PHYSICAL HABITAT ASSOCIATIONS OF FISH SPECIES IN THE KIVALLIQ REGION OF NUNAVUT, CANADA

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Abstract

The Canadian arctic and subarctic (areas north of 60° latitude) support distinct aquatic environments governed by the unique geomorphology and climate of the region. Historically, fish and fish habitat impacted by development activities in this region have been assessed using literature derived from southern populations. Using these assumptions from southern populations on environmental impact assessments for northern regions may not accurately capture differences in physical fish habitat associations. To better characterize northern habitat associations for use in northern environmental assessments, this study sought to achieve three objectives. First, to determine patterns in the depth of occupancy of a model species, Lake Trout, using two databases in Canada, comparing northern and southern regions. Second, to provide an assessment of freshwater fish habitat associations in 11 species specific to the Kivalliq region of Nunavut. Finally, where feasible, to develop Habitat Suitability Indices (HSI) with northern-specific data based on these associations. To achieve these goals, a novel method of estimating depth-of-occurrence was developed and applied to an analysis of standardized fish capture data from both arctic and Ontario (southern) lakes. Habitat association data sourced from populations north of 60° was then used to develop evidence-based arctic-specific HSI values for comparison to the existing Habitat Ecosystem Assessment Toolkit (HEAT) model. Depth-of-occurrence analysis indicated significant differences in the abundance of Lake Trout between northern and southern regions, but not significant differences in habitat associations with depth. However, the results of HSI analysis integrating information from several peer-reviewed studies indicated significant differences in depth patterns across latitude for both Lake Trout and

Burbot; both species had stronger associations with depth in Ontario (southern) lakes across three life stages (adult/juvenile, young-of-the-year and egg/spawning) relative to the arctic, suggesting that depth may indeed more strongly shape habitat associations in southern vs. northern populations. No other species had sufficient data to facilitate quantitative analysis, however, qualitative descriptions of northern habitat associations were summarized where feasible. Conclusions from this study demonstrate potential differences in fish habitat associations between northern and southern regions but a larger sample size of lakes will be required north of 60° latitude to make a determination. Region-specific habitat association models are recommended, along with increased observations and study of fish-habitat associations in the north, as this study highlights many data gaps that exist for several species in establishing HSI models specific to arctic freshwater fishes in the arctic.

Keywords: *Canadian arctic, Broadscale Monitoring, Fish-Out, habitat associations*

Lay Summary

The Habitat Ecosystem Assessment Toolkit (HEAT) was created in the early 1990s, and was designed to assess harmful impacts on lake ecosystems. These activities were often due to human-based construction projects in sensitive coastal wetlands throughout the Ontario Great Lakes region. The model uses exact measures of environmental disturbances, such as shoreline protection or open-pit mining, to assess the net changes of three physical habitat features (depth, bottom-type and vegetation or cover) during environmental impact assessments. The focus of the current study was to assess the validity of physical fish habitat associations in the HEAT model (based on Ontario fish-habitat associations) for use in arctic regions, north of the 60th parallel. The objective was to understand what changes may need to be made to fish-habitat associations within the HEAT model to determine it's applicability outside of the Great Lakes region to other regions across Canada. Depth of occupancy was chosen for the main analyses of habitat associations to complement the HEAT Habitat Suitability Index (HSI) analyses, due primarily to availability of data. This study investigated three research questions:

1. What are the physical habitat associations of 11 common fish species local to the Kivalliq (arctic) region watershed?

2. Are Lake Trout found at different depths in arctic lakes compared to Ontario lakes?

3. Are there differences across Habitat Suitability Index (HSI) values of Lake Trout and Burbot for a depth model in HEAT depending on the region of origin?

Results of this study showed that Lake Trout were significantly more abundant in northern populations compared to southern populations, but that depth-based habitat associations were not region-specific. However, Lake Trout and Burbot had significantly stronger depth associations in Ontario regions than in the arctic region across all three life stages. Since there was not enough data to allow for a statistical analysis of all 11 fish species in the Kivalliq region watershed, a descriptive approach was used. These results suggest a region-specific approach to understanding impacts on habitat change may improve the overall quality of environmental impact assessments across Canada. This research provides a summary of the current state of knowledge on fish habitat associations in the Canadian arctic, on which future research can use to build region-specific HEAT models.

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Glossary

Amaruq – An open-pit gold mine established in 2017 in the Kivalliq region of Nunavut operated by Agnico-Eagle Mines Ltd. which was visited by the primary author for reconnaissance research.

BsM – Broadscale Monitoring

CEE – Collaboration for Environmental Evidence

DM – Defensible Methods

EIAs – Environmental Impact Assessments

FO – Fish-Out

HAAT – Habitat Alteration Assessment Toolkit

HEAT – Habitat Ecosystem Assessment Toolkit

HSI – Habitat Suitability Index

Kivalliq – Southwestern region of the territory of Nunavut

Laurentian Great Lakes – Great Lakes basin that boarders Ontario and the United States in the St. Lawrence River watershed.

Mackenzie Great Lakes – Great Lakes basin within the Northwest Territories in the Mackenzie River Valley watershed.

Meadowbank – An open-pit mine established in 2002 in the Kivalliq region of Nunavut operated by Agnico-Eagle Mines Ltd. which was visited by the primary author for reconnaissance research.

NNL – No Net Loss

Proponent – An individual interested in carrying out a work, undertaking or activity in Canadian fish-bearing waters.

Semi-systematic review – A partial systematic literature review shortened in scope.

WMSs – Wildlife Management Strategies

1. Chapter 1 – Fish habitat associations of species in the Kivalliq region of Nunavut, Canada

1.1 General Introduction

Freshwater fish habitat in the Canadian arctic is widely regarded as a precious natural resource of fleeting refuge due to warming temperatures in temperate environments. Climate change has impacted arctic ecosystems more adversely in the past decade than ever before (Reist *et al*., 2006). In recent history, unprecedented atmospheric temperatures have been observed coincident with a dramatic increase in development activities such as open pit mining for minerals such as iron ore, gold and diamonds. These activities frequently result in the disturbance or total destruction of aquatic resources because these geological formations are known to occur beneath inland water basins and/or require water for transportation from mining sites to refinery facilities.

The average mining operation in the Canadian arctic exists for 15 to 25 years before being decommissioned. As a result, their potential to directly threaten the health, quality and function of freshwater resources remains significant. During the lifetime of these development projects, from claiming the land to creating the product and reclamation, industry representatives (also known as 'the Proponent') interested in doing a work, undertaking or activity in fish-bearing waters must consult with interested stakeholders and the public as regulated under Canadian legislation, including the *Canadian Impact Assessment Act*, *Arctic Waters Pollution Prevention Act*, the *Species at Risk Act* and the *Fisheries Act*. As such, proponents that provide regional economic stimulation and jobs for local Indigenous communities must also actively consult with federal and provincial agencies to implement environmental impact assessments (EIAs) and wildlife management strategies (WMSs). If well documented and implemented thoughtfully, data generated from these EIAs and WMSs have the potential to provide researchers with opportunities to better understand patterns in fish and wildlife populations and their interaction with the physical environment.

Regulatory agencies, such as Fisheries and Oceans Canada, put the onus on the Proponent to provide evidence that the impacts caused by development can be countered by appropriate compensation measures, also known as offsetting, under the *Fisheries Act*. For example, before a proposed open pit area can be dewatered, the Proponent is obligated under the provisions of the *Fisheries Act* to prevent causing death of fish by means other than fishing and identify measures to avoid and mitigate harmful alteration, disruption or destruction of fish habitat. As an aspect of compensation measures during a whole-lake destruction, 'fishing-out' the existing lake and simultaneously collecting complementary fish habitat data (which may be useful for the future scientific research), Proponents are able to partially satisfy the conditions pertaining to offsetting within a *Fisheries Act* authorization. This occurs when the Minister of Fisheries and Oceans approves of the impact given the proposed mitigation and offset measures included in the project plans (Tyson *et al*., 2011).

In order to make use of these data, study design should be standardized, carefully considered and data collection well documented. Proper planning is vital to set landmarks required for evaluating the effectiveness of compensation measures post-construction. Unfortunately, these standards are not rigorously applied or independently evaluated across arctic ecosystems; were this to occur, it would greatly aid in operationalizing scientific data collected during a *Fisheries Act* authorization process. This is not the only instance where data collection exercises could be included in project plans to benefit the greater body of knowledge on the development area; for instance, if physical habitat restoration or creation is not feasible, then complementary offsetting in the form of scientific research projects are commonly used as an alternative (DFO, 2019). When data are collected carefully, with a clear study design, their potential contribution to the longevity and function of Canadian natural resources increases dramatically. These data aid in developing evidence-based tools which are critical as they are used to inform best management practices for contractors working in fish bearing waters.

1.1.1. Quantitative assessment of impacts to fishes and their habitats in Canada

Development activities in or near Canadian waterways are federally regulated by the *Fisheries Act* (2019) and the *Species at Risk Act* (2002) which are implemented following the original guidelines set out in the *Policy for the Management of Fish Habitat* (1986). The guiding principle of the 1986 policy – that has remained mostly unchanged since it was introduced into Canadian legislation – was to ensure no-net-loss (NNL) of fish habitat productivity in Canadian waters. To achieve the goals of this mandate, a variety of evidence-based modelling tools were developed. They are used to objectively assess habitat and the potential offsetting measures in lacustrine and riverine environments across Canada (Minns *et al*., 1997; Hughes *et al*., 1998; Minns *et al*., 1999). For example, the Defensible Methods calculation model can be run using several different ecosystem components including individual species, trophic level, or whole ecosystem productivity (Minns *et al*., 1999). All models used in NNL evaluations allow for the same essential question to be posed and answered multiple ways: "how good is a specific habitat for a fish species in Canada within the context of impact assessments?" (De Kerckhove *et al*., 2008). Models used to address NNL have included (but are not limited to) Habitat Suitability Indices, Bioenergetics Models, Individual-Based Models, Habitat Productivity Indices and Trophic Models (Trial and Nelson, 1983; Randall, 2003). In the 1990s, scientific consultants and researchers began applying these tools to quantify proposed projects or activities and their potential impacts (or losses) and offsetting (or gains) in the context of development activities on aquatic ecosystems. Fish habitat supply (or productivity) were often estimated as benchmark responses in these exercises as they were frequently referenced by fishery management objectives.

In Canada, the Defensible Methods approach was the first modelling tool of its kind to evaluate the losses and gains of lacustrine freshwater fish habitat during the assessment process of proposed development activity (Minns *et al*., 1999). Since its inception, the Defensible Methods protocol has been refined and is now known as the Habitat/Ecosystem Assessment Toolkit (HEAT). Currently, HEAT can be applied as part of the regulatory assessment process to evaluate the Weighted Suitable Area (WSA) changes (i.e. site-specific loss versus gain) based on Habitat Suitability Index (HSI) values in the Laurentian (Ontario) Great Lakes region using an online tool. Physical habitat attributes including depth, substrate, vegetation (or cover) and thermal guilds (i.e. warm water, cool water and cold water) in lacustrine environments are considered to evaluate site-specific whole-fish-community changes based on ecosystem perturbations (www.habitatassessment.ca DFO, January 31, 2020). Development of HEAT has been ongoing to include 1) additional variables, such as water level fluctuations and dissolved oxygen, and 2) a larger spatial focus to include areas beyond the Laurentian Great Lakes (Doka, 2017). A comprehensive literature review of habitat associations in the lacustrine life history of Ontario Great Lakes fishes during the adult/ juvenile, young-of-the-year/nursery and egg/spawning life stages, which informed the HEAT model, were used to parameterize the current online version of the toolkit (Lane *et al*., 1996a, b, c).

