives such as CMGs are increasing and applied more often in natural resource monitoring and management projects (Conrad and Hilchey 2011). While different types of monitoring are common in citizen-science groups, process-based monitoring is generally the most highly regarded (Milne et al. 2006). Given that these lake ecosystems have been monitored since 2002, and concurrent studies are analyzing the importance of littoral carbon and further examining the role of winterkill, this technical knowledge can be used to develop a sound process-based monitoring protocol. The protocol may include a CMG component that can be incorporated into a collaborative adaptive management framework. Collaboration should involve government agencies, universities and local communities to ensure representation.
of diverse stakeholders. If a collaborative approach is taken, it may ultimately yield more decision making power to the general public (Canfield and Canfield 1994, Cooper et al. 2007, Conrad and Daoust 2008). Data from this survey can be used to address issues traditionally faced by citizen-science groups, such as lack of volunteer interest and high volunteer dropout rates by assigning roles volunteers are interested in, as indicated in the responses. Moreover a collaborative approach will help address data fragmentation, data inaccuracy, and data not being used in the decision-making process (Conrad and Hilchey 2011). It is clear from the survey results that a majority of volunteer interest lies in monitoring and committee member roles. Developing monitoring and data collection protocols with scientists who have monitored these lakes and understand knowledge gaps will help counteract other obstacles such as ‘monitoring for the sake of monitoring’ as well as data reliability issues.

Furthermore, a collaborative structure fits well within an adaptive management framework which requires continuous resource monitoring to determine success or failure of management decisions (Williams 2011). The adaptive management framework we hope to propose for these lakes will be informed by this stakeholder survey as well as the long-term ecosystem survey. Ensuring monitoring protocols are scientifically robust and management objectives take stakeholder feedback into consideration.

2.7 Conclusions

Within the constrains outlined above, our study helped close knowledge gaps for lakes in this region and elucidate use patterns, stakeholders’ perceptions about the health of these systems and inclination of the public to get involved in management. Lake-use is
an important aspect of lake ecosystems, effecting lake health, robustness and status in many regions. Therefore it is important to understand what lakes are being used for and the user perceptions about these resources. Results may be particularly important when developing outreach efforts to impact behavior to keep up with a changing climate and human demographics. Once identified, disassociations between science and public knowledge can be remedied through aggressive education campaigns done in collaboration with universities, government agencies and local communities. Engaging with communities and addressing short-falls in societal values and norms so they align with scientific findings, will help ensure the long-term success of resource management strategies, especially given the opportunity for close relationships to develop between diverse stakeholders. Human behavior is often complex, as are natural processes, and both should be considered when hoping to effectively manage any system.

2.8 Acknowledgments

We thank Peter Leavitt, Harry Diaz, Rozzet Jurdi and Bruce Lindsay for their insightful comments. We are grateful to Kenneth Scott for his assistance in survey distribution. Financial assistance was provided by an NSERC grant to B. Wissel, and Teaching Assistance and Research scholarships from University of Regina and the Faculty of Graduate Studies and Research and the Government of Saskatchewan to L. Nanayakkara.
3. RESOURCE-USE, HEALTH, AND SUSTAINABILITY OF POPULATIONS OF STOCKED AND NATIVE FISHES IN CANADIAN PRAIRIE LAKES.

3.1 Abstract

We evaluated the current status and potential resilience of native and stocked fish species in 13 prairie lakes in central Canada over eight years (2007-14) using three parameters; resource-use (benthic vs. pelagic carbon, using Bayesian mixing models MixSIAR), body condition (relative weight indices $W_i$) and parasite load (enumerated from gut analyses). The focal species for this study was walleye ($Sander vitreus$), which is stocked and the most desired game fish in these lakes, while both northern pike ($Esox lucius$) and yellow perch ($Perca flavescens$) occur naturally in these systems. Both walleye and northern pike were significantly more reliant on benthic carbon than yellow perch ($P<0.05$) but this reliance was not statistically associated with any measured environmental variables. Walleye body condition indices were consistently poorer ($<95-105$) than those of the other two species. Parasite loads sufficient for analysis were observed only in walleye and were positively associated with lake water salinity ($r^2 = 0.93$, $P<0.05$). Based on our results walleye appear to be less resilient to environmental variability than are northern pike and yellow perch.

3.2 Introduction

Inland waters provide numerous ecosystem goods and services, including water supply, regulatory services, food production and recreation (Costanza et al. 1997, Cooke et al. 2016). In developed countries, recreational fishing is the most significant use of
fish stocks, as well as an important social and economic driver of recreational use of inland waters (Post et al. 2002, Arlinghaus et al. 2002, Arlinghaus and Cooke 2009). In Canada, recreational fishing contributes $8.8 billion annually to the country’s economy, with most of the fishing taking place in inland freshwaters (Minns 2009, Brownscombe et al. 2014). Currently, recreational fisheries appear to be more resilient than commercial fisheries (Arlinghaus and Cooke 2009, Post 2013); however, evidence is mounting that the synergistic effects of climate change, intensive land-use and invasive species may interact with enhanced fishing pressure (Post et al. 2002) to threaten the adaptive capacity of lake ecosystems (Cooke and Murchie 2015, McMeans et al. 2016).

On average, game fishes feed at higher trophic levels and are less resilient to environmental change than are non-game fishes, in part because of higher metabolic costs and physiological impacts associated with environmental stressors (Whitney et al. 2016). Furthermore, increasing atmospheric and lake temperatures are expected to exert a disproportionate negative impact on cool- and cold-water species, such as walleye (Sander vitreus), as these fishes are more susceptible to sub-lethal effects of temperature on physiology, growth, and reproduction (Ficke et al. 2007, Johnston et al. 2012, Lynch et al. 2016). In addition to thermal stresses, lake warming will also decrease the amount of dissolved oxygen (DO) in the water column, resulting in increased probability of summerkill (Wetzel 2001). Elevated temperatures will also increase lakewater evaporation, leading to higher solute concentrations and possibly osmotic stress during the ice-free season (Starks et al. 2014, Mosley 2015, Whitney et al. 2016). Finally, as temperatures shift away from the optimal range for cool-water species, increased stress
will alter immune system function, potentially increasing vulnerability to diseases and parasites (Wegner et al. 2008, Bowden 2008, Whitney et al. 2016).

Freshwater fishes in prairie lakes may be especially vulnerable to cumulative and synergistic effects of environmental change (Starks et al. 2014). Such lakes are common on the Northern Great Plains, and are typically shallow endorheic basins (Last and Ginn 2005) that exhibit substantial seasonal and interannual variation due to climate variability (Sauchyn and Kulshreshtha 2008, Pham et al. 2009) and anthropogenic activities, including intensive agriculture and irrigation (Meerhoff et al. 2012, Starks et al. 2014). As the Prairie ecozone of Canada is predicted to exhibit higher than average rates of warming (Barrow 2009) and increased aridity, it is essential to both assess current stock status and the vulnerability of prairie fish populations to these threats. Stock assessments of walleye and sauger (*Sander canadensis*) in Lake Winnipeg revealed temporal increases in walleye abundance relative to sauger abundance from 1979-2003, largely in response to changes in lake turbidity (Johnston et al. 2012). Lake Roosevelt burbot (*Lota lota*) populations, an important game fish in Washington state, averaged relatively poor body conditions but exhibited no temporal trends from 1999-2001 (Polacek et al. 2006). In particular, it is important to evaluate potential sub-lethal impacts of changing environmental conditions on key parameters including resource-use, growth and condition, and physiological vulnerability to disease and parasites (Murphy et al. 1991, Marcogliese et al. 2005, Vander Zanden et al. 2011).

The objectives of this study were to quantify temporal and spatial variation in the status of prairie lake fish populations in the Northern Great Plains of Canada. By utilizing
a diverse set of lakes spanning orders-of-magnitude in limnological, physical and chemical parameters, we used these lakes as model systems to evaluate how indicators of fish population health (as resource-use, body condition, parasite loads) respond to changing environmental conditions. The focal game fish species for this study is walleye, because it is the most desired species in these waters (Nanayakkara and Wissel 2017) yet is a stocked taxon which lacks natural genetic diversity (E. Starks, U. Regina, unpublished data). We also assessed two native fish species to estimate how stocked and native species may respond differentially to environmental change. We hypothesized that: 1) game fishes will exhibit variable resource-use, reflecting differences in lake productivity and the physical extent of littoral areas; 2) walleye will have poorer body condition indices than northern pike (*Esox lucius*) and yellow perch (*Perca flavescens*) because they are not native to these lakes, and; 3) all three game fish species will host relatively high parasite loads due to high variability in climate and water quality.

### 3.3 Methods

**Study site**

We sampled 13 fish-bearing lakes in June and August from 2007 to 2014 to evaluate temporal and spatial variation of fishes located in the prairie ecoregion of southern Saskatchewan (SK) in central Canada (Figure 1). These lakes are part of a 21–lake long-term ecosystem survey that has been conducted in most basins since 2002 (Pham et al. 2008, 2009). Study lakes comprised five sites of low fish community complexity lakes (only forage fishes) and eight basins with high complexity (forage fishes, benthivores, and game fishes). The term ‘forage fishes’ herein collectively refers
Figure 3.1 Location of the 21 lakes that are part of a long-term lake ecosystem survey in Saskatchewan (SK), Canada. 13 lakes were included in this study. Lakes are coded by fish community, clear = fishless, grey = low complexity, black = high complexity. The solid line represents the grassland transition zone and dashes lines represent annual precipitation deficits. Boxes indicate the major urban centers in SK.
to both potential prey of game fishes in high complexity lakes and any fishes found in low complexity lakes (Essington et al. 2015). Common game fishes and bottom-feeding benthivorous species included northern pike, walleye, yellow perch, whitefish (Coregonus clupeaformis), cisco (Coregonus artedi) and common sucker (Catostomus commersonii). Seven of 8 high complexity lakes are stocked with walleye fry to compensate for a lack of sufficient spawning habitat (Saskatchewan Stocked Waters Guide (SSWG) 2017). All lakes are located in endorheic (hydrologically-closed) basins that lack channelized surface inflow or outflow, are mainly sustained through winter precipitation, and exhibit high rates of evaporation (Rawson and Moore 1944a, Pham et al. 2009). Limnological parameters (e.g., solute concentrations), morphometric features (e.g., depth), and trophic status vary considerably across survey lakes (Rawson and Moore 1944a, Last and Ginn 2005, Starks et al. 2014) and through time (Pham et al. 2009) (Table 1).

**Sampling and analyses**

Lakes were sampled in June and August annually from 2007 to 2014 using standard methods (Cooper and Wissel 2012a, 2012b, Starks et al. 2014). Water temperature (°C), specific conductivity (μS cm⁻¹), total dissolved solids (g TDS L⁻¹), salinity (g TDS L⁻¹), dissolved oxygen (mg O L⁻¹) and pH were recorded at 1-m intervals at the location of the deepest point in the lake using a YSI model 556 multi probe instrument. Depth values were obtained with a model 71624 electronic depth meter, and
Table 3.1 Environmental and limnological parameters of the 13 lakes included in the study. Complexity refers to fish community complexity; low = (only forage fishes) and high = (forage fishes, benthivores and game fishes). Mean and ±SD for recorded values of maximum depth ($Z_{max}$) in meters, total dissolved solids (salinity as TDS) in g L$^{-1}$, chlorophyll a (Chla) in µ L$^{-1}$, total Kjedahl nitrogen (TKN) in µg L$^{-1}$, total phosphorous (TP) in µg L$^{-1}$ and dissolved organic carbon (DOC) in mg L$^{-1}$.

<table>
<thead>
<tr>
<th>Lake</th>
<th>$Z_{max}$</th>
<th>TDS</th>
<th>Chla</th>
<th>TKN ±SD</th>
<th>TP ±SD</th>
<th>DOC ±SD</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charron</td>
<td>8.15±0.37</td>
<td>3.63±0.87</td>
<td>6.1±3.8</td>
<td>2569.55±544.64</td>
<td>175.49±80.31</td>
<td>29.5±3.9</td>
<td>Low</td>
</tr>
<tr>
<td>Clair</td>
<td>3.16±0.33</td>
<td>0.83±0.18</td>
<td>11.77±8.84</td>
<td>1721.7±725.84</td>
<td>45.75±43.03</td>
<td>22.1±7.3</td>
<td>Low</td>
</tr>
<tr>
<td>Edouard</td>
<td>5.45±0.48</td>
<td>0.33±0.03</td>
<td>16.09±14.9</td>
<td>1842.81±749.87</td>
<td>51.46±40.02</td>
<td>17.3±2.8</td>
<td>Low</td>
</tr>
<tr>
<td>Fishing</td>
<td>11.48±0.93</td>
<td>1.66±0.41</td>
<td>4.54±2.12</td>
<td>1267.77±162.02</td>
<td>22.2±36.77</td>
<td>20.4±3.9</td>
<td>High</td>
</tr>
<tr>
<td>Humboldt</td>
<td>6.24±0.98</td>
<td>0.81±0.11</td>
<td>12.67±13.46</td>
<td>1930.7±1567.45</td>
<td>222.86±102.58</td>
<td>17.9±3.9</td>
<td>High</td>
</tr>
<tr>
<td>Kipabiskau</td>
<td>7.14±0.72</td>
<td>0.45±0.06</td>
<td>3.31±2.59</td>
<td>1511.45±247.58</td>
<td>132.05±67.8</td>
<td>21.2±4.3</td>
<td>High</td>
</tr>
<tr>
<td>Location</td>
<td>pH</td>
<td>Eh (mV)</td>
<td>Conductivity (μS/cm)</td>
<td>Dissolved Oxygen (ml/L)</td>
<td>Calcium Carbonate (mg/L)</td>
<td>Hardness (mg/L)</td>
<td>Calcium (mg/L)</td>
</tr>
<tr>
<td>----------</td>
<td>----------</td>
<td>------------</td>
<td>----------------------</td>
<td>-------------------------</td>
<td>-------------------------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Lenore</td>
<td>9.43±0.9</td>
<td>1.43±0.49</td>
<td>5.41±3.81</td>
<td>1564.55±612.09</td>
<td>38.58±38.25</td>
<td>20.2±4</td>
<td>High</td>
</tr>
<tr>
<td>Lenore SB</td>
<td>9</td>
<td>1.72±0.45</td>
<td>6.5±6.84</td>
<td>3625±5006.02</td>
<td>174.38±61.53</td>
<td>20.9±1.3</td>
<td>High</td>
</tr>
<tr>
<td>Middle</td>
<td>8.53±1.83</td>
<td>3.78±1.13</td>
<td>4.58±2.84</td>
<td>2385.64±696.24</td>
<td>53.37±56.09</td>
<td>31.7±5.4</td>
<td>Low</td>
</tr>
<tr>
<td>Pelletier</td>
<td>8.6±0.75</td>
<td>0.43±0.08</td>
<td>7.48±6.36</td>
<td>758.06±166.01</td>
<td>14.11±5.52</td>
<td>14.1±7.1</td>
<td>High</td>
</tr>
<tr>
<td>Redberry</td>
<td>12.95±1.93</td>
<td>9.36±2.71</td>
<td>1.49±2.22</td>
<td>2060.08±365.93</td>
<td>33.39±39.84</td>
<td>33.3±3.5</td>
<td>Low</td>
</tr>
<tr>
<td>Shannon</td>
<td>9.37±1.47</td>
<td>1.62±0.36</td>
<td>4.6±5.97</td>
<td>1744.39±415.9</td>
<td>49.78±28.54</td>
<td>22.1±4.8</td>
<td>High</td>
</tr>
<tr>
<td>Wakaw</td>
<td>9.48±1.32</td>
<td>1.48±0.34</td>
<td>4.91±2.96</td>
<td>1459.27±643.2</td>
<td>19.69±33.37</td>
<td>15.6±2.9</td>
<td>High</td>
</tr>
</tbody>
</table>
water transparency was measured using a 20-cm diameter Secchi disk. A 7-m tygon tube (5 cm internal diameter) was used to collect a depth-integrated water sample. The tube was lowered to 0.5 m above the bottom for lakes with depth <7m and only the upper 7 m were sampled for deeper lakes.