1.1.2. Fish habitat heterogeneity across Canada

Out of 158 fish species that occupy Canadian freshwaters, 99 occur in the arctic (Reist *et al*., 2006) and several of which are exclusive to arctic regions such as the Arctic Char (*Salvelinus alpinus*) and Arctic Grayling (*Thymallus arcticus*). Within species, there may be ecological specializations across Canada described by individual life cycle affinity to freshwater or to both fresh and sea water (i.e. anadromy), differences in nearshore or offshore habitat usage and differences in their main food sources (Reist *et al*., 2006). On a landscape scale, there are clear differences between temperate and arctic habitats that may influence fish habitat associations. For example, Canadian arctic/subarctic lacustrine nearshore habitats are dominated by boulder substrate with interstitial spaces and little to no vegetation (Callaghan *et al*., 2016); in contrast, temperate nearshore habitats are known to be patchy with variable substrate and vegetation (Doka *et al*., 2004).

Regulatory biologists that provide guidance and oversight on development projects in Canada refer to the most recent literature reviews of fish habitat associations which provide an accurate account of basic biological functions in all fishes across North America (Scott and Crossman, 1998; Holm *et al*., 2009). In Canada, industrial developments north of 60º latitude often lead to the harmful alteration of watersheds due to the vast number of inland freshwater lakes in the region per unit land area (similar geographically to the Dryden and Thunder Bay areas of northwestern Ontario). To ensure that fishery management decisions are based upon the best available evidence in arctic ecosystems, biological assessment of impacts in these ecosystems should be based on geographically relevant syntheses of available literature on fish and fish habitat (McPhail and Lindsey 1970). It has been almost two decades since the most recent synthesis of fish habitat associations for lacustrine ecosystems in the arctic was completed by Richardson *et al*., (2001) and for riverine environments by Evans *et al*., (2001). However, these syntheses included literature sources from both arctic and southern environments. In both cases, rather than highlighting existing gaps in northern environments in these assessments, missing information for arctic populations was simply informed by data from southern populations (Lane *et al*., 1996a, b, c). While this approach provided a starting point for habitat associations for arctic populations, the assumption that species-habitat associations were similar between Great Lakes and arctic populations remains a largely untested assumption. For better or worse, given the lack of information on species-habitat associations in the arctic at that time, most of these habitat associations subsequently used in freshwater arctic environmental assessments became guided by information from southern populations.

1.1.3. Fish habitat associations of the Canadian arctic

Freshwater fish habitats in the Kivalliq region of southwestern Nunavut are experiencing more development pressure than ever before from mining projects (Agnico-Eagle, 2018). The most significant fisheries in Nunavut are associated with Inuit communities that rely in varying degrees on their continued production; subsistence fishing contributes significantly to the Inuit culture for food security, while commercial fisheries operated by

Inuit communities have a significant impact on local economies (Rixen and Blangy, 2016). The subsistence fishery of Arctic Char alone averaged 200,000 kg per year between 1996 and 2001 in the Kivalliq region, while the commercial fishery harvested approximately 155,600 kg per year between 2011 to 2012 (Cott *et al*., 2016). Increased development activity has also provided additional opportunities to collect new data from these regions. For example, whole-lake destruction of fish habitat in the arctic has had a significant adverse impact on important freshwater fisheries and their refuge habitats (Mason *et al*., 2009; Rixen and Blangy, 2016). As a result, existing fish habitat models that rely primarily on information from populations in southern distributions have been heavily debated as to their utility in estimating the impact of these activities when determining best management practices in northern environments. Most notably, the development activities associated with impacts to marine fishes near Baffinland have been an ongoing point of discussion among federal regulators and the Nunavut Impact Review Board (NIRB); the apparent lack of regionally-specific scientific knowledge on fish habitat associations and suitability models north of 60° latitude were highlighted as a major deficiency in these assessments. For example, the Proponent developed a plan to monitor the impacts of increased shipping activity from 50 ships annually to 185 ships annually (Megannety, 2011). The scientific professionals and expert witnesses involved in the hearings that inform the NIRB decision-makers were highly uncertain about the adequacy of the proposed sampling design and mitigation measures meant to conserve the populations and habitats impacted by the proposed activities because of the lack of region-specific information on biota. Scenarios of this nature highlight the uncertainty commonly involved in EIAs that occur in isolated arctic regions of Canada.

1.1.4. Fish species of the Kivalliq region watershed

Of the 99 species belonging to 48 genera of freshwater and diadromous (i.e. anadromous and catadromous forms) fishes in the Canadian arctic region (Reist, *et al*., 2006), this thesis focused on 11 lacustrine fish species that inhabit or are in close proximity to the Kivalliq region, represented by 3 families (Table 1.1).

Table 1.1 - Fish list of species local to the Kivalliq region of Nunavut that comprise the focus of this study in varying capacities.

Common Name	**Scientific Name**	**Family**	**Trophic Preference**
Lake Trout	*Salvelinus namaycush*	Salmonidae	Piscivore
Lake Whitefish	*Coregonus clupeaformis*	Salmonidae	Non-Piscivore
Lake Cisco	*Coregonus artedi*	Salmonidae	Non-Piscivore
Round Whitefish	*Prosopium cylindraceum*	Salmonidae	Non-Piscivore
Arctic Char	*Salvelinus alpinus*	Salmonidae	Piscivore
Arctic Grayling	*Thymallus arcticus*	Salmonidae	Piscivore
Bull Trout	*Salvelinus confluentus*	Salmonidae	Piscivore
Dolly Varden	*Salvelinus malma*	Salmonidae	Piscivore
Ninespine Stickleback	*Pungitius pungitius*	Gasterosteidae	Non-Piscivore
Burbot	*Lota lota*	Gadidae	Piscivore
Slimy Sculpin	*Cottus cognatus*	Cottidae	Non-Piscivore

This species list was determined based upon tertiary watershed distribution information (Mandrak *et al*., unpub data) and expert input (Portt *et al*., 2015; Working Group NWT, 2016). All the families represented in the arctic were also present in lower-latitude temperate and sub-temperate regions; the average spatial extent of their distribution for all species investigated here were south of 60° latitude, except for Arctic Char (Berra, 2001). The species present in the Kivalliq region represent a combination of historical factors (e.g. glacial activity, post-glacial recolonization routes and access) as well as present day stressors (e.g. climate change, habitat diversity and ecological processes) in the environment. The Salmonidae are the most species-rich family in the Kivalliq region with eight species present. Arctic Char are the only species under consideration that has a Holarctic distribution, being present on all landmasses in arctic regions around the globe. Arctic Char also exhibited the widest latitudinal distribution range (about 40 degrees) among all true arctic species as it displays the most northerly distribution of any freshwater fish in Canada (Scott and Crossman, 1998). A few additional species are distributed almost completely across the Holarctic region but are absent in one or more areas (e.g. Burbot, 75%; Lake Whitefish, ~85% of a whole circumpolar distribution). Except for Ninespine Stickleback and Slimy Sculpin, all species considered here are fished extensively where they occur and represent the mainstays of sustenance fisheries for northern communities (Reist *et al*., 2006).

1.1.5. Study objectives and research hypotheses

The focus of this thesis was to apply the principles of the Habitat Ecosystem Assessment Toolkit (HEAT) beyond the Ontario Great Lakes region and explore the suitability of regional models for use in a specific area with emphasis on applications in the Canadian arctic. In this study, physical habitat associations of northern (north of 60° latitude), freshwater, lacustrine fish species in the Kivalliq region of Nunavut, Canada were analysed and compared with southern populations that exist south of 60° latitude, specifically in the northwest region of Ontario, to evaluate potential differences in habitat associations between northern and southern populations. This was conducted to understand the implications of applying southern habitat associations on northern populations, as habitat associations for southern populations may not provide an accurate assessment of habitat associations of the same species in northern environmental conditions.

Sources of literature for northern fish distributions published after the last major synthesis by Richardson *et al*., (2001) were used to identify and extract physical habitat association data for northern populations (i.e. post-2000). The major criticism of the Richardson *et al*., (2001) document was that it was mostly based on southern habitat associations, even though it was meant to characterize northern environments. The information that was arctic-specific was extracted from this document and included in the current analyses. Two fish habitat databases, one sourced from north and other from south of 60° latitude, were also analysed to compare the depth-of-occupancy across latitude (an important habitat association metric used in EIAs and WMSs) of a model species (Lake Trout) between regions. Depth was the main factor that determined differences in distribution patterns across HEAT models because it could be estimated from data sourced for this thesis in sufficient quantity and provided baseline insights into Habitat Suitability Index (HSI) variability across latitude in HEAT models (Rennie *et al*., 2015, Doka, 2017). These findings were used to compare the accuracy of results produced by an arctic HEAT model relative to the HSI values used in the Ontario Great Lakes basin. An individual-species analyses was developed for each region to compare the HEAT base tables for two model species (Lake Trout and Burbot).

This study tested the following hypotheses:

1. Populations of fish species in the Canadian arctic region (i.e. north of 60° latitude) will be significantly more abundant, but will not significantly differ across depth

strata compared to southern populations during the ice-free season due to the ephemeral availability of prey in littoral zones and lack of thermal structure in freshwater arctic environments.

2. The Habitat Ecosystem Assessment Toolkit (HEAT) Habitat Suitability Index (HSI) derived from the Ontario model will have significantly different probability of habitat associations across both species, all depth categories and all life stages, relative to the arctic HSI values due to a greater quantity of evidence south of 60° latitude.

The outcome of this study was anticipated to: 1) provide an assessment of relevant, recent scientific literature available to inform freshwater fish habitat associations in the arctic, 2) assess knowledge gaps and differences in habitat associations across two regions of Canada and 3) develop a HEAT HSI model based on data exclusively from the Canadian arctic region.

2. Chapter 2 –Lake Trout depth-of-occupancy in northern and southern populations of Canada

Abstract

Southern fish habitat associations have been used in the impact assessments of northern populations, however the assumption that species-habitat associations were similar across these regions of Canada remains largely untested. Two datasets representing Ontario and arctic fish populations were selected along with their habitat associations to meet this objective. Depth-of-occupancy (which was represented in both data sets) was selected as the model habitat variable for analysis. The arctic Fish-Out database was selected for areas north of 60° latitude and the Ontario Broadscale Monitoring database was selected for areas south of 60° latitude, with a focus on the northwestern region of Ontario. Catch rates in 5m depth intervals were analysed. Results indicate that while Lake Trout were generally more abundant in northern versus southern regions, their distribution was similar across depth ranges between lakes north of 60° latitude as they were in southern populations. In conclusion, this study indicates Lake Trout fish populations in northern regions occur at similar positions in the water column in northern and southern regions. While future research is likely required to expand the current scope of this study and encompass a greater sample size of lakes with more habitat features, this work provides a template for how such comparisons might be undertaken.

2.1 Introduction

2.1.1 Distinct features of Canadian arctic freshwater ecosystems

Fish and fish habitat data collected from the Canadian arctic are extremely valuable because of increasing pressures from multiple sources in the region including climate change, remote settings, and limited infrastructure; these data are essential to resource managers tasked with understanding the extent and state of suitable freshwater fish habitat for any given species in the arctic region of Canada. Polar environments are unique and support species adapted to these conditions. Periods of everlasting light and dark conditions for months at a time, ice cover for the majority of each calendar year, limited vegetation in tundra regions, a lack of habitat complexity in conditions of negligible turbidity and ephemeral prey availability for non-piscivorous species (Holeton, 1974; Reist *et al*., 2006). These unique qualities, coupled with the logistic challenges involved in highly remote data collection, mean that there is very little information available about the ecological patterns and adaptations of fish species that occupy these environments relative to other regions of Canada. If scientific information on fish and fish habitats from this area are to be used in resource management decisions, it is recommended individual organisms and their population trends are be studied in a way that maximizes comparability across space and time.

2.1.2 Comparison of fish habitat data collection methods north and south of 60° latitude

Standardized sampling techniques used in more accessible areas, such as Ontario, can be applied in the arctic to achieve comparable information across regions. For example, the Broadscale Monitoring program lead by the Ontario Ministry of Natural Resources and Forestry provides a model framework that could be applied more widely (Sandstrom *et* *al*., 2015). As a component of the environmental mitigation measures incorporated into open-pit mining development projects under the *Fisheries Act*, for example, the Proponent must capture and transfer all fish species from the lake impacted by whole or partial lake destruction to another lake (preferably to a neighbouring waterbody), within the same watershed. Prior to Tyson *et al*., (2011) 'Fish-Outs' were not conducted using any standardized protocol; however, they used the same gill net gear type and remain comparable across space and time. These two datasets, the Fish-Out database (FO) used primarily north of 60° latitude and the Broadscale Monitoring database (BsM), primarily used south of 60°, include data that have used comparable gear types and methods. This facilitates analyses of the preferred depth position of fishes in both regions. In a typical FO dataset, multiple sets of variable mesh gill-nets were allocated throughout the lake randomly for as long as it takes to draw down the populations of fish present and no fish are caught for a period of 24 hours (Tyson *et al.*, 2011). These catch data provide some information about patterns of habitat use in the lakes if the catch data can be accurately paired with habitat data (i.e. depth, temperature, substrate or vegetative cover). Moving forward it will be vital to develop experimental designs that not only complement regulatory requirements but also use standardized methods to provide a better understanding of fish species ecology across latitudinal gradients in Canada.

2.1.3. Prior assumptions of habitat quality and quantity

The majority of knowledge that exists historically on fish habitat in the Canadian arctic region is derived from the Indigenous communities and their traditional knowledge of natural patterns on the arctic tundra. The Indigenous communities in the north, specifically in the Kivalliq region, forage mainly on Caribou populations, however their second source of sustenance is freshwater fish (Minns *et al*., 2019). There are no current or historical commercial operations in freshwater environments throughout the Kivalliq region, however traditional harvesting of the Salmonidae family for sustenance is common. Therefore, Indigenous use of these resources is often the highest priority for Proponents. Traditional knowledge is valuable and is the only asset in impact assessments where western science is not available. The most well-known western science publications that provide a summary of arctic fish habitat use and fish populations was McPhail and Lindsey (1970) until Richardson *et al*., (2001) and Evans *et al*., (2001).

Offsetting for proposed impacts to fish and fish habitat in the arctic region often requires the re-constriction, or new construction of habitat. Fish habitat compensation plans have historically incorporated the construction of overwintering shoal structures from existing haul roads within lake basins, channel staging areas to accommodate riffle-pool morphology or the deepening of existing substrate to create a greater area of deep-water fish habitat (i.e. over 10m). These proposed habitat compensation measures are highly debated between Proponents, stakeholders and regulators due to a lack of information on the efficacy of such measures for the re-introduction of fish species in a flooded pit. Unfortunately, outcomes of these proposed compensation measures are rarely evaluated to determine if they achieve the goals which they are designed to accomplish under DFO's 'no-net-loss' policy guidelines.

2.1.4. Spatial patterns in Lake Trout habitat associations across Canada

Fish habitat associations are hypothesized to be dependent upon the presence or absence of a wide variety of environmental variables, including competition with other species, prey availability and physical habitat structure (Chittaro, 2004). The vast spatial availability of physical habitat in the Laurentian (Ontario) or Mackenzie (Northwest Territories) Great Lakes has been proposed to have led to the potential sub-speciation of Lake Trout species based on the habitat features used during key life cycle functions (i.e. spawning), and variation in colouration or morphology (Challice *et al*., 2019; Chavarie *et al*., 2018). The same analogy could apply to the variation in habitat associations between Great Bear Lake populations and those of inland lakes in Ontario; a case study of Lake Louisa and Redrock Lake of Algonquin Provincial Park by Martin (1952) identified that patterns in physical habitat associations of Lake Trout during the open water season in two Algonquin lakes were likely determined by the presence of appropriate thermal habitat. Lake Trout of polar environments are hypothesized to use their physical habitat in a significantly different pattern than those of temperate environments because they have adapted to extreme conditions and do not experience the same physical limitations in habitat availability (Guzzo *et al*., 2016; Mackenzie-Grieve and Post, 2006). Rather, arctic species are more often limited by prey availability, summer refuge areas and are known to focus more intensely on energy conservation with limited resources in the environment (Portt *et al*., 2015).

2.1.5. Depth as an important habitat variable to measure Lake Trout life cycle associations

Depth-of-occupancy in Lake Trout is a commonly studied habitat parameter as it provides a point of reference to measure species response to other environmental variables, such as changes in water temperatures or community changes in response to the invasion of a non-native species (Rennie *et al*., 2015). If a body of water was large enough, such as Lake Superior or Great Bear Lake for example, species may develop into different morphotypes associated with different depths in the water column (Sitar, *et al*., 2008; Chavarie *et al*., 2018). Lake Trout populations and certain morphotypes from the Laurentian Great Lakes are known to inhabit smaller inland lakes in Ontario (Chavarie *et al*., 2017), and move seasonally with the distribution of the thermocline in search of prey availability and optimal habitat conditions (Martin, 1954). The smaller, inland lakes, that make-up the basis of this study within the arctic environment do not experience thermal stratification in the same manner as the temperate, inland lakes of Ontario (Guzzo *et al*., 2016; Portt *et al*., 2015; Milne, *in prep,* 2019); rather they experience thermal stratification for a shorter period of the year and at much shallower depths, leaving the vast majority of the lake below 7^{O}C during the open water season which is inhabitable for the life cycle processes of the species (Guzzo *et al*., 2016). Depth is also a meaningful habitat parameter that is considered by the Habitat Ecosystem Assessment Toolkit (HEAT; Doka *et al*., 2018). Therefore, patterns in the depth of Lake Trout from two regions in Canada were selected to form the basis of this study and inform the application of HEAT in northern environments.

2.1.6. Objective of the study

In order to determine whether significant differences in fish habitat associations with depth exist between Ontario and arctic lakes, habitat associations of Lake Trout estimated as the proportion of occupancy across 5m depth intervals from two standardized sampling programs – Broadscale Monitoring program (applied south of 60° latitude) and Fish-Out protocol (applied north of 60° latitude) – were compared. In addition, in order to detect patterns across regions in these data, statistics were summarized on the depth distributions of 6 additional fish species from four arctic lakes based on the proportion of occurrence values calculated from the depth intervals derived from HEAT (i.e. 0-1, 1-2, 2-5, 5-10, 10+; Appendix II). In doing so, this study should help form the basis of future literature tables to inform the development of HEAT for arctic environments.

2.2. Methodology

2.2.1 Study locations

The availability of information on depths of net sets in the Fish-Out (FO) database provided the opportunity to analyze 4 lakes throughout Nunavut and the Northwest Territories (Figure 2.1). This included Third Portage Lake (2010), and Second Portage Lake (2008) associated with the Meadowbank gold mine development and Sable Lake (2016) and Two Rock Lake (2016) of the Ekati diamond mine exploration. Additional lakes in this database did not have depth of capture data and therefore were not included. The Broadscale Monitoring (BsM) data selected for this study targeted Lake Trout distribution throughout northwestern Ontario from 6 lakes (Figure 2.2). This included Cry Lake, Castle Lake, Kamikau Lake and Tinto Lake of the Thunder Bay area and Mameigwess Lake and Daniels Lake of the Dryden region. The BsM lakes chosen for comparative analyses were selected from the northwestern region of Ontario because they presented the closest proximity to arctic lakes in the dataset that had bathymetric information including maximum and mean depth of the lake basin, and the presence of Lake Trout. These 6 lakes were chosen randomly from approximately 800 lakes to closely match sample sizes of northern lakes (B. Shuter, pers. comm).

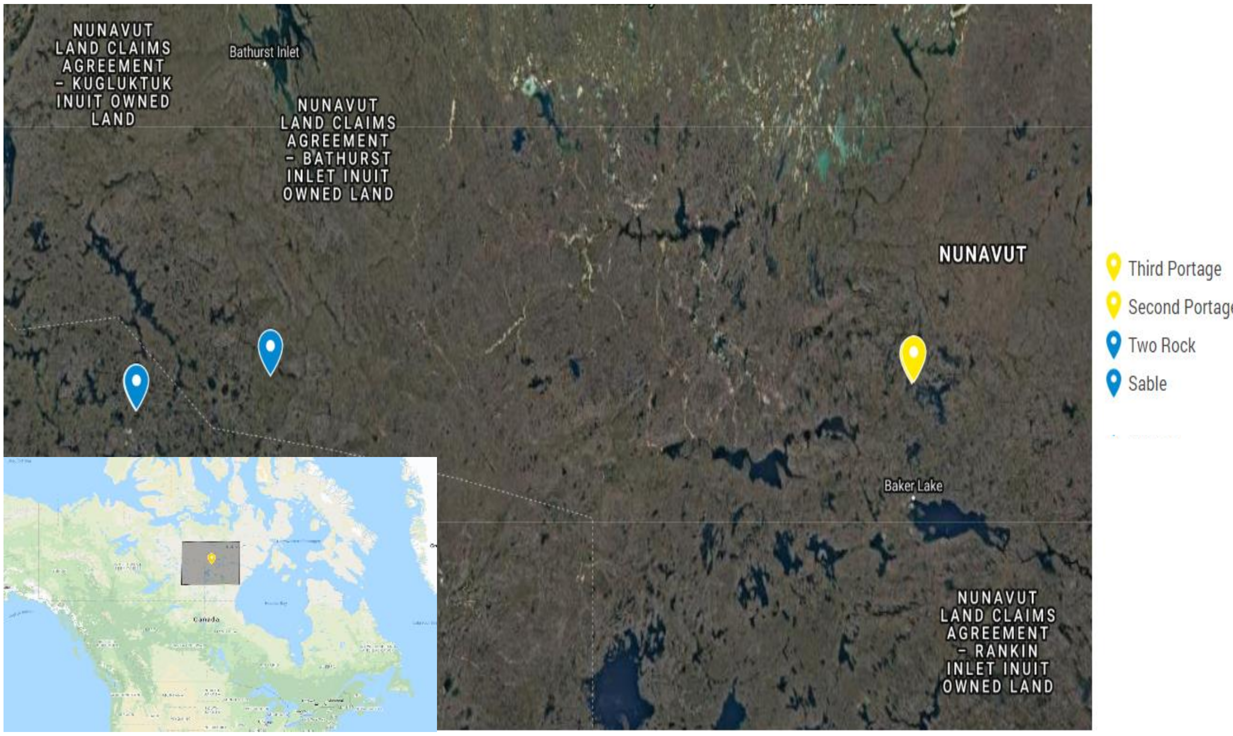

Figure 2.1 – Four lakes that have been fished-out and have data on the physical habitat variable (depth); Meadowbank (yellow) and Ekati (blue) gold and diamond mine development sites, respectively.