Whole water was screened through an 80-μm mesh net prior to filtration for water chemistry analysis. Water chemistry samples were filtered through 0.45-μm pore membrane filters, stored for 2-3 weeks at 4°C, and analyzed for nitrate (NO$_3^-$), ammonium (NH$_4^+$), total Kjeldhal nitrogen (TKN), soluble reactive phosphorous (SRP), total phosphorous (TP) (all μg L$^{-1}$) and Ca (mg L$^{-1}$) at the University of Alberta Water Chemistry Laboratory and the University of Regina following standard procedures (Stainton et al. 1974, Pham et al. 2008). Dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) (both mg L$^{-1}$) were analyzed on a Shimadzu TOC Analyzer 5000A at the Institute of Environmental Change and Society (IECS) at the University of Regina.

The integrated water sample and a 1-L surface water sample were filtered through pre-washed GF/C filters (nominal pore size 1.2 μm) and stored at -10°C until analysis of chlorophyll (Chl $a$, Chl $b$, Chl $c$, total chlorophyll [TC]), carotenoid pigments, and particulate organic matter (POM). POM was collected from depth-integrated water by collecting sufficient particulate matter on the filter and analyzing according to the procedures outlined in (Wissel and Fry 2003, Wissel et al. 2005). Chl$a$ extractions were performed with an acetone-methanol-water (80:15:5 by volume) solution and analyzed using standard spectrophotometric methods (Wellburn 1994).

Pelagic zooplankton were sampled using small (80-μm mesh, 30-cm diameter) and large nets (500-μm mesh, 50-cm diameter) for small and large species, respectively.
Plankton nets were towed vertically from 0.5 m above the bottom to the surface at the sampling station. Collected samples were preserved in a 50% ethanol-sucrose solution for taxonomic identification and enumeration. Samples were identified to species and enumerated at the University of Regina using a SZX12 Olympus microscope. Bulk zooplankton samples from both nets types were also collected for stable isotope analysis. In addition, littoral macroinvertebrates were collected using a large sweep net (500-μm mesh size) in near-shore habitats. Both sets of isotope samples were contained in filtered lake water and stored at 15°C prior to analyses.

Near-shore forage fishes were sampled using a beach seine net (2 m x 30 m, 10-mm mesh size) at mid-day following Cooper and Wissel (2012a). Fish were identified to species and stored at -10°C prior to further analyses. Game fishes and benthivores in high complexity lakes were sampled overnight using a gill net (1.5 m x 30 m, 55-mm mesh) placed perpendicular to shore. Fish were stored at -10°C until dissections and stable isotope analyses. Total length (cm), fork length (cm), standard length (cm), weight (g) and sex were recorded for all samples. Stomach contents were identified to family and enumerated when possible. Stomachs and digestive tracts of individuals from all three game fish species were opened longitudinally with a scalpel and directly examined (Justine et al. 2010) for internal parasites.

Following identification and dissections, a small amount (~1 g) of lateral muscle tissue (Pinnegar and Polunin 1999) was removed from each of 5-10 individuals per species and per lake for stable isotope analysis. Fish muscle samples, abundant taxa from large-bodied littoral macroinvertebrates (~1 individual sample-1) and zooplankton (~30-
150 individuals sample\(^{-1}\)) were rinsed with deionized water, dried to constant mass at 50\(^\circ\)C, and packed into tin capsules. Capsules were combusted in a Costech elemental analyzer connected to a ThermoQuest (Finnigan-MAT) Delta V isotope ratio mass spectrometer (IRMS) at IEC. Internal laboratory standards of bovine liver and wheat flour where used as reference materials. Carbon and nitrogen isotopes were reported in the conventional \(\delta\) notation (\(^\circ\)) relative to the international standards Vienna Pee Dee Belemnite (for carbon) and atmospheric N\(_2\) (for nitrogen) (Peterson and Fry 1987). Due to the potential impacts of chemical lipid extraction on carbon and nitrogen isotope values (Logan et al. 2008), we used C:N based mathematical lipid-corrections outlined in (Braun et al. 2014) to normalize \(\delta^{13}\)C values prior to analyses, to account for depleted \(^{13}\)C values with increasing lipid content (Post et al. 2007).

**Numerical analyses**

Benthic and pelagic primary production at each site and on each sampling date was calculated using the primary production model of (Vadeboncoeur et al. 2008). Similar to previous studies (Vander Zanden and Vadeboncoeur 2002, Vadeboncoeur et al. 2008) ‘benthic’ in our study refers to littoral production. Benthic contribution to whole-lake production was estimated from analysis of surface area, volume, Chl \(a\), depth (maximum and mean), depth ratio, shape factor and day length. Model input for maximum benthic primary production (BP\(_{\text{max}}\)) was set at the intermediate value (50 mg C m\(^{-2}\) h\(^{-1}\)) to account for the possibly confounding balance of large littoral areas and high trophic status, and because prairie lakes are more productive relative to other lake-types. This value for BP\(_{\text{max}}\) represents light-saturated benthic productivity in meso-trophic lakes whereas the lowest value (5 mg C m\(^{-2}\) h\(^{-1}\)) is characteristic of periphyton attached to substrata in low-
alkalinity lakes and the highest value (120 mg C m$^{-2}$ h$^{-1}$) is typical of a wide range of oligotrophic lakes (Vadeboncoeur et al. 2008).

We used carbon stable isotope ($\delta^{13}$C) data to characterize resource-use by different fish taxa, in particular their relative reliance on benthic and pelagic carbon sources. Use of carbon isotope data to differentiate between benthic and pelagic primary producers is based on established trophic relationships in which consumers retain the carbon isotope values of primary producers, and where periphyton (benthic primary producers) are enriched in $^{13}$C due to diffusion processes within the cellular boundary layer (Hecky and Hesslein 1995, Vander Zanden and Vadeboncoeur 2002). Nitrogen stable isotope data (as $\delta^{15}$N) were used to reconstruct trophic levels in the study lakes. Here primary consumers amphipods (benthic) and cladocerans (pelagic) were used as end members in the mixing model instead of primary producers to avoid the high temporal variability of phytoplankton samples, sampling bias, and high lake-to-lake variability (Vadeboncoeur et al. 2003, Vander Zanden et al. 2011).

Contributions of each carbon source to fish diets were estimated using the Bayesian mixing model package *MixSIAR* (Stock and Semmens 2013) available in the R statistical software (version 3.4.1; R Development Core Team 2017). We used a trophic fractionation factor of 0.0 ± 0.5 for carbon (Vander Zanden and Vadeboncoeur 2002) and 3.5 ± 0.5 for nitrogen (Vander Zanden and Rasmussen 2001). Preliminary analyses revealed sufficient isotopic separation between end-members (>3‰) to obtain robust results. As a result, we accounted for two main sources of variability in isotope values by entering ‘process errors’ (e.g., variability in consumer isotope values due to chance) and
'residual errors' (e.g., individual differences in rate of assimilation) into the model configuration (Stock and Semmens 2016). Mixing models were run for each sampling date from 2007 to 2014. To obtain accurate posterior distributions, models consisted of 3 Markov Chain Monte Carlo (MCMC) chains that were run at “long” (300,000, burn-in 200,000) or “very long” (1,000,000, burn-in 500,000), and thinning = 100 parameters. All models passed the Gelman-Rubin and Gewke diagnostic tests for model convergence on the posterior distributions (Stock and Semmens 2013).

Relations between fish resource use and lake parameters were quantified using unreplicated linear regression. Regression models (R package “car”, version 2.1-5: Fox and Weisberg 2011) were developed for associations between lake-specific global mean output (mean of all the species-specific values) for each sampling date, and diverse parameters including f(BP) (fraction of benthic contribution to whole-lake production), year, complexity (reference category: high), month (reference category: August) and lake (reference category: Wakaw). Subsequently we analyzed MixSIAR results for temporal (year, season), spatial (lake), species and group (forage, benthivores and game fishes)-specific differences on benthic reliance (dependent variable) using analysis of variance (ANOVA) models (R packages “car”, version 2.1-5: Fox and Weisberg 2011; “compute.es”, version 0.2-4: Del Re 2013; “ggplot2”, version 2.2.1: Wickham 2009; “pastecs”, version 1.3-18: Grosjean and Ibanez 2014). ANOVA models were tested for and passed Levene’s test for homogeneity of variances (P >0.05). We then ran separate linear regressions for forage and game fishes to examine the role of environmental
predictors (including maximum depth, salinity, temperature, nutrients and Secchi depth) on benthic reliance of each group.

Fish condition was estimated from calculation of relative weight ($W_r$) indices (body condition) for walleye, northern pike and yellow perch following Murphy et al. (1990) and Blackwell et al. (2000). A body condition index was calculated for each game fish species caught from 2009-2014 using the following equation and reported as a whole number;

$$W_r = (W/W_s) \times 100,$$

where $W_s$ values were calculated for each fish exceeding the required minimum total length (walleye >150mm, pike >100mm, perch >100mm). Parameters for $W_s$ were derived from the regression equations of Blackwell et al. (2000). Individual body condition index values were then averaged for each species by month, lake and year. Since $W_r$ values for individual populations were not significantly different among sites within each sample period (ANOVA, $P>0.05$), results from all lakes were combined for each month and species. Values of $W_r = 95$-105 indicate good condition, whereas scores near 80 indicate poor health due to adverse environmental conditions or lack of food and extremely high scores (>115) imply excess energy reserves (Murphy et al. 1990, Blackwell et al. 2000). The number of individuals per sampling period (June or August) varied from 20 to 61 for walleye, 0 to 25 for pike, and 0 to 48 for perch. Unusually high relative weight indices were observed for both walleye and pike in early 2009 when
unstandardized measurement protocols were used, and were not included in further analyses.

Parasite densities sufficient for analysis were only found in walleye samples, consequently, parasite loads of gut tapeworms were compared between lakes over time for that species alone. The quantity of tapeworms found in each fish and the proportion of the population infected were recorded for each lake and date. These values were subsequently regressed against environmental parameters using unreplicated linear regressions. The influence of sex, lake, year and season were evaluated using t-tests or one-way ANOVAs. The abundance of other parasites (e.g., nematodes) was insufficient to be included in the analysis.

### 3.4 Results

Application of the production model of Vadeboncoeur et al. (2008) suggested that benthic contribution to whole-lake primary production exceeded 50% from 2007-2014 in most fish-bearing lakes (Figure 2). Overall mean (± SD) benthic contribution to whole-lake primary production over the entire sampling period was 0.68 ±0.19 in low complexity lakes and 0.79 ±0.14 in high complexity lakes, with similar extremes and ranges in both community types. Despite the importance of benthic primary production, MixSIAR model values suggested that most taxa were not using benthic carbon sources in proportion to their availability (below the 1:1 line in Figure 2). Mean reliance on benthic carbon for all fishes was significantly associated with month, being higher in June than August (P<0.05). Three lakes (Humboldt, Lenore and Pelletier) exhibited
Figure 3.2 Comparison of benthic contribution to whole-lake production (x-axis) to mean whole-lake benthic contribution to fish diets (y-axis). Each point represents a lake in a given month. Open circles = high complexity lakes (includes forage fishes, benthivores and game fishes) and closed circles = low complexity lakes (only forage fishes). Line indicates 1:1 for benthic contribution for whole-lake production and fish reliance on benthic carbon. f(BP) values estimated from the Vadeboncoeur et al. (2008) productivity model and mean benthic contribution estimated from Bayesian mixing models (MixSIAR).
significantly lower reliance on benthic carbon than the reference category (Wakaw Lake). Overall, the proportion of benthic production (f[BP]) to whole-lake primary production was not associated significantly ($r^2 = 0.27$, $P>0.05$) with the use of benthic carbon by fishes.

Both forage and game fishes exhibited high variability in use of benthic resources; mean reliance for all forage fish samples was $0.306 \pm 0.27$, with slightly higher values in high complexity lakes ($0.357 \pm 0.31$) than in sites of low complexity ($0.231 \pm 0.18$) (Figure 3). Similarly, mean benthic reliance for game fish was $0.469 \pm 0.32$, while bottom-feeders use of benthic carbon was $0.308 \pm 0.25$. A two-way ANOVA for group and seasonal difference on benthic reliance for the three groups of fishes revealed that game fish were significantly more reliant on benthic resources throughout the growing season ($P<0.01$) and all three fish groups were more reliant on benthos early on in the season ($P<0.05$) (Figure 3). Forage fishes were significantly more reliant on benthic carbon in high complexity lakes than in low complexity lakes ($P<0.05$) (Figure 3). Subsequent one-way ANOVA showed that darters (Etheostoma nigrum), minnows (Cyprinidae) and stickleback (Pungitius pungitius) were all significantly more reliant on benthos than were other taxa in high complexity lakes, while brassy minnows (Hybognathus hankinsoni) were more reliant on benthos in low complexity lakes ($P<0.001$). Spottails shiner’s (Notropis hudsonius) were only found in one low complexity lake (Figure 4).
Figure 3.3 Mean benthic reliance for each fish group. Vertical comparison by season (Early vs. Late) and horizontal comparison by complexity (High vs. Low). Mean benthic reliance for each group estimated from Bayesian mixing models (MixSIAR). Black circles indicate outliers.
Figure 3.4 Species level reliance on benthic carbon for forage fishes. All species except spottail shiners (*Notropis hudsonius*) were found in both low and high complexity lakes. Vertical comparison by lake complexity (High vs. Low). Mean estimates of benthic reliance obtained from Bayesian mixing models (MixSIAR). Black circles indicate outliers.
There were no significant associations between use of benthic carbon and environmental parameters for either forage or game fishes (each \( P > 0.05 \)), although species-level analysis revealed that walleye and northern pike were significantly more reliant on benthic resources than were yellow perch (\( P < 0.01 \)) (Figure 5). While benthic reliance for whitefish and cisco seemed low, insufficient samples precluded their inclusion in species-specific analyses. Direct estimates of dietary composition revealed that walleye consumed forage fish more than twice as frequently as they did amphipods (Table 2). Northern pike consumed forage fish four times as much as amphipods, but yellow perch diets were almost evenly composed of cladocerans and amphipods.

We estimated \( W_r \) values for 404 walleye, 76 pike, and 165 perch individuals (Table 3, Figure 6). Overall, there were no significant differences among lakes for any of the three species. Walleye achieved mean \( W_r \) indices within the range expected for healthy populations (95-105; Blackwell et al. 2000; Murphy et al. 1990) in only three of 11 sampling periods, while northern pike achieved this range in five out of 10 collection periods, and perch mean \( W_r \) were within the range in six of 10 sampling periods. \( W_r \) of walleye increased through the summer in all years but 2014 (Table 3). Such seasonal increases occurred less frequently for pike and perch (only three years each). Intra-annually, walleye exhibited \( W_r \) values characteristic of healthy populations in at least one of the two annual sampling periods (June or August) in 2010 and 2011 but had less than ideal body condition in both sample periods during 2012-2014, with minima recorded in both June and August 2014. Pike populations were healthy (\( W_r > 95 \)) during at least one of the two monthly sampling periods every year; during August in 2010-2012 and during
Figure 3.5 Species level reliance on benthic carbon for game fishes. Walleye (*Sander vitreus*) and northern pike (*Esox lucius*) exhibited significantly higher reliance on benthos than did yellow perch (*Perca flavescens*). Whitefish (*Coregonus clupeaformis*), cisco (*Coregonus artedi*) are not discussed in the manuscript because of low sample sizes. Mean benthic reliance estimates were obtained from Bayesian mixing models (MixSIAR).
Table 3.2 Comparison of the ratios of amphipod: fish remains found in the stomachs of walleye (*Sander vitreus*), northern pike (*Esox lucius*) and a comparison between amphipod: fish: caldoceran consumption for yellow perch (*Perca flavescens*). Data collected bi-annually from 2008-2014 in all study lakes with game fish species. NA = no data were collected based on foraging patterns reported in the literature (Hartman and Margraf 1992, Sammons et al. 1994, Lott et al. 1996).

<table>
<thead>
<tr>
<th>Species</th>
<th>Amphipod</th>
<th>Fish</th>
<th>Cladoceran</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walleye</td>
<td>31%</td>
<td>69%</td>
<td>NA</td>
</tr>
<tr>
<td>Pike</td>
<td>20%</td>
<td>80%</td>
<td>NA</td>
</tr>
<tr>
<td>Perch</td>
<td>46%</td>
<td>7%</td>
<td>47%</td>
</tr>
</tbody>
</table>
Table 3.3 Body condition (Wr) data for the three main game fishes; walleye (*Sander vitreus*), northern pike (*Esox lucius*) and yellow perch (*Perca flavescens*). All fishes used in this analyses exceeded minimum total lengths (walleye >150mm, pike >100mm, perch >100mm). Intercept and slope parameters for the Wr equations for each species from the following sources: (Murphy et al. 1990) (walleye), (Willis 1989) (pike), (Willis et al. 1991) (perch). Target range for Wr is 95 – 105.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Walleye</th>
<th>Pike</th>
<th>Perch</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>June</td>
<td>156 (n=21)</td>
<td>157 (n=8)</td>
<td>91 (n=48)</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>95 (n=49)</td>
<td>NA</td>
<td>92 (n=35)</td>
</tr>
<tr>
<td>2010</td>
<td>June</td>
<td>81 (n=23)</td>
<td>84 (n=25)</td>
<td>89 (n=27)</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>105 (n=36)</td>
<td>117 (n=3)</td>
<td>123 (n=11)</td>
</tr>
<tr>
<td>2011</td>
<td>June</td>
<td>93 (n=44)</td>
<td>94 (n=19)</td>
<td>139 (n=17)</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>99 (n=61)</td>
<td>101 (n=8)</td>
<td>94 (n=7)</td>
</tr>
<tr>
<td>2012</td>
<td>June</td>
<td>90 (n=38)</td>
<td>93 (n=5)</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>91 (n=54)</td>
<td>97 (n=2)</td>
<td>98 (n=1)</td>
</tr>
<tr>
<td>2013</td>
<td>June</td>
<td>89 (n=24)</td>
<td>97 (n=3)</td>
<td>94 (n=2)</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>90 (n=29)</td>
<td>81 (n=3)</td>
<td>97 (n=4)</td>
</tr>
<tr>
<td>2014</td>
<td>June</td>
<td>85 (n=20)</td>
<td>95 (n=5)</td>
<td>95 (n=4)</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>83 (n=26)</td>
<td>91 (n=3)</td>
<td>96 (n=9)</td>
</tr>
</tbody>
</table>
Figure 3.6 Body condition values are vertically divided by the three dominant game fishes; walleye (*Sander vitreus*), northern pike (*Esox lucius*), and yellow perch (*Perca flavescens*). All fishes used in this analyses exceeded minimum total lengths (walleye >150mm, pike >100mm, perch >100mm). Intercept and slope parameters for the $W_s$ equations for each species from the following sources: Murphy et al. 1990 (walleye), Willis 1989 (pike), Willis et al. 1991 (perch). Target range for $W_s$ is 95 – 105. Closed triangles = June and closed circles = August values.
June in 2013 - 2014. Perch also exhibited good body condition during at least one sampling period each year, including August 2010 and 2012-2013, June 2012, and both months in 2014. Seasonal variations in body condition were unrelated to the number of days (119) between the optimal temperature (10-22 °C) range for the three game fishes (Table 4). Despite the observation that 2010 had the highest number of days between the optimal temperature range, condition indices were below ideal values for both walleye and pike in June 2011 (Table 4). Optimal temperatures were less common in 2011 (64), although body condition values in June 2012 were similar to June 2011.

Walleye were infected with significantly more parasites in 2009 than in 2010. Parasite load was correlated positively and strongly ($r^2 = 0.93, P<0.05$) with lake water salinity (g TSD L$^{-1}$) in 2009 but not in 2010, and not with other environmental predictors in either year. Salinities were significantly higher in 2009 ($P<0.05$). Tapeworm load was also significantly correlated with fish size (total length), with individuals >10 cm hosting more parasites than did smaller fish ($P<0.05$). Despite similar infection rates in 2009, females were infected with a significantly higher quantity of tapeworms ($P<0.05$) in 2009. No males were infected in 2010.
Table 3.4 Climate conditions from 2008 to 2014. Temperature records obtained from the Saskatoon weather station and ice cover data (ice-on, ice-off) were taken from the Buffalo Pound water treatment facility. Mean highs and lows are recorded for the full ice off period. Optimal temperature ($T_{OPT}$) for all three game fish species are between 10 to 22-24°C, ideally 22°C (Krieger et al. 1983, McMahon et al. 1984, Harvey 2009). Bioenergetic thermal maxima for walleye is 27 °C (Bozek et al. 2011).

<table>
<thead>
<tr>
<th>Year</th>
<th>Mean low (°C)</th>
<th>Mean high (°C)</th>
<th>Ice duration (days)</th>
<th>Ice free (days)</th>
<th>Ice off date</th>
<th>Ice on date</th>
<th>Days above 22 °C</th>
<th>Days above 27 °C</th>
<th>Days below 10 °C</th>
<th>No. of optimal days</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>4.2</td>
<td>18.5</td>
<td>150</td>
<td>216</td>
<td>19 April</td>
<td>22 Nov</td>
<td>87</td>
<td>26</td>
<td>13</td>
<td>116</td>
</tr>
<tr>
<td>2009</td>
<td>3.6</td>
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<td>159</td>
<td>206</td>
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<td>23 Nov</td>
<td>78</td>
<td>24</td>
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<td>2010</td>
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<td>141</td>
<td>224</td>
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<td>19 Nov</td>
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<td>163</td>
<td>202</td>
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<td>191</td>
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<td>80</td>
<td>24</td>
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3.5 Discussion

In general, use of benthic C sources by fish was unrelated to the modeled importance (%) of the phytobenthos in the total primary production of prairie lakes, with most sites recording an underutilization of benthic resources relative to their abundance (Figure 2). This finding contrasts Vander Zanden et al. (2011), who document a positive correlation between the two metrics ($r^2 = 0.29, P<0.05$) and a high benthic reliance by fish even when f(BP) was low. Similarly, Ask et al. (2009) found benthic energy use by higher trophic levels was tightly coupled with benthic primary production ($r^2 = 0.96, P<0.001$) whereas Karlsson and Byström (2005) found arctic char (Salvelinus alpinus) exhibit high reliance (62-94%) on benthic energy despite availability of prey fish. In contrast to the predominantly boreal and subarctic lakes of these previous studies, the present work focuses on eutrophic hardwater lakes, basins which constitute ~50% of the global water volume (Hammer 1986, Finlay et al. 2015). This observation suggests that benthic resource-use by fish may differ among continental lake districts (boreal, subarctic, grassland). Interestingly, mean benthic contribution to whole-lake production in prairie lakes was higher than reported in previous studies (Ask et al. 2009, Vander Zanden et al. 2011). Similar to our analysis, Vander Zanden et al. (2011) also found no significant association between mean benthic reliance and limnological, morphological and environmental parameters.

Higher benthic reliance during early summer may reflect competitive interactions between periphyton and phytoplankton (Vadeboncoeur et al. 2003), as benthic primary producers predominate early in the ice-free season until phytoplankton productivity
increases and limits light penetration. Similar to our findings, García-Berthou and Moreno-Amich (2000) noted a decrease in pumpkinseed (*Lepomis gibbosus*) dependence on benthic prey over the course of the summer, from June to August, while Hayden et al. (2014) found seasonal decreases in dependence on benthic prey by fish species in subarctic lakes. However, despite generally high use of benthic resources in early summer (Figure 3), there remains a high degree of variation among some lakes. Although speculative, we infer that high among-lake variation among lakes may reflect the wide gradient of human and hydrological controls in regional ecosystems (Leavitt et al. 2006, Pham et al. 2008, Starks et al. 2014), ranging from wastewater pollution in Humboldt Lake (Cooper and Wissel 2012b), to dramatic lake level changes in Lenore Lake, and simplified food-web structure in Lake Pelletier (yellow perch alone, Cooper and Wissel 2012a). Alternately, high variation in benthic production and use among lakes in June may arise because of differences in the strength of the clearwater phase in June (Dröscher et al. 2009). During that period, herbivorous zooplankton clear the water of particles, increase light penetration to the bottom of shallow lakes, and stimulate benthic primary production (McGowan et al. 2005). Further research will be required to distinguish among these possibilities.

Benthic energy pathways were similarly important to forage and game fish in these study lakes (Figure 3). In general, a higher reliance of forage fish on benthic resources occurred in lakes of high food-web complexity. Such increased reliance can reflect variations in forage fish community composition as a result of predation pressure (Findlay et al. 2000, Jackson et al. 2001, MacRae and Jackson 2001), differences in
overall lake production among low- and high-complexity lakes (Persson et al. 1991, Mehner et al. 2005), or behavioral responses of forage fish to avoid piscivory (Turner and Mittelbach 1990, Biro et al. 2003). We infer that community composition did not influence the use of benthic resources by forage fishes, as all forage species except spottail shiners were present in all lakes. Similarly, there was no significant difference in modeled benthic and planktonic primary production as a function of food-web complexity. While speculative, we infer behavioral responses of fish to avoid predation affected forage fish diets, with these taxa spending a higher proportion of the day in shallow littoral habitats where benthic production is greatest and where the more heterogeneous environment provides refugia from predation (Eklöv 1997, Sass et al. 2006, Ajemian et al. 2015).

We supplemented stable isotope analysis of resource-use with direct observations of consumption patterns by quantifying stomach contents of the three most prevalent game fish species found in these lakes (Figure 7). While fish dominated the diets of both walleye and northern pike, amphipods were common in both species-specific assessments and may indicate a lack of vertebrate prey. Additionally, diets of adult yellow perch were almost equally split between zooplankton and amphipods (Table 2), consistent with the tendency of percids to supplement their diets with macroinvertebrates despite potential for reduced growth without fish prey (Knight et al. 1984, Bethke et al. 2012, Feiner and Höök 2015). But overall walleye direct reliance on amphipods in our lakes was higher than that reported in past studies (Slipke and Duffy 1997, Vander Zanden and Vadeboncoeur 2002). Quist et al. (2002) found that even when invertebrates were
Figure 3.7 Comparison of the mean benthic reliance results from the two methods utilized in this study. Closed circles = gut content analysis and closed triangles = Bayesian mixing model (MixSIAR) result values for the three species of game fishes.
abundant in walleye diets, they did not substantially contribute to the total biomass consumed relative to vertebrate prey. Taken together, the relatively poor body condition of some species may indicate lower than expected trophic transfer efficiencies to top predators.