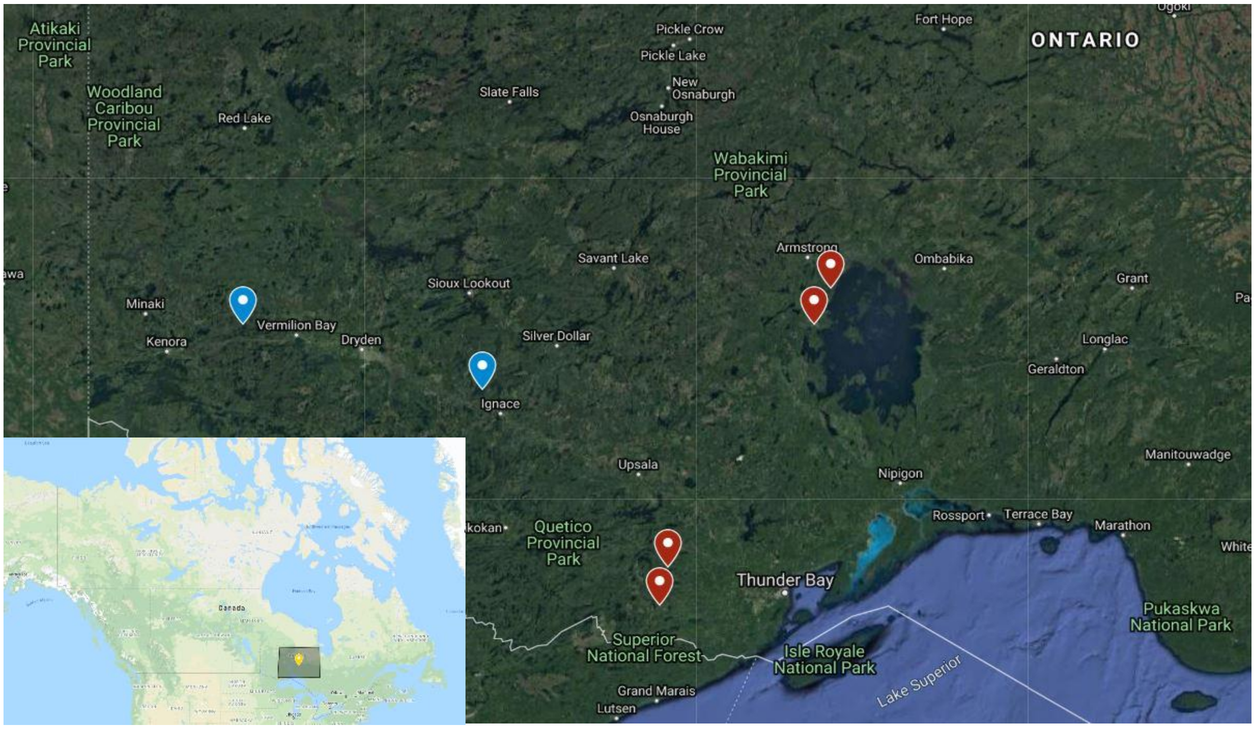

Figure 2.2 – Six randomly-selected lakes from the Dryden (blue) and Thunder Bay (red) regions mentioned in BsM.

2.2.2. Fish-Out protocol north of 60° latitude

If a proposed development activity in Canada results in a whole or partial lake destruction, a 'Fish-Out' program is mandated as a component of the *Fisheries Act* s.35(2) authorization process. Prior to partial or whole lake dewatering, these regulations ensure the fish population in the lakes can be harvested according to the contingency plan within the authorization, known as a 'Fish-Out' (Tonn, 2006). The guiding principle was to ensure that both the ecological data and fish specimens collected can be used to their maximum extent to facilitate scientific studies of patterns across regions without causing undue mortality (Tyson, *et al*., 2011). Like whole lake studies, Fish-Out programs hold the potential to provide a comprehensive source of data on fish populations and their environmental relationships. Since the protocol was developed, a total of 79 lakes have been fished out in total and all are in north of 60° including lakes that pre-date the 2011 protocol (Figure 2.3; K. Hedges, pers. comm). These other lakes were not included in the study due to lack of available habitat data to match net set data. Further examination of the larger dataset is warranted, based on the analysis of four lakes chosen for this study, if the net data could be associated with habitat data. All the Fish-Outs that have been entered into the existing database were associated with the development activity at either Ekati or Diavik diamond mines in the Northwest Territories or the Meadowbank gold mine in Nunavut.

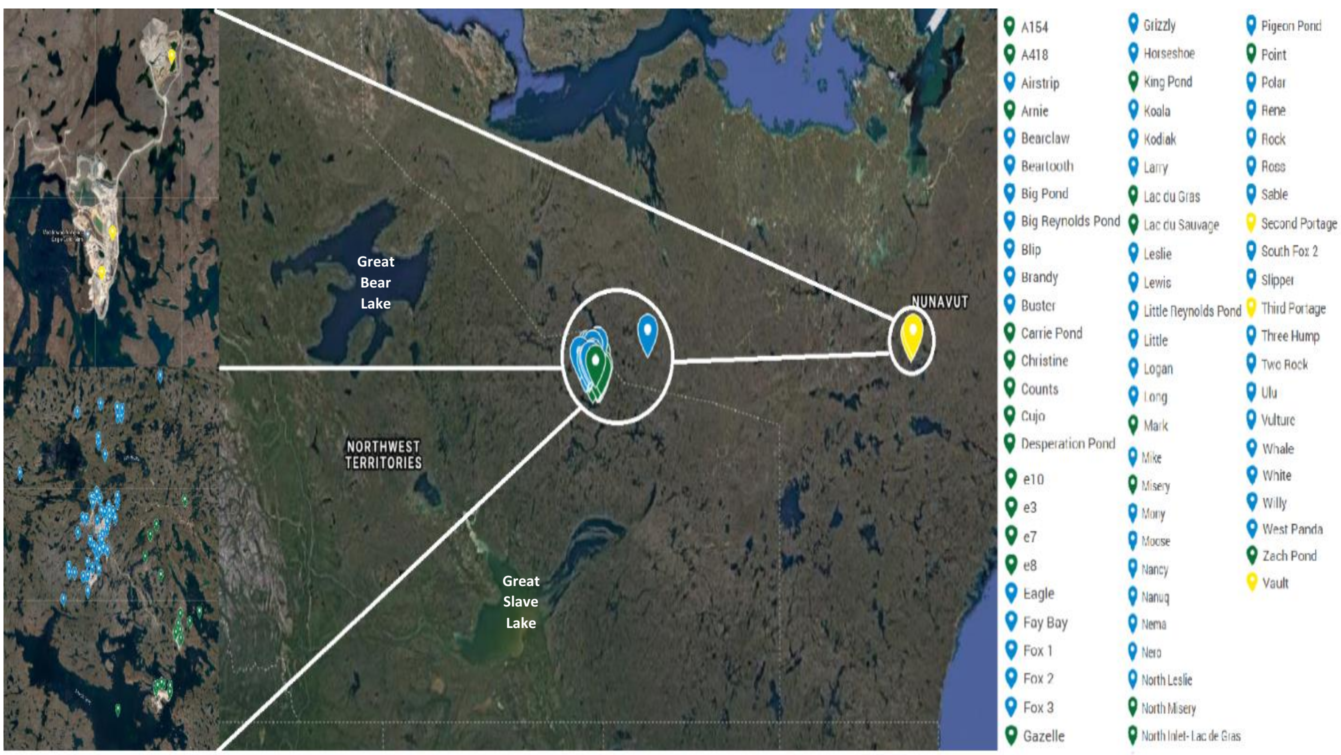

Figure 2.3 – Lakes that have been fished-out and data entered into the FO database as of June, 2014 from three development activities north of 60° including Meadowbank (yellow), Ekati (blue) and Diavik (green).

2.2.3. Broadscale Monitoring south of 60° latitude

The Ontario Broadscale Monitoring (BsM) program for inland lakes was developed under the new ecological framework for fisheries management as announced by the Minister of Natural Resources in 2004. The method uses a combination of two types of gillnets, known as 'large mesh' and 'small mesh', set during maximum water temperatures over specific depth strata between 0-75m (Figure 2.2; Sandstrom *et al*., 2015). Since the protocol was first introduced, a total of approximately 800 lakes have been surveyed and the data input into a database (B. Shuter, pers. comm).

2.2.4. Species list and characteristics

Data on 6 species belonging to 5 genera were available from 4 Fish-Out lakes north of 60° latitude, including Lake Trout (*Salvelinus namaycush*), Burbot (*Lota lota*), Round Whitefish (*Prosopium cylindraceum*), Arctic Char (*Salvelinus alpinus*), Slimy Sculpin (*Cottus cognatus*) and Arctic Grayling (*Thymallus arcticus*) (Appendix II). Each of these species have ecological niches that allow them to coexist in northern lakes (Guzzo, *et al*., 2016). Of all species examined, only Arctic Char (*Salvelinus alpinus*) and Arctic Grayling (*Thymallus arcticus*) have distributions that do not occur in high abundance south of 60° latitude.

Lake Trout (*Salvelinus namaycush*) was the target species chosen for analyses testing on depth distribution during the open water season across northern (NWT/NU) and southern (Northwestern ON) lakes in Canada. Lake Trout are frequently used to set threshold values for lacustrine impacts in assessment frameworks because of their significance to Indigenous peoples for sustenance. Lake Trout were also the only species that was well represented enough in all regions to support statistical analyses. Therefore, until a greater database can be compiled to analyse whole ecosystem or fish community level impacts in arctic regions, Lake Trout inferences could be used as surrogates for cold-water salmonids to provide baseline depth of occupancy associations in lacustrine species north of 60°.

2.2.5. Estimation of depth of capture

Charles K. Minns wrote R code meant to identify the proportion of fish occurrence and mean catch at depth from the Fish-Out dataset from arctic lakes, and this has been used in this study for data analysis. Comparisons between FO and BsM lakes presented many challenges; there was a lack of balance in design and no standardization in the collection methods, confounded by very low catch rates (Appendix II). The length of individual nets, mesh sizes and their associated set times were standardized (see below) and applied over the entire range of depths sampled in a lake in equal proportions. As such, the depth range of each net set was extended between the minimum net depth (Z_{min}) and maximum net depth (Z_{max}) of assigned net set depths (Table 2.1).

Table 2.1 – Variation in sampling protocols for the 'Fish-Out' database (Tyson, *et al*. 2011) and the 'Broadscale Monitoring' database (Sandstrom, *et al*. 2015).

	Stretched mesh size (mm)	Number of panels	Total net length (m)	Set duration	Location of net sets
Fish-Out	13, 25, 38, 51, 76, 102	6	45	4 to 24 hours	Random
Broadscale Monitoring	13, 19, 25, 32, 38, 51, 64, 76, 89, 102, 114, 127	13	40.3	12 to 22 hours	Depth stratified

Ideally, the setting of nets in FO lakes would target defined depth contour intervals as in the BsM protocol (Sandstrom, *et al*., 2015); however, the primary intent of the FO surveys was different because it documented community structure while facilitating fish removal. BsM documented community structure and estimated abundance across predefined depth strata. The BsM method had twice the number of shorter panels compared to the FO method, resulting in a total net length of 40.3m for BsM and 45m for FO, respectively, with comparable mesh sizes. It was then assumed that the set duration were similar, only more variable in the FO data than the BsM. These factors made the databases inherently more comparable.