Poor body condition observed throughout the sampling period may also arise from thermal stress for all three game fish species during the growing season (Table 3, Figure 6). Bioenergetic models show that excessive temperatures may induce thermal stress and result in net energy loss even in the presence of abundant prey (Kitchell et al. 1977, Kocovsky and Carline 2001, Quist et al. 2002). In general, higher number of thermally-optimal days (10 – 22 °C) for all three species recorded in 2010 may have favoured an increase in condition indices observed over the course of the growing season (Table 4). However, water temperature alone does not explain variations in condition indices, as indices also increased during 2011 despite a low number of thermally-optimal days. Similarly, (Johnston et al. 2012) reported that adult walleye and sauger growth rates in Lake Winnipeg were not correlated with optimal temperatures. Our findings suggest body conditions of game fishes in prairie lakes may be determined by a combination of sub-lethal stressors and prey availability.

Water chemistry may have interacted with the presence of endo-parasites to further reduce the body condition of some prairie fishes. For example, salinity was significantly associated with walleye parasite load and prevalence in 2009, although it was not significantly correlated with the body condition indices of this species. During 2009, lakewater salinities were in excess of 2.0 g TDS L⁻¹ in all the gamefish-bearing
lakes, approaching the upper limit of the salinity threshold (<3.0 g TDS L\(^{-1}\)) identified by (Cooper and Wissel 2012b), while in 2010 salinities were <1.5 g TDS L\(^{-1}\). Previous studies have documented significant correlations between environmental stressors and parasite loads and identified parasites as useful bioindicators of environmental impacts on fish condition (Vidal-Martínez et al. 2010). Similarly, elevated salinities are known to affect walleye growth (M. Wilson and J. Nagler 2006), although the critical threshold for population effects is thought to be greater (4-8 g TDS L\(^{-1}\)) than those recorded in most of our study lakes (Cooper and Wissel 2012b).

**Future sustainability of stocked and native prairie fishes**

Increased temperatures in the future are expected to decrease the overall fitness of game fish populations through poor body conditions and increased parasite loads. Without sufficient energy reserves walleye may not be able to sustain populations during warmer summers until temperatures decrease again in the milder fall season. Quist et al. (2002) reported that warmer temperatures resulted in lower \(W_r\) condition indices, growth rates and higher occurrence of empty stomachs, likely due to decreased foraging. In our lakes, a parallel analysis revealed empty stomachs for a high proportion of game fish; 30-60% of walleye and 35-40% of northern pike. In dimictic lakes, walleye seek thermal refuges and decrease forage activity when water temperature exceeds 22°C (Quist et al. 2002); however, this option is less common in these polymictic basins which may lack deepwater thermal refuges. As projected temperature maxima may exceed 30°C in the Prairies (Barrow 2009), we infer that walleye may be eliminated from shallow systems,
largely on the basis of severely limiting growth, feeding activities, higher metabolic costs, and other factors (Quist et al. 2002, Whitney et al. 2016).

Walleye in prairie lakes may be more susceptible to synergistic effects of lake warming and osmotic stress than northern pike or yellow perch, particularly in concert with endoparasitic infections. Projected temperature increases of 5°C by 2050 (Sharma et al. 2007, Barrow 2009) will favour evaporative concentration of prairie lakes (Pham et al. 2009, Wissel et al. 2011) and salinity-induced suppression of the immune system may make walleye more susceptible to parasitic infections (Whitney et al. 2016, Barber et al. 2016), compromising their long-term sustainability in these lakes. Even though parasite load was not significantly associated with increased temperature in our lakes, Macnab and Barber (2012) found that parasitic infection were positively correlated with increasing temperatures by increasing life cycle completion rates and providing parasites the warmer habitat required for proliferation. Additionally, Britton et al. (2011) observed decreased body conditions associated with parasitic infections.

3.6 Conclusions

Comparison of resource-use, body condition, and parasite load suggested that stocked walleye were less resilient to environmental change than were native prairie fishes, despite their key economic and recreational status. In particular, walleye in prairie lakes are more reliant on macroinvertebrates, exhibited poorer body conditions than the native species, and are more susceptible to parasitic infections. Overall, their current status indicates a stressed population with high susceptibility to the unique and interactive
effects of climate change, intensified land-use, and invasive species. Additionally, as the species most desired by regional recreational anglers (Nanayakkara and Wissel 2017), walleye may be subject to disproportionately high angling pressure. Based on our results and those of previous studies (Barica and Mathias 1979, Cooper and Wissel 2012b, Starks et al. 2014), we posit that the long-term habitability of these lakes for large game fishes maybe a balance between osmotic and thermal stress brought on by climate change, susceptibility to parasitic infections, their influence on body condition and fluctuations in winterkill risk.

3.7 Acknowledgements

Funding for this study was provided by a Natural Sciences and Engineering Research Council of Canada (NSERC) grant to B. Wissel, and Teaching Assistance and Research scholarships from the University of Regina and the Government of Saskatchewan to L. Nanayakkara. Field assistance during sample collection was provided by D. Bateson, D. Braun, B. Hesjedal, K. Murphy, and M. Beaton.
4. IN LAKES BUT NOT IN MINDS: STAKEHOLDER KNOWLEDGE OF INVASIVE SPECIES IN PRAIRIE LAKES

4.1 Abstract

Humans are key vectors in the spread and establishment of aquatic invasive species (AIS), and human behavior can exacerbate or help prevent further spread of non-native species. Therefore, stakeholders’ knowledge is critical to preventing establishment of AIS. However, stakeholders’ AIS knowledge in prairie lakes remains poorly understood. We used a survey questionnaire in Saskatchewan, Canada, to assess the state of AIS knowledge, identify predictors of knowledge, and optimize management strategies. Statistical analyses of the responses of 440 participants indicated a generally low level of AIS knowledge, suggesting low communication success. Respondents were generally more aware of non-native fishes than plants. Of concern was the observation of substantial knowledge gaps regarding non-native mussels and important preventative behaviors that may have devastating ecological, social, and economic consequences if left unaddressed. Better understanding of AIS issues was significantly associated with several trans-situational (age, sex and education), situational (recreational purpose and using multiple lakes), and lake-related knowledge (awareness of eutrophication) predictors. Exploitation of these predictors is recommended to improve effectiveness of outreach and communication efforts. Specifically, we propose that management strategies focus on improving communications by streamlining outreach messages, targeting low-knowledge groups (e.g., swimmers, cabin owners), and expanding education campaigns.
4.2 Introduction

Invasive species are a critical threat to freshwater ecosystems in North America (Dextrase and Mandrak 2006). Their spread is tightly linked to human activities (e.g., economic development, disturbance, travel, trade), which can result in accidental or deliberate introductions of non-native species to new habitats (García-Llorente et al. 2008, Gates et al. 2009, Drake et al. 2014, Touza et al. 2014, Ansong and Pickering 2015, Edwards et al. 2016, Seekamp et al. 2016). Therefore, human behavior, including knowledge of environmental issues, should be a key component of efforts regulating the spread of invasive species (Jetter and Paine 2004, Bremner and Park 2007, Shackleton and Shackleton 2016). Support for invasive species management increases with the public’s understanding of invasive species’ biology and mechanisms of prevention or control. But uneven education of the public regarding invasive species can also lead to divisive debates on the desirability of, control and eradication efforts (Bremner and Park 2007). In particular, lack of community consensus for eradication of invasive species can cause management efforts to fail (Moon et al. 2015). Support for management efforts can markedly increase when focus group discussions with stakeholders relay the rationale and methodology of invasive species eradication (Bremner and Park 2007). Findings suggest that stakeholders’ knowledge about invasive species can influence their prevention, spread, and control, both through direct public action and support for management strategies (García-Llorente et al. 2008, Eiswerth et al. 2011, Sharp et al. 2011, Carlson and Vondracek 2014, Ford-Thompson et al. 2015).
Quantitative assessment of stakeholders’ knowledge concerning aquatic invasive species (AIS) is a critical first step in facilitating optimal human behaviors and developing stakeholders support for effective management strategies. For example, an econometric investigation of AIS awareness and knowledge determinants of near-lake property owners revealed that college-educated water recreationists and boat owners who visited lakes outside their area are more likely to be aware of different aspects of AIS compared to non-recreationists (Eiswerth et al. 2011). In general, active members of formal associations (e.g., lake stewardships, fishing groups) are more likely to be knowledgeable about AIS and less prone to engage in risky behaviors than non-members, even when the latter exhibited some understanding of AIS issues (Gates et al. 2009, Eiswerth et al. 2011). However, those exhibiting passive membership in such organizations may falsely report a degree of higher environmental awareness than is supported by their factual knowledge (Heck et al. 2016). Low levels of awareness and concern can also lead to risky behaviors associated with AIS spread, such as incomplete cleaning of personal items and equipment (Gates et al. 2009). Overall, surveys suggest that fishers are more knowledgeable about AIS and outreach campaigns than other recreationists (water skiers, swimmers, etc.), but their participation in AIS prevention behaviors is inconsistent or low and depends on fishing experience (Lindgren 2006, Gates et al. 2009, Eiswerth et al. 2011, Edwards et al. 2016, Seekamp et al. 2016).

As with other environmental issues (Dean et al. 2016) preventative behaviors are usually positively correlated with stakeholders’ AIS knowledge (Gates et al. 2009, Dean et al. 2016), but confounding or undesirable outcomes can arise despite high
understanding of AIS. For example, transient boaters are more likely to reuse the same bait in different water bodies compared to other boaters, even though all boaters tend to have attitudes and beliefs that support AIS spread prevention (Witzling et al. 2016). Some studies have found that even educated fishers are likely (25-33%) to release live bait into water bodies (Lindgren 2006, Drake et al. 2014). Similarly, well-informed fishers and boaters often did not properly rinse used equipment (Connelly et al. 2016, Seekamp et al. 2016). Disposition for risky behavior may be attributed to stakeholders tendency to underestimate the ecological costs of individual actions (Drake et al. 2014).

Additionally, trans-situational or situational predictors of AIS knowledge may also affect the success of AIS outreach and education campaigns (Eiswerth et al. 2011). Trans-situational factors are variables that generally remain static regardless of the situation (e.g., age, sex and education). These variables have been shown to influence levels of environmental knowledge in many countries (Steel et al. 2005b, 2005a, Pierce et al. 2010, Heck et al. 2016, Dean et al. 2016). Better educated, older, males tend to be more knowledgeable about public policy issues, although the gender gap is closing in the younger population (Steel et al. 2005b, 2005a, Pierce et al. 2010, Otto and Kaiser 2014), and may be becoming more dependent on the specific environmental issue (Otto and Kaiser 2014, Harvey et al. 2016, Dean et al. 2016). In contrast, context-dependent situational variables arise as a result of encounters between individuals and their environments irrespective of individual characteristics like age, sex and education (Belk 1975, Steel et al. 2005b, 2005a, Pierce et al. 2010, Heck et al. 2016, Dean et al. 2016). Situational factors are impacted by the degree of exposure to the issue and in turn,
influence knowledge-seeking behavior of the stakeholders (Steel et al. 2005b, 2005a). Trans-situational and situational factors can interact to influence the ontogeny of environmental awareness and knowledge, but situational factors can also help override the influence of trans-situational factors. For example, coastal recreationists are more likely to be knowledgeable about important ocean and coastal issues regardless of individual trans-situational profiles (e.g., Steel et al. 2005a; Steel et al. 2005b). Given their static nature, trans-situational predictors are inherently more difficult to address through outreach and education campaigns, whereas pliable situational predictors are more receptive to communications strategies. By identifying AIS knowledge predictors and understanding their characteristics, managers have the opportunity to influence AIS knowledge by engaging in more targeted outreach which can lead to better AIS management successes.

This study aims to assess the knowledge base of diverse stakeholders associated with freshwater and sub-saline lakes of the Northern Great Plains of the Canadian prairies. Lakes are abundant in Saskatchewan (SK), Canada, and provide important ecosystem services and economic opportunities (Wissel et al. 2011), and AIS are a critical threat to water quality, native flora and fauna, recreation, and economic investments (Pimentel et al. 2005, Dextrase and Mandrak 2006). Additional information about the study region can be found in Nanayakkara and Wissel (2017). Several AIS are already present in SK and, given its geographic position, the region is considered highly vulnerable to a non-native mussel invasion (Provincial Auditor 2016). The most recent evaluation of the effectiveness of AIS outreach and education efforts was conducted in
2010 as part of a joint Federal-Provincial survey of sport-fishing in SK (Koob and McGuire 2013). Results indicated low levels of awareness (23%) among SK residents about AIS outreach efforts and similar to studies discussed earlier, identified risky watercraft use patterns that may exacerbate vulnerability to non-native mussels (Koob and McGuire 2013). Therefore, despite increased AIS outreach and education efforts (including a formal mussel strategy initiated in 2014), we contend that attempts to influence knowledge and foster preventative behaviors via communications campaigns have been ineffective in SK. We posit instead that knowledge and attitudes of the regional stakeholders towards AIS are mainly informed by trans-situational factors, particularly education. Specifically, in the present study, we seek to: 1) examine AIS knowledge levels among stakeholders to measure effectiveness of current outreach efforts; 2) evaluate the contribution of trans-situational, situational and knowledge-related variables to identify targeted outreach to increase AIS knowledge, and; 3) offer management recommendations based on findings to help ensure prevention and control of AIS.

4.3 Methods

Data for this study were obtained from the Prairie Lake Use and Management Survey (PLUMS), a 4-page self-administered questionnaire instrument that contained fixed and open-ended questions. Prior to the survey, the questionnaire was pretested in 2013 to enhance the instrument’s validity and reliability (Nanayakkara and Wissel 2017). On the basis of this pilot study, we eliminated inconsistencies in the questionnaire and the survey was expanded to include AIS questions. The current questionnaire included five
sections: lake-use information such as purpose of lake-use and fishing habits; knowledge of aquatic systems including awareness of eutrophication and winterkill; knowledge of invasive species; lake management strategies, including satisfaction with lake management and willingness to participate in a citizen science initiative, and; demographic information. Given the relatively small sample size in the 2013 study (65 respondents), we presented the survey in two formats, a paper as well as a web-version.

We utilized multiple methods for survey distribution and outreach to maximize participation. The survey was distributed in August 2015 using an on-site, convenience intercept survey methodology at entrance and exit points of nine study lakes in SK (Uysal et al. 1994, Floyd et al. 1997, Pan and Ryan 2007, Luo and Deng 2008). Sites chosen represent popular visitor destinations and a range of sizes and distances from population centers in the region (Figure 1). We approached 250 people on-site at beaches, boat ramps and park entrances at study lakes. Survey participants chose to complete the survey right away, mail it at a later time (stamped/addressed envelope was provided) or complete it online (link was provided) at a time of their convenience. Complete questionnaires were collected by interviewers (the lead author was the principal interviewer) on-site once they were filled out by participants. If a group of visitors was encountered, one to three (depending on the group size and composition) representatives from the group were asked to fill out questionnaires. On average, respondents spent 15 minutes filling out the questionnaires. Recruitment fliers with the web-link to the survey were placed on every other vehicle windshield in the parking lot as well. We conducted additional outreach and participant recruitment through articles (with web-link to the survey) in local newspapers.
Figure 4.1 Map of study lakes in Saskatchewan, Canada. Inset identifies the location of the study area within the province. The Qu’Appelle River catchment consists of the following lakes: Pasqua, Echo, Katepwa, Crooked and Round. Surveys were distributed at Redberry, Wakaw, Lenore, Kipabiskau, Little Manitou, Fishing, Buffalo Pound, Last Mountain, and Echo lakes. Regina and Saskatoon are the major urban centers in Saskatchewan.
and through community members. The web version was available from August 2015 to November 2015. Incentive for survey participation was provided through a prize draw to win one of three fishing rods (each valued at CAD $89.99). Questionnaire format ensured anonymity but contact information was needed for prize draw participation. Approval to complete this study was obtained from the University of Regina research ethics board.

We utilized a subset of questions on AIS and potential knowledge predictors (trans-situational, situational and lake-related knowledge) from the PLUMS survey for this study (Appendix 1). In additional ‘yes/no’ questions participants indicated awareness of the term ‘invasive species’ as well as zebra (Dreissena polymorpha) and quagga (Dreissena bugensis) mussels. Zebra and quagga mussels are currently absent in SK, but have been detected in waters to the south, east and west of the study location (Benson et al. 2017; personal communications with SK Ministry of Environment 2016). Given the potential for an invasion by these non-native mussels and the economic consequences of such an invasion (Strayer 2009, Robinson et al. 2013), the SK Ministry of Environment has included an information pamphlet in the Anglers’ Guide since 1993 and initiated a strategy in 2014 to curtail arrival of non-native mussels. Analyses of public knowledge about non-native mussels were expected to help assess the successes and failures of these outreach efforts.

The matrix formatted AIS question section included the two mussels and a list of six invasive species found in the province. It consisted of a series of 16 ‘yes/no’ questions about: three fishes: common carp (Cyprinus carpio), goldfish (Carassius auratus), koi (domesticated ornamental varieties of Cyprinus carpio) three plants: flowering rush (Butomus umbellatus), purple loosestrife (Lythrum salicaria), salt cedar (Tamarix
ramosissima, Tamarix chinensis, Tamarix parviflora), and two mussels. Eight questions asked respondents about their knowledge of presence or absence of a specific (fish, plant and mussel) organism and eight questions probed respondents about their knowledge of the negative impacts of each organism. Six questions asked about presence/absence and impact of fish organisms (common carp, goldfish and koi), six questions asked about presence/absence and impact of plant organisms (flowering rush, salt cedar, and purple loosestrife) and 4 asked about presence/absence and impact of mussel organisms (zebra mussels and quagga mussels). For knowledge of presence or absence of invasive species, we modelled each of the three outcome variables as the number of correct answers given per species for each type of organism (fish, plant and mussel) separately. We did the same for correct knowledge of negative impact of invasive species, separately for each type of organism. This lead to the construction of six separate outcome variables that conveyed information about the number of correct answers regarding knowledge of presence/absence and impacts of AIS by type of organism. From this information, we assessed participants’ knowledge of invasive species and used information from other relevant sections of the survey to identify trans-situational, situational and lake-related knowledge predictor variables associated with this knowledge.

We used univariate, bivariate and multivariate statistical techniques to define the composition of respondents and quantify the relationship between the various trans-situational, situational and lake-related knowledge variables, and the respondents’ knowledge of AIS issues. Data processing, management and statistical analyses were conducted using IBM’s Statistical Package for the Social Sciences (SPSS), Version 23. Univariate analyses provided descriptive statistics for all variables, including frequency
distributions for awareness of the term ‘invasive species’, presence/absence, and impact of invasive species. Crosstab analyses with chi-square tests conducted for all three groups of organisms examined the relationship between correctly identifying presence/absence and the species’ impacts. Regression analyses undertaken for each group of organisms assessed the influence of predictors on the outcome variables, namely presence/absence and impact of invasive species. Informed by the extant literature, our analyses also controlled for socio-demographic characteristics previously shown to influence these outcomes (Steel et al. 2005a, Bremner and Park 2007, García-Llorente et al. 2008, Eiswerth et al. 2011, Ansong and Pickering 2015, Edwards et al. 2016, Heck et al. 2016, Dean et al. 2016), including respondent’s sex, age, type of place of residence, ethnicity, education, and self-identified socio-economic status. The reviewed literature provided a reasonable basis for organizing these factors into a tentative conceptual model of knowledge of presence/absence and impact of AIS (Figure 2). The operational definition of the predictors considered in the analyses are presented in Appendix 2. Dummy coded variables were created for all categorical variables.

A series of regression analyses were performed to model the effects of the selected predictors on the six outcome variables. Stepwise variable selection procedure was applied to help select the “best” (most parsimonious) subset of predictors by removing redundant predictors, as unnecessary predictors add noise. The 95% significance level was used as a cut-off for statistically significant results. At each step, all eligible variables are considered for removal and entry till no more variables are eligible for inclusion or removal; thus, leading to more parsimonious models (Tabachnick and Fidell 2006). Because of the concern that linear regression is not always well-suited for analyzing these
Figure 4.2 Conceptual framework of influence of trans-situational, situational, and lake-related knowledge predictors on presence/absence and impact of AIS.
kinds of “limited dependent variables” (e.g., Cameron & Trivedi 2005; Long 1997, 2005; Wooldridge 2013), we also conducted count regression analyses (e.g., Poisson Regression, Negative Binomial Regression) to ensure our results are robust (results not reported here). Ultimately, we are presenting the results of the linear regression because there were no major differences in terms of statistical significance, direction of association, and model fitness in the findings by technique used, and multiple linear regression is a more intuitive model for an interdisciplinary audience to interpret and understand. We also examined frequency distributions of zebra and quagga mussel awareness (yes/no), and conducted forward conditional stepwise logistic regression analyses to identify significant predictors of mussel awareness.

The AIS question section also included open-ended questions probing respondents to explain the cleaning procedure for a boat with mussels on it and to identify who they would contact if mussels were discovered on a boat. Content analysis was used to categorise the respondents’ answers to these questions (Neuman and Robson 2011). For this analysis, we examined common themes about contaminated boat cleaning procedures (‘clean, drain, dry’) and who to contact (SK Ministry of Environment TIP ‘Turn In Poachers’ line) in the event of discovering mussels on a boat. Additionally, answers were scrutinized for a clear indication of knowledge about the need to 1) clean a contaminated boat using high pressure, hot tap water (50°C) thoroughly scrubbing and rinsing surfaces; 2) drain all onboard water (including motor, livewell, bilge and bait buckets); and 3) dry contaminated boat and all gear for five days in the hot sun (if unable to rinse). Answers to this question were categorized as correct, incorrect or partially correct (if the answer contained some aspect of ‘clean, drain and dry’).
4.4 Results

A total of 476 participants filled out the survey questionnaire. Overall, the online option was more widely used than the in-person paper survey. We received 427 survey submissions online while only 49 opted to fill out the paper copy on-site. A comparison of the demographic characteristics of survey respondents to the general Saskatchewan population revealed that in our sample, only 4.6% of respondents identified as First Nations compared to 15.6% of the SK population identified as First Nations in the National Household Survey (Statistics Canada 2011). Unfortunately, additional outreach efforts in January and February 2016 did not significantly increase First Nations recruitment in the survey and these communities remain underrepresented.

Many participants visited lakes in at least two geographic regions in the province (44.3%, \( n = 211 \)), and single-region visitors were most common on lakes along the west-to-east draining Qu’Appelle River catchment (20.6%, \( n = 98 \)) (Appendix 3). Overall, lakes were used mostly for fishing, swimming, boating, and recreation (activities other than fishing and swimming) purposes, with some differences between regions in terms of lake-use purpose (Appendix 4). A total of 36 respondents (7.6%) did not use lakes in Saskatchewan and were excluded from subsequent analyses.

Most respondents were aware of the term ‘invasive species’ (92.4%). Many were also aware of presence of carp in SK waters (79.5%) and about half were aware of purple loosestrife (51.1%), but most respondents were unaware of the presence of goldfish (58.0%), koi (58.5%), flowering rush (88.4%) and salt cedar (93.7%) (Table 1). Additionally, many participants were unaware that zebra (72.6%) and quagga (76.0%) mussels had not yet colonized waterways in the province (Table 1). Only about 33% of
Table 4.1 Presence/absence and impact knowledge for each species, PLUMS 2015-2016. Valid percent (%, first row) and frequency (n, second row). All fishes and plants are present in SK, mussels are absent. All AIS listed are associated with negative impacts.

<table>
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<tr>
<th>Species</th>
<th>Presence/absence</th>
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<tr>
<td></td>
<td>Present</td>
<td>Absent</td>
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<tr>
<td>Carp</td>
<td>79.5%</td>
<td>3.3%</td>
</tr>
<tr>
<td>(n = 333)</td>
<td>(n = 14)</td>
<td>(n = 72)</td>
</tr>
<tr>
<td>Goldfish</td>
<td>42.0%</td>
<td>18.7%</td>
</tr>
<tr>
<td>(n = 170)</td>
<td>(n = 76)</td>
<td>(n = 159)</td>
</tr>
<tr>
<td>Koi</td>
<td>41.5%</td>
<td>13.5%</td>
</tr>
<tr>
<td>(n = 169)</td>
<td>(n = 55)</td>
<td>(n = 183)</td>
</tr>
<tr>
<td>Flowering Rush</td>
<td>11.6%</td>
<td>12.2%</td>
</tr>
<tr>
<td>(n = 46)</td>
<td>(n = 48)</td>
<td>(n = 301)</td>
</tr>
<tr>
<td>Salt Cedar</td>
<td>6.3%</td>
<td>14%</td>
</tr>
<tr>
<td>(n = 25)</td>
<td>(n = 55)</td>
<td>(n = 315)</td>
</tr>
<tr>
<td>Purple Loosestrife</td>
<td>51.1%</td>
<td>7.5%</td>
</tr>
<tr>
<td>(n = 206)</td>
<td>(n = 30)</td>
<td>(n = 167)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>Zebra mussels</strong></td>
<td>36.3% (n = 151)</td>
<td>27.4% (n = 114)</td>
</tr>
<tr>
<td><strong>Quagga mussels</strong></td>
<td>14.7% (n = 60)</td>
<td>24.0% (n = 98)</td>
</tr>
</tbody>
</table>
respondents had heard about quagga mussels, but a majority of respondents (86.7%) had heard about zebra mussels (Appendix 5). Many (80.3% zebra mussels and 58.3% quagga mussels) participants were, however, aware of the negative impacts of exotic mussels (Table 1). In contrast, most respondents were unaware of the potential negative impact of flowering rush and salt cedar on native ecosystems, and only half of them had an understanding of the potential negative impacts of goldfish (Table 1). Crosstabulations with chi-square tests yielded significant (p<0.001) positive relationships between correctly identifying presence/absence of a given organism and correctly identifying negative impact of that organism for all three groups (Table 2).

Regression analyses identified the importance of trans-situational, situational and lake-related knowledge predictors associated with correctly identifying presence/absence (Table 3, see also Figure 3) and impacts of AIS in southern Saskatchewan (Table 4, see also Figure 4). Specifically, fishing and awareness of lake-related environmental issues (eutrophication, winterkill, and industrial water extraction) were positively and significantly related to correctly identifying the presence of fishes. Age, rural residence (compared to residence in medium or large cities), swimming, and recreation were all negatively associated with correctly identifying the presence of fishes. In contrast, older participants, and those who used all three lake regions, or used lakes for work, and aware of eutrophication were more likely to be knowledgeable of presence of listed plants. Similarly, using all three lake regions, using lakes for work and awareness of eutrophication were positively and significantly related to correctly identifying absence of invasive mussels in SK waters. Awareness of eutrophication was a significant predictor of presence/absence knowledge for all three groups of organisms (Table 3,
Figure 3). More educated respondents and fishers were more knowledgeable about the negative impacts of all AIS (Table 4, Figure 4). Males and those aware of industrial water extractions were more knowledgeable of the negative impact of invasive fishes, whereas age was inversely related to awareness of negative impact of invasive fishes.
Table 4.2 Crosstabulations with chi-square tests for associations between correctly identifying presence/absence of a group of AIS and correctly identifying negative impacts of a group of AIS, PLUMS 2015-2016. *p<0.001