The depth estimation model considered three main observations and assumptions. First, as the depth range covered by each individual net increased and became more variable, catch information became less specific to any given depth (Figure 2.4). This meant the wider the depth range of the net set, the greater the uncertainty associated with the assignment of fish caught to a specific depth.

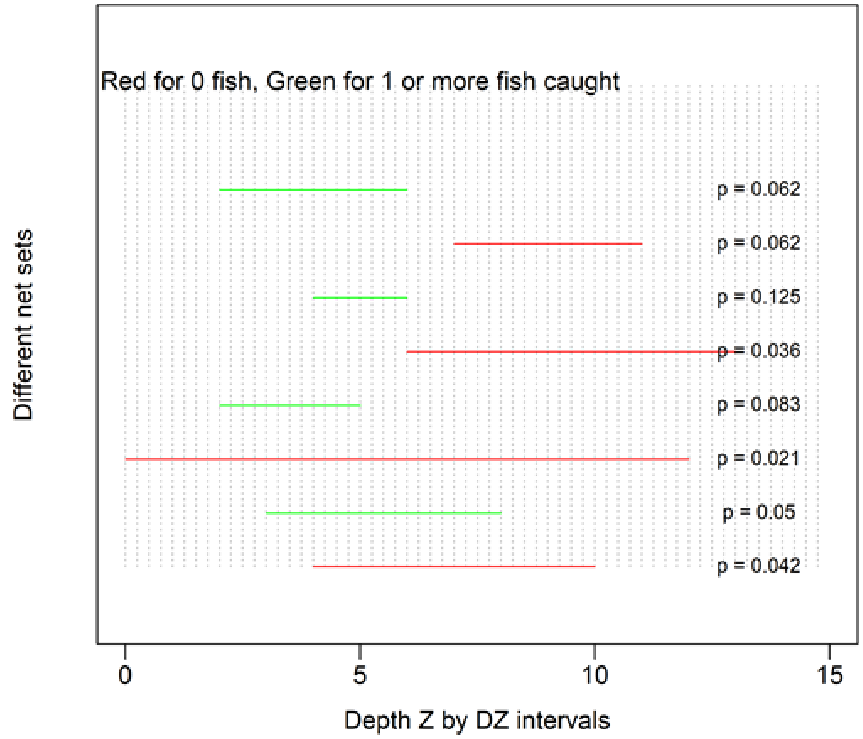

Figure 2.4 – Diagram demonstrating how the use of a proportion of effort (**p**) gives greater weight of evidence to net sets with narrower depth ranges and vice versa. A kernel-like estimation process is adopted here and for each unit of effort, presence, absence and catch is assumed to be normally distributed over the depth range of sampling from Z_{min}-Z_{net} to Z_{max} using a depth interval of dZ.

Second, there was also a need to account for the height of the net (Z_{net}) when set such that the full depth range was from the minimum depth (Z_{min}-Z_{net} (or 0 if Z_{net} is > Z_{min} near the surface of the lake)) to the maximum depth (Z_{max}) (Figure 2.5). The height of the net used may have been modified based on knowledge about the benthic or pelagic life history characteristics of a fish species; for example, if all fish species were benthic and known to be caught in the bottom half of nets, the adjustment value would be $Z_{net}/2$. Finally, for each unit of fishing effort (I), the information about the presence, absence, and/or the catch when present of each species (K) was assumed to be uniformly distributed over the depth range of sampling from the top of the net above the minimum set depth recorded (i.e., Z_{minI}-Z_{netI}), to the maximum set depth, (Z_{maxI}) where Z_{minI} was the minimum net set depth (0.1 metre accuracy), Z_{maxI} was the maximum net set depth, and Z_{net} was the standard effective fishing height of a net set (Figure 2.5).

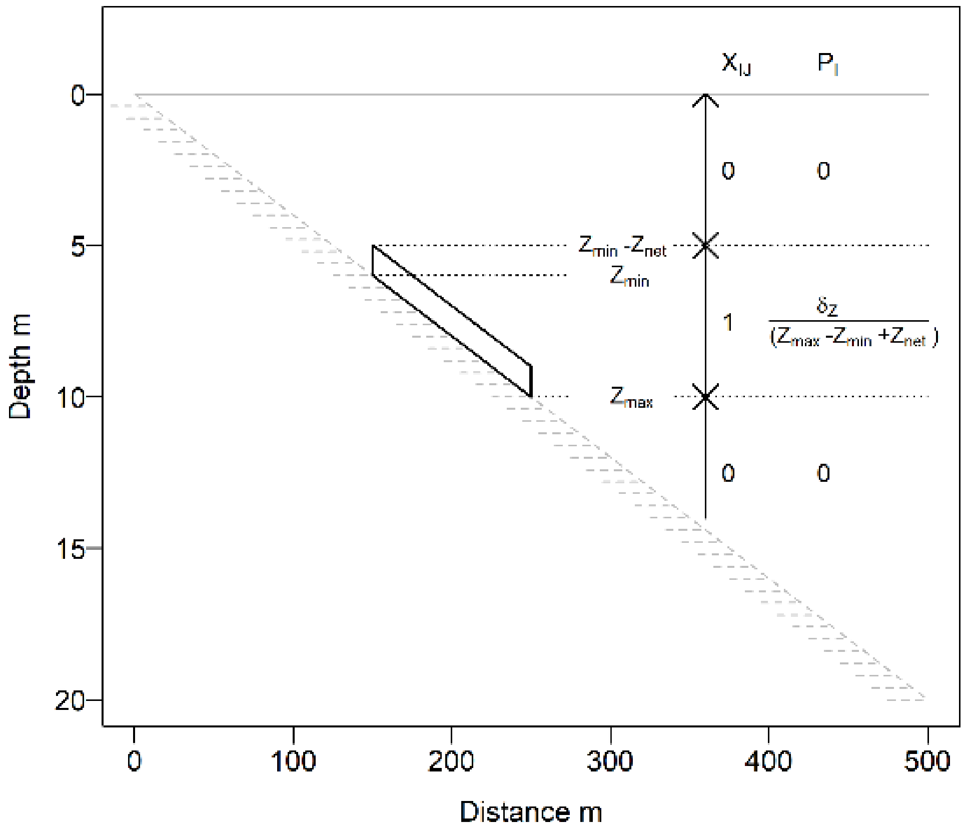

Figure 2.5 – Conceptual layout for the analysis of depth preference using the catches from gillnets set with various depth ranges. Here the allocation of effort and catch information among the groups of δ_Z depth intervals is illustrated for a single net set.

Using a small depth interval of δ_Z, arbitrarily set at 0.1 metres in this case, the bathymetry of the whole lake was divided into a series of layers (N_L), each Δ_Z thick (in 0.1m increments) from the surface to the maximum lake depth ($LZ_{max\ m}$). Then a procedure was followed whereby equal portions (P_I) of the information obtained from each unit of fishing effort (I) were allocated to each δ_Z-thick lake depth layers between Z_{minI}-Z_{net} and Z_{maxI}. In all the depth layers for the lake (N), a series of sums was calculated for each lake depth layer (J) across all net sets (I = 1 to M):

- **X_{IJ} = 1 if Z_J => Z_{minI}-Z_{net} and Z_J+ δ_Z <= Z_{maxI} else 0** – *a binary mapping for each net (I) of which Δ_Z depth layers it intersects*;
- **$NN_J = \sum_I X_{IJ}$** - *the total number of net sets intersecting the interval Z_J to $Z_J + \Delta_Z$*;
- **$P_I = \delta_Z /(Z_{maxI} – (Z_{minI}-Z_{net}))$** – *the proportional unit of fishing effort per Δ_Z interval in the depth range of the net set (I)*;
- **$CN_{JK} = \sum_I X_{IJ} \cdot P_I$** - *the sum of the proportions of units of fishing effort across all net sets (M) in each depth layer (J)*;
- **$CP_{JK} = \sum_I X_{IJ} \cdot P_I \cdot$[where $C_{IK} > 0$ is TRUE]** – *the sum of the proportions of units of fishing effort across all net sets (M) in each depth layer (J) when fish species (K) is captured in the net set (I)*;
- **$CA_{JK} = \sum_I X_{IJ} \cdot P_I \cdot$[where $C_{IK} = 0$ is TRUE]** – *the sum of the proportions of units of fishing effort across all net sets (M) in each depth layer (J) when fish species (K) is not captured in the net set (I)*;
- **$CC_{JK} = \sum_I X_{IJ} \cdot P_I \cdot C_{IK}$** – *the sum of the proportion-weighted catches (C_{IK}) for fish species (K) is captured in the net set (I)*;
- **$CC2_{JK} = \sum_I X_{IJ} \cdot P_I \cdot C_{IK}^2$** – *the sum of the proportion-weighted catches (C_{IK}) squared for fish species (K) is captured in the net set (I) to allow calculation of variance of mean catch*.

Once the effort and catch data for all nets were allocated across the layers of the lake (vertically in the water column), and before percent occurrence and mean catch were computed, the raw data sums were pooled into a set of larger, more practical., five metre depth layers (e.g., 0-5, 5-10, 10+). The advantage of pooling data into larger depth layers was that the pseudo-sample sizes increased and thereby the confidence limits on estimated values became narrower. For each depth layer (J) and fish species (K) mean percent occurrence, standard error of the estimate and mean estimate of catch were computed using the cumulative sum equations:

- *Estimated mean percent occurrence* **(PO_{JK}) = CP_{JK}/CN_{JK}**
  - *Standard error of percent occurrence* **($SE.PO_{JK}$)= $\sqrt{(PO_{JK} * (1- PO_{JK}) / CN_{JK})}$**
- *Mean estimate of catch* **(C_{JK})= CC_{JK}/CN_{JK}**
  - *Standard error of the estimate* **$(SE.C_{JK})= \dfrac{\sqrt{[(CCS_{JK} - CN_J * C_{JK}\text{^}2)/ (CN_{JK} -1)]}}{\sqrt{(CN_{JK})}}$**

In each depth range, percent occurrence (PO_{JK}) was assumed to follow a binomial distribution with the sample size assumed to be the pseudo net count (CN_{JK}) and the catch (C_{JK}) was assumed to be normally distributed. The distribution of net sets was examined covering each of the depth intervals of the full depth range of all sets. The calculation of the catch statistics was constrained by setting a minimum number of net sets in each interval to ensure a sample size of at least 10 for statistical rigour in the FO data. The BsM data were analyzed using a lower net threshold (N.Thresh) of three. This was due to the proportional sampling protocol that was adhered to when the BsM data were collected in offshore areas relative to nearshore areas because nearshore areas occupy a greater area compared to the availability of offshore habitat, typically. Therefore, a fewer number of observations were required in the δ_Z increments because one could assume things were more representative of a particular stratum than in the FO data.