<table>
<thead>
<tr>
<th>Impact</th>
<th>Correctly identified presence/absence (%)</th>
<th>Chi-square</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>None</td>
<td>One organism</td>
</tr>
<tr>
<td>Fishes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None correct</td>
<td>70.0</td>
<td>31.4</td>
</tr>
<tr>
<td>One correct</td>
<td>10.0</td>
<td>41.5</td>
</tr>
<tr>
<td>Two correct</td>
<td>-</td>
<td>8.2</td>
</tr>
<tr>
<td>Three correct</td>
<td>20.0</td>
<td>18.9</td>
</tr>
<tr>
<td>Plants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None correct</td>
<td>76.3</td>
<td>13.6</td>
</tr>
<tr>
<td>One correct</td>
<td>4.6</td>
<td>57.4</td>
</tr>
<tr>
<td>Two correct</td>
<td>1.4</td>
<td>8.0</td>
</tr>
<tr>
<td>Three correct</td>
<td>17.8</td>
<td>21.0</td>
</tr>
<tr>
<td>Mussels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None correct</td>
<td>34.4</td>
<td>8.7</td>
</tr>
<tr>
<td>One correct</td>
<td>23.8</td>
<td>43.5</td>
</tr>
<tr>
<td>Two correct</td>
<td>41.8</td>
<td>47.8</td>
</tr>
</tbody>
</table>
Table 4.3 Stepwise multiple linear regression for predictor variables associated with correctly identifying presence/absence of fish, plant and mussel organisms, PLUMS 2015-2016. ¹Reference category = Medium-to-large population center: population of 30,000 or more; ²Reference category = Diefenbaker – Qu’Appelle system; (−) = Predictor variable did not enter the model. In each model, we entered the following predictors: respondent’s sex, age, race, highest educational level, self-perceived SES, city/town/RM of residence, lake’s region, purpose: fishing, purpose: swimming, purpose: boating, purpose: recreation, purpose: work, purpose: cabining, awareness of eutrophication, awareness of winterkill and awareness of water extraction. Dummy coded variables (no. of categories -1) were created for categorical predictors.
<table>
<thead>
<tr>
<th>Predictor Variables</th>
<th>Correctly identifying presence/absence of:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fish Organisms</td>
</tr>
<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td>(Constant)</td>
<td>1.775</td>
</tr>
<tr>
<td>Age</td>
<td>-0.011</td>
</tr>
<tr>
<td>City/Town/RM of Residence&lt;sup&gt;1&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Rural area</td>
<td>-0.343</td>
</tr>
<tr>
<td>Small population center</td>
<td>-</td>
</tr>
<tr>
<td>Lakes' Region&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>South of Diefenbaker Qu'Appelle</td>
<td>-</td>
</tr>
<tr>
<td>North of Diefenbaker Qu'Appelle</td>
<td>-</td>
</tr>
<tr>
<td>Two different lake regions were used</td>
<td>-</td>
</tr>
<tr>
<td>All three lake regions were used</td>
<td>-</td>
</tr>
<tr>
<td>Purpose: Fishing</td>
<td>0.344</td>
</tr>
<tr>
<td>Purpose: Swimming</td>
<td>-0.332</td>
</tr>
<tr>
<td>Purpose: Work</td>
<td>-</td>
</tr>
<tr>
<td>Purpose: Recreation</td>
<td>-0.250</td>
</tr>
<tr>
<td>Awareness of Eutrophication</td>
<td>0.276</td>
</tr>
<tr>
<td>Awareness of Winterkill</td>
<td>0.310</td>
</tr>
<tr>
<td>Awareness of Water Extraction</td>
<td>0.266</td>
</tr>
<tr>
<td><strong>R</strong></td>
<td><strong>0.453</strong></td>
</tr>
</tbody>
</table>
Figure 4.3 Findings-based layout of the impact of trans-situational, situational, and lake-related knowledge predictors on presence/absence of AIS. Unless otherwise specified, the predictor impacts all three groups (fish, pant, mussel) of organisms. (+) and (-) indicates the direction of the relationship. For example, older respondents are less knowledgeable about presence of non-native fishes but more knowledgeable about plants.
Table 4.4 Stepwise multiple linear regression for predictor variables associated with correctly identifying negative impact of fish, plant and mussel organisms, PLUMS 2015-2016. Reference category = Female; Reference category = Diefenbaker – Qu’Appelle system; \((-\)) = Predictor variable did not enter the model. In each model, we entered the following predictors: respondent’s sex, age, race, highest educational level, self-perceived SES, city/town/RM of residence, lake’s region, purpose: fishing, purpose: swimming, purpose: boating, purpose: recreation, purpose: work, purpose: cabining, awareness of eutrophication, awareness of winterkill and awareness of water extraction. Dummy coded variables (no. of categories -1) were created for categorical predictors.
<table>
<thead>
<tr>
<th></th>
<th>Fish Organisms</th>
<th>Plant Organisms</th>
<th>Mussels Organisms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Beta</td>
<td>Sig.</td>
</tr>
<tr>
<td>(Constant)</td>
<td>0.540</td>
<td>0.090</td>
<td>0.090</td>
</tr>
<tr>
<td>Age</td>
<td>-0.013</td>
<td>-0.156</td>
<td>0.002</td>
</tr>
<tr>
<td>Male&lt;sup&gt;1&lt;/sup&gt;</td>
<td>0.441</td>
<td>0.160</td>
<td>0.002</td>
</tr>
<tr>
<td>Highest Level of Education</td>
<td>0.128</td>
<td>0.142</td>
<td>0.005</td>
</tr>
<tr>
<td>Lakes' Region&lt;sup&gt;2&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>South of Diefenbaker Qu'Appelle</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>North of Diefenbaker Qu'Appelle</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Two different lake regions were used</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>All three lake regions were used</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Purpose: Fishing</td>
<td>0.583</td>
<td>0.203</td>
<td>0.000</td>
</tr>
<tr>
<td>Purpose: Swimming</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Awareness of Eutrophication</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Awareness of Water Extraction</td>
<td>0.389</td>
<td>0.139</td>
<td>0.007</td>
</tr>
</tbody>
</table>

| R                              | 0.399    | 0.319 | 0.388       |
| R square                       | 0.159    | 0.102 | 0.151       |
Figure 4.4 Findings-based layout of the impact of trans-situational, situational, and lake-related knowledge predictors on negative impact of AIS. Unless otherwise specified, the predictor impacts all three groups (fish, pant, mussel) of organisms. (+) and (-) indicates the direction of the relationship. For example, older respondents are less knowledgeable about the impact of non-native fishes.
In turn, those aware of both eutrophication and water extraction were more likely to correctly identify negative impact of plants. Swimmers, on the other hand, were significantly less likely to be familiar with negative impacts of both plants and mussels. Male respondents using all three lake regions, and those aware of eutrophication were more knowledgeable about impacts of mussels. Awareness of eutrophication increased the likelihood of having heard about both zebra and quagga mussels (Table 5). Additionally, better educated, older males were more likely to have heard about zebra mussels and those using lakes for work were more likely to have heard about quagga mussels, while respondents using lakes for seasonal cabins were less likely to have heard about quagga mussels.

Only 5.7% of participants correctly answered ‘clean, drain, dry’ as the best method to prevent a mussel invasion, whereas 61.1% were aware of at least one step, and one-third (33.2%) were completely unaware of recommended cleaning processes. Among those who correctly identified the need to dry the infected boat, there was no consensus on length of drying time, with responses ranging from 72 hours to 90 days to ‘let it freeze over winter’. Similarly, participants aware of the need to clean the boat did not identify a uniform protocol, with answers including using household bleach, domestic cleaning substances, vinegar, muriatic acid, chlorine, disinfectant, chemical treatments, poisons, acid-based cleaners, dish washing detergent, bug killer and pesticides. Regarding who to contact in the event of mussel discovery, only 4.4% correctly stated the SK government TIP telephone line, while 72.1% stated various levels of government, ranging from the local municipality’s office, to the local Conservation Officer, specific provincial
Table 4.5 Forward conditional stepwise logistic regression of awareness of zebra and quagga mussels, PLUMS 2015-2016. Reference category = Female; (-) = Predictor variable did not enter the model. In each model, we entered the following predictors: respondent’s sex, age, race, highest educational level, self-perceived SES, city/town/RM of residence, lake’s region, purpose: fishing, purpose: swimming, purpose: boating, purpose: recreation, purpose: work, purpose: cabining, awareness of eutrophication, awareness of winterkill and awareness of water extraction. Dummy coded variables (no. of categories -1) were created for categorical predictors.

| Have you heard about: | Zebra Mussels | | Quagga Mussels | |
|---|---|---|---|---|---|---|---|---|---|---|
| | B | Sig. | Exp(B) | Model Entry | | B | Sig. | Exp(B) | Model Entry | |
| (Constant) | -2.259 | 0.012 | 0.104 | | | -1.057 | 0.000 | 0.347 | |
| Age | 0.025 | 0.039 | 1.025 | 5 | | | | | |
| Male¹ | 1.804 | 0.000 | 6.074 | 1 | | | | | |
| Highest Level of Education | 0.465 | 0.001 | 1.591 | 2 | | | | | |
| Purpose: Swimming | -0.909 | 0.052 | 0.403 | 6 | | | | | |
| Purpose: Work | - | - | - | - | | 1.649 | 0.000 | 5.201 | 1 | |
| Purpose: Cabining | - | - | - | - | | -0.495 | 0.051 | 0.610 | 3 | |
| Awareness of Eutrophication | 1.417 | 0.009 | 4.124 | 4 | | 0.982 | 0.000 | 2.670 | 2 | |
| Awareness of Winterkill | 0.690 | 0.086 | 1.993 | 3 | | | | | |

-2 Log likelihood 214.860 409.776
Nagelkerke R Square 0.329 0.168
ministries, federal agencies (e.g., Environment Canada, Fisheries and Oceans Canada), or the Royal Canadian Mounted Police (RCMP), a federal law enforcement agency in Canada. Almost a quarter (23.5%) of participants did not know who to contact or simply would not contact any authority if mussels were found.

4.5 Discussion

Our study highlights the dynamic nature of AIS knowledge among stakeholders. Findings suggest that current outreach and communication methods are either ineffective at reaching desired audiences or important information is not being retained, or a combination of the two. As noted elsewhere (Steel et al. 2005b, 2005a, Eiswerth et al. 2011, Dean et al. 2016), the regression analyses identified trans-situational (e.g., age, sex, education), situational (e.g., mode and location of recreation) and lake-related knowledge (e.g., eutrophication) predictors. Consistent with prior analyses of AIS knowledge across organisms (Lindgren 2006, Strayer 2009), respondents were more aware of effects and presence of invasive fishes than plants. Surprisingly, substantial knowledge gaps were identified concerning the presence and prevention of non-native mussel transmission. In our study, awareness of eutrophication was found to be a simple but near-universal predictor of respondent’s knowledge concerning AIS, while previous studies identified breadth and depth of recreational involvement as near-universal predictors (Eiswerth et al. 2011, Seekamp et al. 2016). Therefore, our study provides further evidence for the overall importance of lake-based activities and lake-related knowledge as determinants of AIS knowledge. Based on our results, we propose that future management strategies
focus on improving communications by streamlining outreach messages, targeting low-
knowledge groups (e.g., swimmers, cabin owners), and expanding education campaigns.

Aquatic invasive fish vs. plant species

Although most respondents were aware of the term ‘invasive species’, knowledge
about presence/absence and impacts of AIS was organism-dependent. Overall knowledge
of invasive fishes was greater than that of invasive plants. This observation may be an
extension of the general bias towards an increased interest in animals over plants (Martín-
López et al. 2007). It may also be a reflection on the regulation of non-native animals
(Ministry of Environment) and plants (Ministry of Agriculture) by separate ministries
with different communications strategies (Provincial Auditor 2016). Relatively high
knowledge about presence and impacts of carp may be attributed to attention in the
media, its inclusion in the annual Anglers’ Guide, and the presence of a commercial
fishery that was operational until the 1980’s. In contrast, goldfish are often purchased as
pets and koi are ornamental species, thus, familiarity with them in these contexts may
limit concern over their environmental impacts relative to carp (Touza et al. 2014,
Shackleton and Shackleton 2016, Lindemann-Matthies 2016). Comparable to findings in
neighboring Manitoba (Lindgren 2006), most respondents did not know about the
presence or negative impacts of invasive plants such as flowering rush and salt cedar.
However, similar to Lindgren (2006), many respondents correctly identified presence and
negative impact of purple loosestrife. In this instance increased familiarity may be
attributed to its identification and description as an aquatic invasive plant on the
Government of SK (Ministry of Environment) website.
Mussels

As shown in previous studies (Strayer 2009), respondents exhibited variable knowledge about invasive mussels. Despite low awareness of mussel absence in SK, many respondents correctly identified the negative impact of both invasive mussels, which may be attributed to the high visibility of mussels through widespread media coverage in North America (Strayer 2009, Haag and Williams 2014). Results on mussel presence/absence should be of concern to managers, government, stakeholders and scientists alike because if non-expert stakeholders incorrectly assume SK waters have already been invaded by mussels or are unaware of their status in the province, they may be less inclined to engage in preventative and/or control behaviors, as seen elsewhere (Gates et al. 2009, Drake et al. 2014).

Inconsistent nature of the answers to the open-ended questions provides evidence that current outreach efforts are either not delivering the message in a clear, understandable manner or that it is not being retained. The message of ‘clean, drain, dry’ is a central tenant of invasive mussel prevention and control campaigns around the world (Gates 2009, Zook and Phillips 2012, Seekamp et al. 2016), and needs to be delivered successfully to recreationists utilizing water-crafts to prevent mussel invasion. Even when water-craft users are willing to drain their boats, they are unlikely to use a hot water rinse as recommended (Seekamp et al. 2016, Connelly et al. 2016). Therefore, such a program needs to include better transmission of information on precise protocols, as most respondents did not know the length of time a watercraft should be dried, or the cleaning procedures needed to ensure adult mussels and veligers are completely removed from
contaminated boats and equipment. Of added concern is the predisposition of some respondents to clean watercrafts with chemicals (only hot water is recommended in the protocol) that are not only harmful to waterways but also to individuals themselves. Additionally, outreach material should prominently display relevant contact information and emphasize the need to contact authorities via the TIP line if watercraft is contaminated with mussels.

**Role of predictors**

As organized in Figure 1, this study explored the impact of a number of trans-situational, situational, and lake-related knowledge factors related to AIS knowledge. Consistent with previous studies, certain trans-situational variables were important predictors of invasive species knowledge. While increased respondent age is generally associated with higher levels of environmental awareness (Steel et al. 2005a, Lindgren 2006), the relationship between age and knowledge in our study was less straightforward. We are unsure about the exact causes behind the heterogeneity (negatively associated with fishes but positively associated with plants) of the influence of age on AIS knowledge. The positive influence of age on environmental awareness is partly attributed to the accumulated impact of exposure to environmental information since the 1960s environmental awareness movement (Otto and Kaiser 2014). Even though past empirical research indicates that the relationship between sex and environmental awareness is complicated (Otto and Kaiser 2014, Harvey et al. 2016), males in our study were generally more knowledgeable about invasive fish impacts, more aware of zebra mussels’ colonization patterns, and more informed of mussel impacts on the environment.
Consistent with the observation that level of formal education is an important predictor of AIS awareness (Eiswerth et al. 2011), we noted that education was associated positively with increased knowledge of negative impacts of fishes, plants and mussels. Finally, residential location was an important predictor of AIS issues, as rural residents were less likely to be knowledgeable about fish presence than urban participants. These “non-modifiable” predictors are more static compared to contextually impressionable situational and knowledge predictors (Steel et al. 2005a) and therefore, management efforts should prioritize situational predictors and focus less on trans-situational variables.

In our study, we identified several key situational factors. Fishing was an important predictor of AIS knowledge. This effect is generally attributed to fishers increased familiarity with invasive outreach information and campaigns, better developed sense of personal responsibility to control AIS, and engagement in preventive behaviors (Eiswerth et al. 2011, Edwards et al. 2016, Seekamp et al. 2016). Higher knowledge of the presence of plants and absence of mussels and their negative impacts among respondents who used all three lake regions and used lakes for work may be due to repeated interactions with lake environments. Such interactions often result in more positive experiences with that environment, increase environmental concern and acts as a situational motivator to promote knowledge-seeking behavior (Steel et al. 2005b, 2005a, Eiswerth et al. 2011).

Not all situational predictors were positively correlated with increased understanding of AIS issues. For example, use of lakes for recreational swimming was
associated negatively with knowledge of fish presence, and impacts of both plants and mussels. Similar to Strayer’s (2009) findings, recreationists (non-fishing/non-swimming) were also generally less knowledgeable about the presence of invasive fish organisms. Additionally, cabin-use was related negatively to awareness of quagga mussels. Possibly, recreationists and cabin owners are more concerned about other well-publicized threats to their lakes (e.g., eutrophication, industrial water extraction, pesticide exposure, etc.) (Eiswerth et al. 2011). Low knowledge among cabin-users may also be attributed to the highly seasonal nature of cabin use in SK, which may limit cabin owners’ contact with lake-relevant information, including AIS.

In addition to trans-situational and situational predictors of AIS knowledge, knowledge of lake-related environmental issues increased understanding of AIS-related issues. In particular, awareness of eutrophication was a near-universal predictor of AIS for both presence/absence and impact. Noxious summer algal blooms have been reported in southern Saskatchewan since the early 20th century (Rawson and Moore 1944), and have become a well-publicized water quality issue that has resulted in upgrades (> CAD $200 million) to the City of Regina wastewater treatment plant (CCPPP 2014). Similarly, industrial water extractions from Qu’Appelle Valley lakes have been prominent in the media for over five years (WSA 2012), possibly explaining its linkage to knowledge of AIS-related topics (fish presence, fish impacts and plant impacts). Likely, exposure to lake-related environmental issues such as eutrophication or industrial water extraction has engendered greater overall knowledge about lakes through stimulation of knowledge-seeking behavior, as seen elsewhere (Steel et al. 2005b, 2005a, Dean et al. 2016).
Management implications

Low levels of AIS knowledge recorded across all organisms indicate a need to critically evaluate current outreach and communication efforts. Our findings echo results from an earlier survey (Koob and McGuire 2013) that outreach campaigns are not effectively reaching the desired audience. Many factors may contribute to reduced effectiveness, including: stakeholders inability to recall campaign messages (Seekamp et al. 2016); public preference for new or non-traditional media (e.g., Twitter, Facebook) not employed by managers (Koob and McGuire 2013); messages are convoluted or overly-complex (technical) (Seekamp et al. 2016); strategies place insufficient emphasis on personal responsibility and potential damages (Strayer 2009, Drake et al. 2014, Seekamp et al. 2016) and; unreceptive or inattentive stakeholders (Drake et al. 2014). We recommend a focus group methodology that includes a variety of stakeholders to help identify mechanisms responsible for campaign ineffectiveness and how strategies should be modified to enhance message retention and recall. A dual outreach portfolio may be particularly effective, with education and outreach campaigns expanded province-wide, utilizing multiple social media formats (blogs, Twitter, Facebook) in addition to more traditional media avenues (television, radio, print), while also directly providing critical information at each lake to increase awareness of AIS. In particular, we suggest that campaign developers and implementers be cognizant of the need to keep the AIS information direct, concise, and jargon-free (Shu and Carlson 2013). We also recommend careful study of similar campaigns underway in comparable regions to determine their effectiveness before implementation.
Along with expansion of education and communication strategies, managers should target the use of situational information identified from the findings of the present study to increase knowledge levels in individual groups. For example, to capitalize on the positive relationship between multiple-lake use and AIS knowledge, the province could use tourist advertising or competitions to encourage stakeholders to visit many lakes. Targeting information at non-fishing/boating recreationists may be more effective in improving general understanding than primarily posting information boards at fishing sites. It is important to draw connections between recreationists desired lake-related activity and the impact of AIS. For example, bird-watchers should be informed about potential decreases in food, shelter and nesting areas due to purple loosestrife encroachment. Similarly, cabin-owners could be educated about detrimental impacts of mussels on their personal infrastructure (water intake pipes, swimming) and property values to address the inverse relationship between cabining and quagga mussel awareness. While recreationists and cabin-users may not be direct vectors of AIS dispersal, increased engagement by this group may help apply pressure to boat-owning or fishing neighbors to be more attentive to AIS transmission. In particular, the strong positive association between lake-relevant knowledge and AIS knowledge illustrates benefits of increasing ‘lake-literacy’ among general stakeholders. More knowledgeable citizens are also more likely to support AIS management efforts and engage in more responsible behaviors (Reed 2008, White and Ward 2010).

Based on our findings that stakeholders are poorly informed about the status of exotic mussels in SK and the province’s vulnerability to a mussel invasion, managers
should develop a long-term, multi-party AIS strategy focused on prevention (Leung et al. 2002, Lovell et al. 2006, Sharp et al. 2016), early detection, and eradication (Vander Zanden et al. 2010). Invasive mussels are now established in most regions surrounding SK, particularly at sites such as Lake Winnipeg, which are directly linked to the Qu’Appelle drainage by river flow. Poor knowledge about mussel presence, combined with uneven understanding of effective preventive behaviors, makes the province especially vulnerable to invasive mussels along east-west corridors. Therefore, we propose the development of a multi-stakeholder coalition between universities, lake associations, fishing tournaments, recreation organizations and citizen science groups to help prevent mussel contaminated watercrafts entering the province. Such a coalition may also alleviate resource burdens and provide more buy-in for stakeholders. For example, once potential invasion corridors are identified, industrial partners may be willing to provide necessary funding to construct watercraft wash-stations, and well-trained community volunteers may be willing to operate such stations.

4.6 Conclusions

Studies such as ours help understand important knowledge gaps about effectiveness of invasive species outreach campaigns (Strayer 2009). Given the global significance of invasive species in both aquatic and terrestrial environments, application of methods used and insights gained from our study are not limited to prairie lakes. We found that public perceptions of AIS were organism-dependent, emphasizing the importance of addressing invasive species issues on a context-specific basis. Results also highlight the need for a multi-stakeholder approach to rectify low AIS knowledge. In
particular, we feel it may be important to quantify knowledge levels at the onset of the decision-making process, involve diverse stakeholders, and continue knowledge assessments at regular intervals. A survey instrument similar to ours will help assess baseline invasive species knowledge and evaluate effectiveness of outreach efforts. Results from such a survey will be particularly applicable if questions are sourced (in part) from managers and practitioners (Matzek et al. 2014). Assessing and understanding public knowledge about environmental issues can be an invaluable tool that helps prioritize education, outreach and management goals which may ultimately facilitate adoption of desired environmental behaviors. Additionally, increased AIS knowledge may have a ‘spill-over’ effect and positively impact knowledge seeking behavior about other issues (e.g., overfishing, industrial pollution) that affect lakes, increasing overall ‘lake literacy’ levels. More knowledgeable citizens will, in turn, be able to better engage in management decisions that impact the health of lakes.

4.7 Acknowledgements

We thank Ron Hlasny from the SK Ministry of Environment for his assistance in this study. Fishing rods offered as prizes were generously donated by Cabela’s. Funding for this study was provided by a Natural Sciences and Engineering Research Council of Canada (NSERC) grant to B. Wissel, and Teaching Assistance and Research scholarships from the University of Regina and the Government of Saskatchewan to L. Nanayakkara.
5. CONCLUSIONS

5.1 Synthesis and management relevance of results

Prairie lakes are a model example of complex socio-ecological systems (SES) (Ostrom 2009, Hinkel et al. 2014) and this study was a novel attempt at advancing the understanding of both human and ecological dimensions of these systems by adopting an interdisciplinary research approach (Holm et al. 2013). Examining stakeholder patterns of lake-use identified the main purposes of recreational lake-use and elucidated user perceptions and concerns regarding prairie lakes. Assessing the current status of stocked game fish species along with naturally-occurring fish populations helped evaluate their vulnerability to changing environmental conditions, including sub-lethal effects, and quantify the sustainability of populations to future environmental change (Figure 1). Developing a deeper understanding of stakeholder knowledge about aquatic invasive species (AIS) also helped identify critical knowledge gaps that may further compromise the long-term sustainability of fish populations and continuous lake-use.

Recreational activities (fishing, boating) are important ecosystem services of lacustrine ecosystems, which inform values and norms that in turn, establish human behaviours capable of influencing lake health and robustness to change. Preliminary and follow-up investigations of human dimensions identified the main recreational uses and knowledge gaps related to prairie lakes. Overall, fishing was a key recreation, in particular for walleye (*Sander vitreus*), potentially subjecting them to disproportionate angling pressure compared to native taxa such as northern pike (*Esox lucius*) and yellow perch (*Perca flavescens*). While lake users were concerned about pollution and
overfishing, they considered climate change and invasive species to be of minimal concern. This pattern indicates a possible decoupling among key stakeholders, with science and management objectives on one side, and public perceptions on the other, as regards to anthropogenic influences on prairie lakes.

These patterns were largely corroborated in the follow up survey. Although stakeholders were generally aware of non-native fishes and plants, they exhibited significant knowledge gaps regarding non-native mussels and important behaviours to prevent invasion. These findings are especially alarming because humans play a central role in the spread and establishment of AIS (Hulme 2009). Therefore, I infer that identification of baseline knowledge levels about AIS is a critical component of assessing the risk of invasive mussel introductions to Saskatchewan. In particular, limited knowledge of lake users suggest low communication success by managers. Furthermore, as demonstrated elsewhere (Connelly et al. 2016), failure to communicate the impacts of invasive mussels in a timely manner may have catastrophic ecological, social, and economic consequences.

In addition to the societal impacts of SES, environmental stressors such as climate change are expected to interact in complex and difficult to predict ways to significantly impact game fish populations in temperate regions. In advance of these changes, this study evaluated the current status and potential resilience of native and stocked fish species in prairie lakes. Results from this study and those of previous studies (Barica and Mathias 1979, Cooper and Wissel 2012b, Starks et al. 2014) suggest that the long-term habitability of these lakes for large game fishes may depend on a balance between sub-lethal impacts of environmental changes including influences on body
Figure 5.1 Conceptual diagram of threats facing game fish, especially walleye, in Saskatchewan, Canada. The left column describes the most imminent threats facing these fish populations and the right column notes the primary impacts of these threats. Threats may act synergistically and impacts may be attributed to more than one threat.
condition, susceptibility to parasitic infections, and fluctuations in winterkill risk. Based on our results, walleye appear to be less resilient to environmental variability than are northern pike and yellow perch, suggesting that they will need to be continuously stocked in the future, particularly under climate change scenarios.

5.2 Management recommendations

Based on the results of this study, I propose the following strategies to address communications challenges and help align public perceptions with management objectives. These recommendations focus on ensuring the long-term sustainability of recreational angling, improving AIS knowledge through re-structured outreach campaigns, and enhancing efforts for detecting AIS transfer. However, government and managers must remain cognizant of the importance of public support, without which management objectives will likely result in failure (Kareiva and Marvier 2012, Adams and Sandbrook 2013). In particular, I urge caution in implementing overtly top-down policies that have not been assessed for levels of public support. While acknowledging the danger of panaceas (Ostrom et al. 2007), I am optimistic that the solutions offered below are applicable to similar systems in developed countries.

1) **Implement practices that decrease walleye injury and mortality:**

As climate change, land-use, and impacts of AIS intensify, walleye may require strategic amnesty from intensive angling pressure, including prolonged recovery periods following intensive fishing periods. Catch-and-release designations could be expanded to additional lakes (especially those with high angling pressure) and gear restrictions (e.g.,
requiring barbless hooks at all lakes) may decrease angling related injury and post-release mortality where implemented (Meka 2004). Additionally, strict and low harvest limits (both length and number) have been shown to aid vulnerable fish species recover from overharvesting elsewhere (Pierce 2010). As an added measure, I recommend stationing community volunteers around lakes during high angling pressure periods to help provide information and guidance on safe catch-and-release practices to encourage this behaviour. Rather than enforcement, the goal of these personnel is to reinforce the understanding that improved survival from non-lethal capture will improve fishing opportunities in the future.

2) Promote naturally occurring northern pike and yellow perch as an alternative to walleye:

Marketing and publicity campaigns focused on the challenge of catching a pike or the abundance of yellow perch may help alleviate some pressure on stocked walleye. If lakes become uninhabitable for walleye, this strategy may help also minimize the economic consequences to the recreational fishing industry and local communities dependent on it. Johnson and Carpenter (1994) demonstrated the propensity for anglers to switch to alternative species or fishing opportunities when one fishing population diminished over time. Therefore, by proactively promoting these naturally occurring alternative species, managers may alleviate some of the pressure on walleye, and maintain the recreational fishing industry at desired levels in SK despite fluctuations in fish community composition.

3) Restructure AIS education and outreach campaigns:
I recommend using a focus group approach (Nyumba et al. 2018) to help identify reasons for AIS knowledge gaps. This approach could identify any features in the format, messaging, and dissemination of AIS information that can be improved to increase knowledge levels. During discussions, facilitators could also present information using positive (e.g., mussel invasions are associated with water clarity), negative (e.g., mussels have been shown to harm recreational fisheries), and neutral (e.g., facts about mussel reproduction) messaging to identify lake users’ underlying attitudes about mussels, how convincing they find each theme, (believability, educational value), and whether it helps change their attitude about mussels. (Echeverri et al. 2017) used a similar method to identify people’s attitudes about species at risk. Their exercise helped managers use persuasive communication strategies to explore what was effective for their context and close knowledge gaps. Following this analysis, messaging content should ideally be pilot-tested prior to dissemination (Echeverri et al. 2017). In addition, although knowledge levels in boater sub-groups were not assessed in our study, we recommend specifically targeting fishing guide operations. Rothlisberger et al. (2010) found that among boater sub-groups, fishing guide vessels were the most transient and posed the highest risk for transporting AIS. Finally, education campaigns targeted at specific high-risk user groups identified through focus groups and previous studies may help improve mussel-related knowledge levels more than broad, generalized education efforts.