Depth estimates were adjusted to accommodate for lake morphometry and ensure the methodology was applied proportionally across depth intervals in a lake where bathymetric data such as maximum depth and mean depth of a lake were recorded. This data was obtained for all ten lakes involved in this study. For example in the BsM, a lake was divided into a number of approximately equal-sized areas and samples were allocated similarly among all of the areas. The minimum strata sampling requirements by lake size and maximum stratum depth (i.e. deepest stratus with >5% surface area) for large and small mesh nets in lakes were up to 10,000 hectares. For lakes greater than this threshold, a formula was provided to calculate appropriate sample sizes as follows (Sandstrom, *et al*., 2015):

- *If lake >10, 000(ha) then 0.0987(Lake_Area)0.2581 x Allocation for a 5,000-10,000 hectare lake of similar depth

The equation above was extended to compute mean catch when present (CC_{JK}/CP_{JK}). Those results were then used to compute mean percent occurrence across lakes, regions and depth layers, and then the 95% confidence intervals. It was the goal of these analysis to include an account of trends across the two protocols and across spatial scales (northern vs. southern environments).

To complete the analysis and detect overall patterns a two-way ANOVA was used to evaluate differences in proportion of occurrence among depth intervals (0-5, 5-10 and 10m+), across all the sampled lakes based on their region. Depth intervals were selected based on a sufficient sample size of net sets (greater than 10) in each interval while maintaining a normal distribution pattern. This method was selected for hypothesis testing of population means between two independent samples of regions in Canada with an approximate normal distribution. The proportion of occurrence was examined across regions (north and south) and depth strata (0-5m, 5-10m, 10-15+m) as well as the interaction between these variables were tested. Before running the ANOVA, all assumptions of the model were met by performing a log transformation and assessing the diagnostic plots to ensure homogeneity of variance and normality of residuals.

2.3 Results

A two-way ANOVA indicated that there was no significant interaction between region and depth ($F_{2,24}$= 0.982, p= 0.30; Table 2.2). There was a significant difference between Lake Trout proportion of occurrence across regions ($F_{2,24}$=14.2613, p<0.0001) but not across depth intervals ($F_{2,24}$= 0.5248, p= 0.60; Figure 2.6). Lake Trout in arctic regions are therefore more abundant than southern regions, but do not differ between regions in their association with depth.

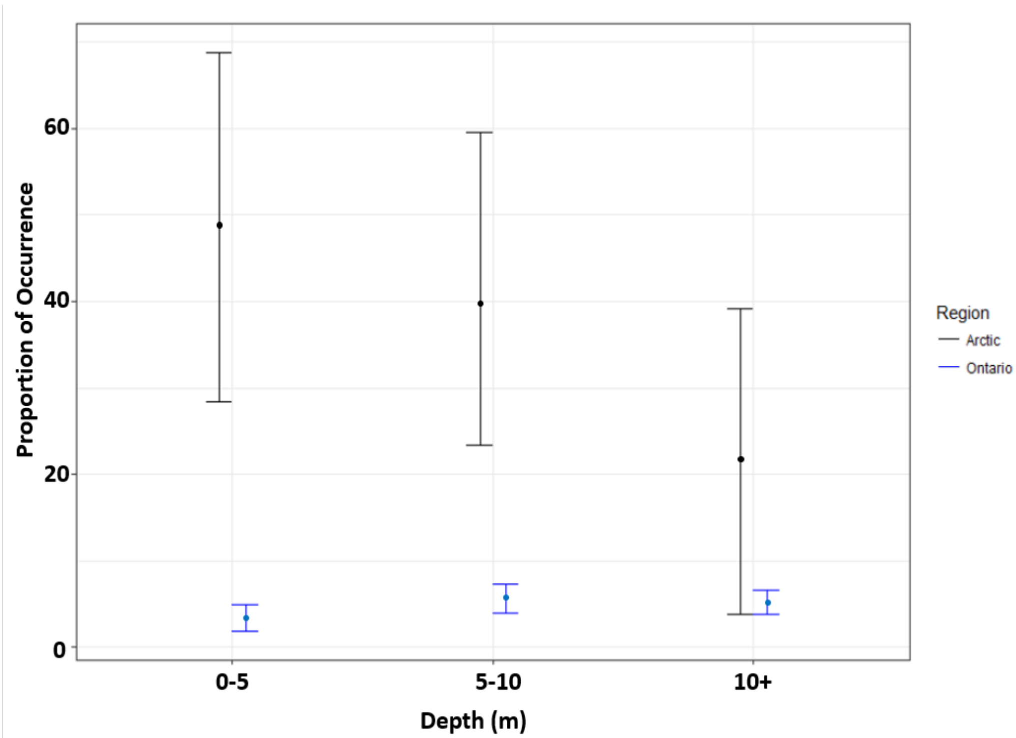

Figure 2.6 – Interaction plot of two-way ANOVA. Points represent means for proportion of occurrence of Lake Trout across 5m depth intervals ranging from 0-5m, 5-10m and greater than 10m north 60° latitude (arctic) and south of 60° latitude (Ontario). Error bars indicate ±1 standard error of the mean.

Table 2.2 – Two-way ANOVA results of proportion of occurrence of Lake Trout across two regions in Canada, the Arctic and Ontario.

Source	Df	SS	MS	F	p
Region	1	7576.4	7576.4	14.26	<0.0001
Depth	2	557.6	278.8	0.524	0.598
Interaction term (Region:Depth)	2	1043.6	521.8	0.982	0.389
Residuals	24	12750.2	531.3		

In the 0-5m depth strata, arctic Lake Trout populations from the four lakes proportion of occurrence ranged from 28-69%, and in the six Ontario they ranged from 3-5%. In the 5-10m depth strata, arctic Lake Trout populations proportion of occurrence ranged from 24-60%, and in Ontario they ranged from 6-8%. In the 10+ depth strata arctic Lake Trout populations proportion of occurrence ranged from 5-40%, and in Ontario they ranged from 5-7% (Appendix II- Figure A.2-A.23).

2.4 Discussion

Lake Trout did not use their physical habitat (depth) in a significantly different manner across regions considered in this study. The datasets employed by this study were limited in scope due to the lack of available habitat data north of 60° latitude to complement existing catch data from southern regions. Recent research indicated that datasets such as these might be used in conjunction with substrate mapping, lake bathymetry and other physical habitat variables to definitively characterize habitat associations of fish species within and across lakes (Rennie *et al*., 2015; Challice *et al*., 2019). Such ecological knowledge was in limited supply for northern Canadian lakes but could play an important role in determining future valuation of habitats for offset habitat calculations.

Improvements in standardization of methods to obtain fish habitat data have the potential to minimize the net cumulative impact of development and restoration activities on fish habitats overall. Current research taking place in the Kivalliq region suggests that fish habitat preferences in freshwater, arctic ecosystems are driven by the availability of prey species that require the least amount of energy expenditure (Milne, 2019; Portt *et al*., 2015). For example, fishes will occupy specific depths based upon the availability of thermal refugia during overwintering. Therefore, a great deal of information could be gleaned from patterns in depth of occupancy.

The survey information and method presented here represent an analysis of patterns in Lake Trout depth associations across randomly selected datasets north and south of 60° latitude. Selected lakes north of 60° latitude were chosen systematically based upon the available habitat data in the Fish-Out database. The data were insufficient for any meaningful analyses other than that presented in this chapter of the depth preferences in Lake Trout between 0m and 10m+ of water. This analysis showed that the depth of occurrence was similar between arctic and southern regions at all depths. It should also be noted that the inflated variation present within the FO data, relative to the BsM data, was likely an artefact of the sampling design due to a lack of standardization of net sets within pre-determined depth intervals of a lake (which was the case for the BsM data). As a result, there may have been patterns that remain undetected by the analysis presented in this thesis (i.e., among depth intervals) due to a lack of statistical power associated with poor sampling design in arctic regions.

The physical habitat variable that was observed most consistently across the available datasets was depth, and even then, only four lakes north of 60° latitude had accessible, basic ecological habitat data in the database with which to evaluate this metric (e.g. water temperature, bathymetry, substrate and vegetation or cover) with existing catch data. Arctic Char, Round Whitefish, Arctic Grayling, Slimy Sculpin and Ninespine Stickleback were only encountered in one or two lakes north of 60° where net set depth data was also available, making statistical analyses regarding comparisons of depth of capture challenging. Lake Trout was the species that was best represented in all four lakes reported here, and as such it was selected for comparison across regions.

To facilitate the analysis that was conducted in this chapter, a significant amount of data manipulation was required to create a standardized dataset. A pseudo-sample size was generated to ensure enough net sets were accounted for in each depth interval., which varied from ten in the FO database to three in the BsM database. This lower threshold of 10 net sets that was used because the BsM net sets were set proportional to the size of each intervals surface area; as such, fewer nets were set in deeper sites. The assumption was that the sum of net sets across all depth categories was equivalent to a sample size in each depth category. As a result, it did not make sense to analyze mean catch data computed as per the methodology described in this chapter due to confounding issues associated with the sample sizes and inability to detect differences in catch rates over time based on a visual inspection of the data. Therefore, the percent occurrence results were utilized as a part of the overall analysis in this study to determine the probability of encountering a target species at a given depth interval.

Given the logistical challenges associated with the sampling and protocols north of 60° latitude, data were only presented for species during the open-water, summer months for adult and juvenile life stages. As such, this study illustrates that basic, physical habitat information along with fish species data north of 60° latitude in Canada was not adequately represented in the study design implemented in the existing FO protocol followed by development Proponents and their contractors. In particular, the FO database was missing details clearly laid out in the Tyson *et al*., (2011) methodology regarding the allocation of effort to area and depth stratum to ensure habitat data could be collected systematically. Since the data provided does not capture these essential details, Fisheries and Oceans Canada (DFO) should discuss and better communicate proper study design with Proponents by pointing to the importance of following standardized, published protocols (Tyson et al., 2011). For example, the BsM database provided a standardized template that could be applied in the regulatory process north of 60° latitude to ensure nets were deployed in a stratified manner as per some physical habitat attributes, such as depth (as used by the BsM). Given the exceptional amount of data collected since it's implementation in Ontario, following a BsM protocol (rather than the Tyson et al. 2011 protocol) for Fish-out activities would provide the opportunity to facilitate meaningful, comprehensive analyses of the variation that exists in fish habitat preferences across latitude in Canada. If physical habitat data (particularly depth of sets) became an essential aspect of the FO data collection protocol (under either existing published methodology, or under the BsM methods), fish habitat associations with depth could be more effectively evaluated.

2.4.2. Future research

This study highlighted the lack of information regarding physical habitat associations of fish species in the Kivalliq region of Nunavut, and north of 60° latitude in Canada overall. Without these data, there will continue to be a significant knowledge gap with regards to arctic fisheries-related research. This information provides a basic ecological framework upon which to build a baseline understanding of anthropogenic impacts to freshwater ecosystems. There was a significant amount of available data presented in privately-owned environmental consulting reports that are associated with development activities north of 60° latitude. Data are collected by a multitude of companies and by governmental agencies, such as Fisheries and Oceans Canada, that store the data in physical reports but may not publish or archive them electronically. Building off this study, it would also be useful to identify methods of using these data to facilitate habitat suitability indexing for future studies to better inform decision making. In terms of the Fish-Out database, if the sampling of a species for a net set draws from a horizontal area or volume defined by the movement of the fish relative to the fixed net within the depth range of the net set, a few shallow net sets to sample a smaller portion of the available lake space in that depth range compared to a larger portion of the available space sampled at greater depth ranges proportionately is recommended to better evaluate depth-specific associations. To correct this, one possibility could be to adjust the percent occurrence figures by depth interval for the relative size of the lake space in each depth interval. If the surface area, mean depth and max depth of a lake is known, one can devise a measure of the cross-sectional area and volume in each depth interval (dz) and then divide all values by the maximum which occurs in the shallowest depth layer from 0 to dz. Finally, multiplying the percent occurrence by the appropriate lake ratio will produce morphometry-adjusted estimates. This was not possible in the scope of this study due to the inaccessibility of bathymetric data for remote lakes north of 60° latitude. These data are presented in environmental assessment reports on the Nunavut Impact Review Board public registry; however these files could not be distilled down to a functional format in the time available for this study. Furthermore, modern gear types that are applied extensively south of 60° latitude, such as hydro-acoustic sonar-imagery, can be applied north of 60° latitude and paired with tried-and-true methods, such as netting, to identify evidence-based environmental thresholds that define impacts to productivity.