4) *Strategically place mandatory inspection stations and high pressure washing stations:*
Unfortunately, knowledge gaps about AIS and unwillingness to observe preventative behaviours are common phenomena in recreational lake management (Rothlisberger et al. 2010, Seekamp et al. 2016). Given the lack of knowledge about key boat-cleaning protocols, I recommend mandatory inspection stations at major highways to inspect boats entering from Manitoba, North Dakota and Montana, particularly along roads which link known sites of infestation to SK waters. Additionally, I recommend constructing staffed pressure washing stations at high-risk lakes, possibly staffed with volunteers. Prevention remains the best method of safeguarding lakes against AIS because once established, invasive mussels are virtually impossible to eradicate (Vander Zanden and Olden 2008, Sousa et al. 2014). Although more expensive than advertising, the resources required for construction and maintenance of these stations is worth the investment if prevention efforts are successful. Since cleaning and draining of one’s own boat is often perceived as an inconvenience with little reward to the individual (Rothlisberger et al. 2010), preventative behaviours are unlikely to occur at an individual level. Therefore, strategically placed pressure washing stations at high-risk lakes are likely required to ensure compliance with boat cleaning protocols. This can occur in tandem with education campaigns and can be phased out if they are successful.

5.3 Future work

Consulting practitioners during the development phase of the second stakeholder survey allowed this study to develop an instrumental first step towards co-producing knowledge by all involved stakeholders. Future research to integrate human and ecological dynamics of prairie lakes, as well as similar SES, will be more successful if
they originate from a community of practice. Communities of practice are transdisciplinary teams (Holm et al. 2013) composed of academics, policy and management practitioners, and lake users who come together to identify knowledge requirements to help solve a common problem (Roux et al. 2006, Young et al. 2014, Christie et al. 2017). Resources required for such an effort (e.g., funding, space) could be obtained from multiple sources and should involve representatives of all relevant stakeholder groups (e.g., natural scientists, social scientists, practitioners, First-Nations, community organizations, and industrial partners). The group should meet regularly to discuss relevant research priorities, identify salient themes for information needs, and set priorities for knowledge co-production. Ultimately, this may be a critical step towards building the necessary capacity to effectively facilitate knowledge exchange across the science-policy boundary by ensuring the policy- and management- relevance of research.

This research represents a novel attempt at integrating the human and ecosystem dynamics of prairie lakes by adopting an interdisciplinary research approach. However, I acknowledge limitations associated with the level of detail of this study, as it does not cover the complete array of prairie lake SES attributes. The complex nature of SES, and resource constraints (including time and personnel) limit the capacity of a single study to obtain all the necessary information. To address this issue, future studies would benefit from a detailed socio-economic (e.g., financial, econometric) analysis of the loss of revenue to the province if walleye are unable to survive in these lakes under future conditions.
Benthic production in this study was estimated using the productivity model of (Vadeboncoeur et al. 2008). This approach allowed comparison of benthic productivity and fish benthic resource-use in prairie lakes to that in boreal lakes (Vander Zanden et al. 2011). However, this model was developed using parameters for boreal lakes that are generally less productive than prairie ecosystems (Vadeboncoeur et al. 2003). Therefore, future studies examining pelagic and benthic production in prairie lakes may benefit greatly from a productivity model specific to these systems. The model parameters should account for the shallow depth, large littoral areas, and high trophic status characteristic of these lakes (Rawson and Moore 1944a, Hammer 1986).

In this study, the status of fish populations was assessed using resource-use, body condition, and parasite load. Future work focused on developing a modified fish health assessment index (FHAI) for prairie lakes will be especially useful for researchers and managers, help identify effects of changing environmental conditions on fish populations, and enact regulations in a timely manner. FHAI, first developed by (Adams et al. 1993), is a comprehensive quantitative index that can be applied across water bodies; it uses individual index values of numerous indicators (e.g., parasites, skin condition) to compare mean population statuses over time. Previous studies have modified FHAI to increase its applicability at different sites (Schleiger 2004). Ideally, such an FHAI database for prairie lakes should include additional high complexity lakes with game fishes and different age-classes of fishes, as adults and juveniles may respond differentially to changing environmental conditions (Mélard et al. 1996, Wang et al. 2009).
Finally, exploiting lake users’ interest in participating in citizen science may be a useful method for fostering interest in prairie lakes and closing knowledge gaps. Citizen scientists may assist with various aspects of lake protocols, including collecting necessary samples. A thorough analysis of potential challenges (e.g., poor data quality) and strategies for overcoming them may help ensure the sustainability (e.g., volunteers lose interest) of such an effort (Conrad and Hilchey 2011, Nanayakkara et al. 2017). Additionally, following the models of successful programs such as Lakewatch in Florida, USA (Hoyer et al. 2012) and the Lake Partner Program in Ontario, Canada (Weyhenmeyer et al. 2017) may prove a useful starting point for a region-wide citizen science initiative.
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Improving the science-policy dialogue to meet the challenges of biodiversity

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Concept and explanation

I. Species

- List of eight invasive species.
- Three fishes*: common carp (*Cyprinus carpio*), goldfish (*Carassius auratus*), and koi (domesticated ornamental varieties of *Cyprinus carpio*).
- Three plants*: flowering rush (*Butomus umbellatus*), salt cedar (*Tamarix ramosissima, Tamarix chinensis, Tamarix parviflora*), and purple loosestrife (*Lythrum salicaria*).
- Two mussels: zebra mussels (*Dreissena polymorpha*), and quagga mussels (*Dreissena bugensis*).

II. Presence/Absence

- All fish and plant organisms present, and mussels absent in Saskatchewan at the time surveys were administered.
- Assessed using “yes/no/don’t know” answers to inquiry about awareness of presence/absence of organism.

III. Impact

- Organisms listed in the survey have negative impacts on invaded aquatic ecosystems.
- Assessed using “positive/negative/don’t know” answers to inquiry about impact of organisms. **Increased water clarity due to mussel presence is an example of a positive impact while decreased biodiversity and habitat loss are examples of negative impacts.**

IV. Mussels

- Zebra and quagga mussels are particularly destructive invasive species with far reaching consequences on invaded habitats and regional economies. Therefore, success/failure of government outreach efforts to increase public knowledge of mussels was assessed using yes/no answers to inquiry about awareness of two mussels.
V. Open-ended Questions

- How to clean a contaminated boat, inquired about procedure to clean a boat contaminated with zebra or quagga mussels.
- Who to contact, inquired about who should be contacted if mussels are discovered on boat.
APPENDIX 2. Operational definitions of predictor variables considered in the multivariate analyses, PLUMS 2015-2016.

Variable label and explanation

I. Socio-Demographic Factors

- **Sex**, a discrete, nominal variable. Female is the reference category.
- **Age**, a continuous, interval/ratio variable that inquired about age at time of survey.
- **Residence**, self-reported variable that indicates town/city/rural municipality of residence at time of survey. Medium-to-large population center – population of 30,000 or more is the reference category.
- **Race**, a discrete, nominal variable (White vs. Others). Other is the reference category.
- **Level of Education**, self-reported variable that indicates highest level of education at time of survey.
- **Socio-economic status** (SES), reported as self-perceived value on a five-point Likert scale item (1 = “low SES” and 5 = “high SES”).

II. Situational/Contextual Factors

- **Geographic region**, three, separate questions that inquired about lake-use in each of all three regions. These were combined into one variable, containing the following responses: A_Diefenbaker – Qu’Appelle system; B_South Diefenbaker QuAppelle; C_North Diefenbaker QuAppelle; Two different lake regions were used; and All three lake regions were used. Diefenbaker – Qu’Appelle system is the reference category.
- **Lake-use purpose**, seven, separate “yes/no” items that inquired about purposes of lake-use by geographic region.

III. Knowledge Factors

- **Eutrophication** (“yes/no”), refers to increased algal production due to increased nutrient inputs from watershed.
- **Winterkill** (“yes/no”), refers to increased fish mortality over winter due to increased biological oxygen demand (especially in eutrophic lakes).
- **Extraction** (“yes/no”), refers to extraction of water from lakes for industrial, agricultural and municipal purposes.
APPENDIX 3. Frequency and percent of lake-use by region, PLUMS 2015-2016.

<table>
<thead>
<tr>
<th>Region</th>
<th>Frequency</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>36</td>
<td>7.6</td>
</tr>
<tr>
<td>Diefenbaker – Qu’Appelle</td>
<td>98</td>
<td>20.6</td>
</tr>
<tr>
<td>South of Diefenbaker – Qu’Appelle</td>
<td>64</td>
<td>13.4</td>
</tr>
<tr>
<td>North of Diefenbaker – Qu’Appelle</td>
<td>67</td>
<td>14.1</td>
</tr>
<tr>
<td>Two lake regions</td>
<td>129</td>
<td>27.1</td>
</tr>
<tr>
<td>All three lake regions</td>
<td>82</td>
<td>17.2</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>476</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>
APPENDIX 4. Profiles for the respondents’ lake-use by region, including significant Chi-squared results for region differences, PLUMS 2015-2016. Valid percent (%, first row) and frequency (n, second row). *p<0.05; **p<0.01; + few cases.

<table>
<thead>
<tr>
<th>Purpose (yes)</th>
<th>Lake region</th>
<th></th>
<th></th>
<th></th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diefenbaker – Qu’Appelle</td>
<td>South of Diefenbaker – Qu’Appelle</td>
<td>North of Diefenbaker – Qu’Appelle</td>
<td>Two lake regions</td>
<td>All three lake regions</td>
</tr>
<tr>
<td>Fishing*</td>
<td>73.5% N = 72</td>
<td>60.9% N = 39</td>
<td>77.6% N = 52</td>
<td>81.4% N = 105</td>
<td>82.9% N = 68</td>
</tr>
<tr>
<td>Swimming</td>
<td>72.4% N = 71</td>
<td>75.0% N = 48</td>
<td>65.7% N = 44</td>
<td>68.2% N = 88</td>
<td>70.7% N = 58</td>
</tr>
<tr>
<td>Boating*</td>
<td>75.5% N = 74</td>
<td>85.9% N = 55</td>
<td>61.2% N = 41</td>
<td>76.0% N = 98</td>
<td>70.7% N = 58</td>
</tr>
<tr>
<td>Recreation</td>
<td>72.4% N = 71</td>
<td>67.2% N = 43</td>
<td>59.7% N = 40</td>
<td>62.8% N = 81</td>
<td>63.4% N = 52</td>
</tr>
<tr>
<td>Work*</td>
<td>7.1% N = 7</td>
<td>4.7% N = 3</td>
<td>7.5% N = 5</td>
<td>6.2% N = 8</td>
<td>18.3% N = 15</td>
</tr>
<tr>
<td>Farm+</td>
<td>3.1% N = 3</td>
<td>1.6% N = 1</td>
<td>0.0% N = 0</td>
<td>1.6% N = 2</td>
<td>1.2% N = 1</td>
</tr>
<tr>
<td>Cabin**</td>
<td>35.7% N = 35</td>
<td>59.4% N = 38</td>
<td>44.8% N = 30</td>
<td>30.2% N = 39</td>
<td>36.6% N = 30</td>
</tr>
</tbody>
</table>
APPENDIX 5. Frequency and percent results for awareness of non-native mussels, PLUMS 2015-2016. *4 respondents did not answer; ++8 respondents did not answer.

<table>
<thead>
<tr>
<th>Have you heard about?</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency</td>
<td>Percentage (%)</td>
</tr>
<tr>
<td>Zebra mussels⁺</td>
<td>378</td>
<td>86.7</td>
</tr>
<tr>
<td>Quagga mussels⁺⁺</td>
<td>141</td>
<td>32.6</td>
</tr>
</tbody>
</table>
APPENDIX 6. Copy of ethics approval (File #87S1213) issues by the University of Regina Research Ethics Board

OFFICE FOR RESEARCH, INNOVATION AND PARTNERSHIP
MEMORANDUM

DATE: June 18, 2013
TO: Lushani Nanayakkara
   4602 Queen St.
   Regina, SK S4S 5Y9
FROM: Dr. Larena Hoeber
       Chair, Research Ethics Board
Re: Saskatchewan Lake Use and Management Survey (File # 87S1213)

Please be advised that the University of Regina Research Ethics Board has reviewed your proposal and found it to be:

☐ 1. APPROVED AS SUBMITTED. Only applicants with this designation have ethical approval to proceed with their research as described in their applications. For research lasting more than one year (Section 1F), ETHICAL APPROVAL MUST BE RENEWED BY SUBMITTING A BRIEF STATUS REPORT EVERY TWELVE MONTHS. Approval will be revoked unless a satisfactory status report is received. Any substantive changes in methodology or instrumentation must also be approved prior to their implementation.

☐ 2. ACCEPTABLE SUBJECT TO MINOR CHANGES AND PRECAUTIONS (SEE ATTACHED). Changes must be submitted to the REB and approved prior to beginning research. Please submit a supplementary memo addressing the concerns to the Chair of the REB. ** Do not submit a new application. Once changes are deemed acceptable, ethical approval will be granted.

☐ 3. ACCEPTABLE SUBJECT TO CHANGES AND PRECAUTIONS (SEE ATTACHED). Changes must be submitted to the REB and approved prior to beginning research. Please submit a supplementary memo addressing the concerns to the Chair of the REB. ** Do not submit a new application. Once changes are deemed acceptable, ethical approval will be granted.

☐ 4. UNACCEPTABLE AS SUBMITTED. The proposal requires substantial additions or redesign. Please contact the Chair of the REB for advice on how the project proposal might be revised.

Dr. Larena Hoeber

cc: Dr. Bjoern Wissel - Biology

** supplementary memo should be forwarded to the Chair of the Research Ethics Board at the Office for Research, Innovation and Partnership (Research and Innovation Centre, Room 109) or by e-mail to research.ethics@uregina.ca

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160