2.5 Conclusion

The objective of this chapter was to estimate the depth of occurrence of fish species across two regions – Broadscale Monitoring applied across random lakes in Ontario and the Fish-Out protocol applied across lakes impacted by mining operations, most often in Nunavut and the Northwest Territories. The null hypothesis that stated depth associations would not be significantly different across regions was not rejected by the outcome of the two-way ANOVA as there were no significant differences in Lake Trout depth of occurrence across the two study regions. The knowledge gap in arctic fish habitat data identified by this study emphasized the difficulty associated with assessing the productivity of one habitat relative to another in the arctic due to the inability to use baseline data that applied to the populations impacted by development pressures. Under the currently model there was a tendency to imply principles known to be evident in southern populations, given statistical similarities in depth of occurrence between regions.

In conclusion, this research identified a method of analysing fish habitat data associated with depth that can provide comparisons among non- standardized datasets across regions. Critically, the issues associated with a lack of physical habitat data in major databases across the Canadian arctic region was highlighted by this study. Thus, the analyses were limited to one species and only one habitat variable due to the lack of available data for comparable analyses. It will be vital to the longevity of freshwater arctic lake environments to develop a more robust, evidence-based understanding of patterns in the distribution and habitat preferences of arctic fish species for use in decision making. Future research and monitoring of fish habitat associations and species size spectra during major sampling events, such as a Fish-Out, should adopt some of the Broadscale Monitoring principles like depth stratification of sampling effort and collecting thermal profiles to ensure comparability of datasets in future research.

3. Chapter 3 – Comparing fish habitat associations across northern and southern Canada in the Habitat Ecosystem Assessment Toolkit (HEAT)

Abstract

A semi-systematic literature review and data synthesis of arctic fishes was combined to quantify information compiled for use in base tables of the Habitat Ecosystem Assessment Toolkit (HEAT). Habitat associations of two model species, Lake Trout and Burbot, across two regions in Canada (Kivalliq region and the Great Lakes region of Ontario) were compared. The Kivalliq region had 11 freshwater fish species present in its watersheds which formed the basis of the review. Habitat associations of each species with depth, substrate, temperature and cover (or vegetation) were extracted from literature and/or datasets. A total of 5,299 peer-reviewed articles were screened at the title and abstract level and 52 were screened at full-text level based on the presence of basic ecological habitat data, coupled with catch data from areas north of 60° latitude sourced from an existing government database. These sources were combined with existing literature review tables from a 2001 literature survey. From this review, only Lake Trout (*Salvelinus namayacush*) and Burbot (*Lota lota*) had sufficient data to estimate habitat suitability index (HSI) values, which were calculated and compared to the existing values for depth preference intervals in the Ontario HEAT database (e.g. depth intervals of 0-1, 1-2, 2-5, 5-10 and 10+ m). The estimated HSI values for depth of Lake Trout and Burbot differed significantly between the Ontario and Arctic database. Ontario Lake Trout were more likely to be encountered across all depth intervals and all life stages relative to the arctic region. This study also revealed that basic ecological habitat features, such as depth, substrate and vegetative cover, which are required to differentiate habitat

suitability in HEAT, are absent from most existing literature sources regardless of origin. Finally, a need remains in the arctic for a wider-scale systematic assessment of habitat use by fishes in the region, which this study suggests differ between regions. Therefore, future research should focus on filling the data gaps identified in this study. This new information is required to develop regionally-specific HEAT models that can more accurately reflect ongoing perturbations in arctic habitats.

3.1. Introduction

Different fish habitats have shaped fish communities and their distributions based on resource availability and species home range (Minns, 1995; Woolnough *et al*., 2009). Depending on their physiology, speciation may occur sympatrically through differential habitat preferences and associations (Chavarie *et al*., 2018). Habitat heterogeneity in the freshwater environment favours niche and life stage specializations which are at least partly based upon depth, substrate, vegetation temperature and dissolved oxygen (Minns *et al*., 1999; Tang *et al*., 2018). All fishes are known to have a home range typically based on two main factors: their body size and life history strategy (i.e. riverine, lacustrine, etc.), both which contribute to their energy and reproductive dynamics (Lucas and Baras, 2008). For example, a Pacific Salmon born within a river may travel many kilometers in search of appropriate depth and prey availability that will mitigate competition and enable growth in an open lake before returning to their birthplace for reproduction. In contrast, a freshwater Lake Trout that remains under ice for over nine months each year may remain sedentary at the bottom of a deep lake to conserve energy in anticipation of the emergence of ephemeral spring invertebrates. Depending on the availability and proximity of fishes to appropriate habitat features which facilitate their major life cycle functions (which include growth, survival., and reproduction), these functions may be vastly different within one region of Canada compared to another (Lucas and Baras, 2008). The sheer diversity of Canada's freshwaters from coast to coast to coast gives credence to the hypothesis that fishes might use physical habitat features in significantly different ways in the Great Lakes or boreal Ontario lakes compared to the lakes in the arctic region.

3.1.1. HEAT in the Laurentian Great Lakes basin

The Habitat Ecosystem Assessment Toolkit (HEAT) has evolved over the years to respond to the need to evaluate the impacts of development projects and to try and establish ecological 'offsets', or compensatory activities that equal or surpass the ecological value of habitats (and the organisms they support) due to development. The scientific framework underlying the present-day HEAT was developed in the 1990s by Minns (1995, 1997), who used a basic accounting equation to assess the net change in the productive capacity of fish habitats using habitat valuation or equivalents. Development impacts are described via changes in habitat areas and their characteristics via losses, modifications and offsetting classes defined by physical parameters and life stages (i.e. depth at 0-1m for adult/juvenile Lake Trout).

Subsequent work further refined this approach and it became known as 'Defensible Methods' (Minns *et al*., 2001). This version targeted assessments of fish habitat in lacustrine environments throughout the Laurentian Great Lakes' primary watershed by using a Habitat Suitability Matrix (HSM) model to implement the valuation of habitat features. The HSM model integrated matrices based on primary literature that represent cumulative habitat 'preferences' for water depth ranges, substrate types, and vegetation or woody structure types. Associations and their strengths for all Great Lakes fish species and their life stages were incorporated to ensure that the complete life cycle needs of all species were considered (Abdel-Fattah *et al*., 2018). It was later renamed the Habitat Alteration Assessment Tool (HAAT) by Fisheries and Oceans Canada's (DFO) Fish Habitat Management program upon implementation in a modern computing environment allowing for better user interface and accessibility. HEAT is the newest development of the Tool that stems from expanding HAAT to online access and including new functionality and variables, such as water levels and temperature (Tymoshuk *et al*., 2017). Lake HEAT incorporates fish distribution data by tertiary watershed, fish guild information and life stage-specific habitat associations for calculating composite HSM values for whole fish communities. The HSM values are applied to user-input scenarios in order to generate weighted suitable area (WSA) calculations as an output from the model. The WSA output of Lake HEAT facilitates pre- and post-impact comparisons for Environmental Impact Assessments (EIAs) and DFO's review of available habitat supply, aggregated for the fish community (DFO, 2019). Lake HEAT, or "HEAT" hereafter, incorporates data into base tables sourced from the Laurentian Great Lakes basin (Lane *et al*., 1996a, b, c). The software package allows pre and post construction assessments of limnological and physical habitat changes and their impact on fishes, through scenario-testing.

3.1.2. HEAT in the Canadian Arctic

HEAT holds the potential to be applied as a national tool across Canada because of the transferable approach and methods employed in its framework. The output of HEAT is dependent upon the reliability and source of two types of input files. These are (a) inputs that are defined by the user (which will vary in complexity and detail depending on the particular ecosystem and proposed severity of the development scenario) and (b) information that has been pre-defined or is embedded in the programming of the model or the base tables (which describe fish-habitat associations through a series of 0-1 index values). Customization or substitution of HEAT base tables has been employed by DFO Science to meet the demand for quantitative assessments under the *Impact Assessment Act* (IAA) and the *Fisheries Act* related to authorized mining operations that involve whole-lake destruction projects in regions outside of the Great Lakes basin (Doka, 2017). For example, Phaser Lake in Nunavut was chosen as a candidate expansion lake on the Meadowbank Mine property operated by Agnico-Eagle Mines Limited due to rich geological features present in the lakebed (Minns, 2019). In a scientific review of valuation methods used, this lake was opportunistically selected to build an alternate habitat suitability model based on habitat preference ratings reported by Richardson *et al*., (2001). Fish species present in Phaser Lake were used for the fish list and alternate suitability and equivalency methods were developed by Minns (2019). The objective of this analysis was to assess how WSA values might change by using different suitability ratings based on arctic-derived values in the habitat suitability model. This resultant model produced similar results for adults to those provided by the mining company, however the results for other life stages within respective guilds were significantly different. It was concluded that, given the uncertainties associated with the derivation of either model, there was no sound basis for recommending one model over the other. Ultimately, a recommendation was made for a more systematic regional method of documenting and reporting results (Minns, 2019).

3.1.3. Contributions to impact assessment and compensation monitoring

Historically there has been a need for methods, models and tools that could be used to quantitatively assess impacts on fish and fish habitat and evaluate the potential to compensate, or offset, for these activities. HEAT has managed to meet these requirements and expectations of both the industry and regulators at Fisheries and Oceans Canada within the Fish and Fish Habitat Protection Program for project impact assessments in the Laurentian Great Lakes region. In-water development activities on the Laurentian Great Lakes that have received the most attention by users include offset, or restoration projects, where calculations were deemed necessary under *Fisheries Act* authorizations (Gertzen *et al*., 2012). These development activities are often large-scale impacts that have a component of infilling a wetted area, thus resulting in a loss or modification to surrounding water depth, substrate and available structure or vegetation.

As of August 28, 2019, the new regulations of the *Fisheries Act* came into force. Changes to the Act restored previously lost protections and introduced modern safeguards for all fish species in Canada, not only those that are commercially, recreationally or aboriginally significant. New provisions also incorporated factors such as productivity and cumulative effects under the assessment framework that are likely to increase the application of HEAT use in the assessment process across Canada. Where development projects pose a risk to fish bearing waters, the tool can be applied because the likelihood of a project leading to prohibited impacts has been elevated. HEAT provides the only functional., quantitative, evidence-based equivalency tool for assessing trade-offs. However, the current HEAT base tables are based on Great Lakes data; these models are applicable in the Great Lakes basin but require more eco-regional data to accurately represent fish populations and their habitat associations in other locations (Chapter 2).

3.1.4. Relevance of systematic literature reviews in evidence-based decision making

One of the major challenges facing environmental decision-makers is meaningfully summarizing and using the best available information to properly apply policy. Recent estimates suggest roughly two and a half million scientific articles are published in ecological journals annually, representing an increase of approximately three percent each year for the last two centuries (Ware and Mabe, 2015). To support well-founded decision-making in environmental management, it would be best to identify methods to generate a rigorous, defensible and transparent synthesis of scientific evidence. A systematic literature review facilitates the improved use and uptake of science in decision-making by making research more compatible with operational objectives. The Collaboration for Environmental Evidence (CEE) published an approach that considers the risk of bias when designing a study and reporting results. It evaluates all relevant contextual information, analyzes all the data by using standard effect sizes and publishing raw data. Depending on the nature and volume of studies on a subject, systematic reviews may be limited by certainty about the effectiveness of an intervention, or even the strength of a relationship. Nonetheless, this approach can provide valuable information by summarizing variability and uncertainty among studies while identifying gaps in the available scientific knowledge of a given subject.

3.1.5. Objective

In this chapter of the thesis, regionally-based HEAT Habitat Suitability Index (HSI) values were compared between Ontario and arctic Lake Trout and Burbot depth associations. It was hypothesized that HSI values for these two species would be statistically different between regions; the average value will be higher for the Ontario region and therefore the species are more detectable relative to the arctic region. Lake Trout and Burbot were selected as model species because a sufficient quantity of data was available compared to other species to create HSI tables with evidence in each category either to confirm presence or absence north of 60° latitude using the Richardson, *et al*., (2001) literature and the literature presented in this chapter. The semi-systematic review method established for this thesis is an evidence-based procedure for data mining to inform HSI values which are inputted into models. It was anticipated that data from these analyses will provide insight for future applications of HEAT to arctic ecosystems and provide more information to development proponents and federal regulators by placing emphasis on regional-based modelling methods. In addition, systematic data collection and evidence synthesis methods were used to combine existing data (Richardson, *et al*., 2001) and develop a qualitative analysis of all available pan-arctic data north of 60° latitude for 11 species of the Kivalliq region. The habitat associations that were researched included dominant substrate type, dominant vegetation cover, mean depth and mean temperature. Mean values were extracted from literature sources over distributional data across a given habitat parameter in order to accommodate the constraints of the CEE screening methodology, match the existing Richardson, et al. (2001) and Lane *et al*., (1996) habitat association tables and meet the timeline allotted for this study.

3.2. Methodology

3.2.1. Systematic literature review

The Canadian Centre of Collaboration for Environmental Evidence (CEE) at Carleton University provided guidance and review protocols to address the need for rigour, objectivity and transparency in reaching conclusions from a body of scientific information in ecology (CEE, 2018). The methodologies were adapted and developed over more than two decades in the health services sector (Lefebvre, *et al*., 2009) and informed by developments in other sectors such as social sciences and education (Gough, *et al*., 2012). Through peer review, research and adaptation of existing methodologies, specific guidelines were then developed for the application to environmental management (CEE, 2018).

The primary aim of this semi-systematic review was to establish Habitat Suitability Index (HSI) values for three life stages (spawning, young-of-the-year and juvenile/adult) of lacustrine fish species local to the Kivalliq region watersheds (Scott and Crossman, 1998; Richardson *et al*., 2001; Evans *et al*., 2001; Mandrak *et al*., unpub data). An emphasis was placed on data related to HEAT inputs for similarity with data collected from other regions (i.e., Great Lakes) by combining new arctic data (post-2000, assembled here) and previously assembled arctic data (Richardson *et al*., 2001). These data were then used to determine if the default, Ontario HSI values differ from arctic environments using depth associations in Lake Trout and Burbot. The remaining data collected without sufficient replication to complete statistical analyses were included in a qualitative review of each species, across the three life stages and four habitat variables.

The search strategy that was entered in the database for each individual species was written as:

"Arctic AND Canad* AND Freshwater AND Fish* AND Habitat AND Distribution AND <u>Common name</u> OR *<u>Scientific name</u>*"

The number of results for each search was recorded individually for each of the 11 fish species in the Kivalliq region. Additional information was solicited in the form of grey (unpublished) literature from industry professionals, local communities, landowners, consultants, local authorities, or others involved in the management of local fisheries. Targeted and general evidence requests were sent to industry partners and stakeholders to collect as much unpublished literature as possible, resulting in approximately 100 additional documents from 17 data sources.

Searches on published literature were conducted using Web of Science (Core Collection, September 2017 – June 2019). This publication database encompassed ScienceDirect, JSTOR and other smaller databases.

Unpublished (non-peer reviewed) literature searches were sought by evidence call-outs published in October, 2018 to the Society of Canadian Limnologists, the Canadian Conference for Fisheries Research (CCFFR) and internally through the Department of Fisheries and Oceans (DFO) requesting any unpublished physical habitat data from north of 60° latitude with the species list provided from the Kivalliq region tertiary watersheds. Two responses were received by the deadline and they included the following 17 sources of non-peer reviewed publications literature from north of 60°:

1. Fish-Out database (Hedges, *et al*. 2018);

2. Nunavut Impact Review Board (http://www.nirb.ca/);
3. Mackenzie Valley Review Board (http://reviewboard.ca/);
4. Environment Impact Review Board (https://eirb.ca/);
5. Gwich'in Renewable Resources Board (http://www.grrb.nt.ca/fisheries.htm);
6. Tłı̨chǫ Aquatic Ecosystem Monitoring Program (https://www.wrrb.ca/projects/t%C5%82%C4%B1%CC%A8cho%CC%A8-aquatic-ecosystem-monitoring-program);
7. ʔehdzo Got'ı̨nę Gots'ę́ Nákedı Sahtú Renewable Resources Board (http://www.srrb.nt.ca/index.php?option=com_content&view=article&id=247&Itemid=743);
8. Fisheries Joint Management Committee (https://jointsecretariat.ca/co-management-system/fisheries-joint-management-committee/);
9. Nunavut Wildlife Management Board (https://www.nwmb.com/en/about-nwmb/working-groups-a-committees2/125-fisheries-advisory-committee);
10. Polar Data Catalogue ();
11. Arctic Science and Technology Information System (http://www.aina.ucalgary.ca/scripts/mwimain.dll/1613/1/0?SEARCH);
12. Arctic Net publications (http://www.arcticnet.ulaval.ca/media/publications.php);
13. Arctic Ocean Diversity (http://www.arcodiv.org/Database/Data_overview.html);
14. Arctic Journal (https://arctic.journalhosting.ucalgary.ca/arctic/index.php/arctic/issue/archive);
15. Fisheries and Oceans Canada anecdotal data;

16. Federal Science Library (https://science-libraries.canada.ca/eng/fisheries-oceans/);
17. Committee on the Status of Endangered Wildlife in Canada (https://www.canada.ca/en/environment-climate-change/services/committee-status-endangered-wildlife.html).

A number of these sources, such as the Tłı̨chǫ Aquatic Ecosystem Monitoring Program and the Nunavut Impact Review Board, provided overlapping data from the same project but presented it in different ways to fulfill various mandates and answer different research questions. These data from gray literature reports was ultimately omitted from the study due to inaccessible, tabular data that would require figure extraction software and extensive data analyses to properly extract the habitat parameters sought by this study. However, this comprehensive list was presented here because it could be compiled into a CEE Systematic Map, pointing future researchers to untapped data sources with basic habitat information on arctic fish communities. For the purposes of this thesis, a dataset was extracted from the Fish-Out database (Hedges *et al*., 2018) which presented raw catch data matched by depth measurements to answer one of the research questions in this study. A total of four Fish-Out lakes were selected to evaluate habitat suitability because these were the only lakes that presented habitat data (i.e. net depth) associated with catch data. This information was used in addition to the data compiled from published literature reviews and existing arctic habitat suitability tables (Richardson *et al*., 2001).

For all published literature sources in the Web of Science the following series of yes-or-no questions were posed in a two-tier approach; first applied exclusively at the title and abstract level, and second at the full-text level:

1. Is the study located north of 60° latitude?
2. Was the study published after the year 2000?
3. Does the study examine a lake ecosystem?
4. Does the study present physical habitat data with species information?

If the answer to any of these questions was ‘no’ at any tier, the literature source was excluded from the synthesis of evidence.

The EcoEvidence framework (Webb *et al*., 2013; Tang *et al*., 2018) guidelines were employed for weighing the relevance of any given study to provide physical fish and fish habitat data (Table 3.1).

Table 3.1 – EcoEvidence default weights applied to study types gathered in this study and the number of control/reference and impact/treatment sampling units.

STUDY DESIGN COMPONENT	WEIGHT
STUDY DESIGN TYPE:	
• **AFTER IMPACT ONLY**	1
• **REFERENCE/ CONTROL VS. IMPACT NO BEFORE**	2
• **BEFORE VS. AFTER NO REFERENCE/CONTROL**	2
• **GRADIENT RESPONSE MODEL**	3
• **BACI (BEFORE/AFTER/CONTROL/IMPACT)**	4
REPLICATION OF FACTORIAL DESIGNS	
NUMBER OF REFERENCE/CONTROL SAMPLING UNITS (LAKES):	
• **0**	0
• **1**	2
• **>1**	3
NUMBER OF IMPACT/TREATMENT SAMPLING UNITS (LAKES):	
• **1**	0
• **2**	2
• **>2**	3
REPLICATION OF GRADIENT RESPONSE MODELS (FISHES):	
• **<4**	0
• **4**	2
• **5**	4
• **>5**	6

The HEAT approach (Minns *et al*., 2001; Abdel-Fattah *et al*., 2015) was then used for assigning HSI values by life stage. Data was extracted from each of the references screened-in at the full-text stage (Appendix III). The following steps were then taken by species:

- *Step 1*- Physical habitat parameters were recorded from each literature source (herein referred to as a '*reference*') using the following values where a fish was present*:
    - Mean depth (m)
    - Dominant substrate category
    - Dominant vegetation (or cover) category
    - Mean temperature (^{O}C);
- *Step 2*- Each reference was assigned a weight of evidence (herein referred to as a '*reference weigh*t') based on experimental design and level of replication – i.e.

greater weight for studies with greater replication, measured by quantity of lake and fishes involved and reported (Table 3.1);

- *Step 3*- Reference weights were then summed across all studies (screened-in at full text level) by relevant habitat strata (herein referred to as '*class*')– i.e. 0-5m, 5-10m, 10+m for depth and life stage;
- *Step 4*- Reference weights by class and life stage were summed for each physical habitat parameter (i.e. depth, substrate, etc.);
- *Step 5*- Sum of each parameter by life stage was divided by each class and assigned a proportion of occupancy (0-100%);
- *Step 6*- The proportion of occupancy value was converted to a HSI value according to the following criteria:
    - No association (0.00)
    - Low association (0.01-0.33)
    - Moderate association (0.34-0.66)
    - High association (0.67-1.0).

*Data, where available, was also recorded for absence of a species.

3.2.2. Qualitative analyses of habitat associations

A summary of the existing prior literature on physical habitat associations of all 11 species from the Kivalliq region of Nunavut was prepared, including all the new knowledge from the literature review. Knowledge gaps were also identified in these populations north of 60° latitude based on the four physical habitat parameters involved in this study (depth, substrate, vegetative cover and temperature). References from Scott and Crossman (1998), Richardson *et al*., (2001) and literature compiled from the semi-systematic literature review described in this study were used to identify regional patterns north of 60° latitude.

3.2.3. Quantitative analyses of habitat associations

Mean depth estimates were isolated for all life stages (spawning/egg, young-of-the-year, juvenile/adult) of Burbot and Lake Trout, individually, from literature sourced north of 60° latitude with replication that satisfied the conditions of the analyses (Table A3.1).

Depth was the habitat metric of focus due to lack of available data on other habitat parameters. Habitat Suitability Index (HSI) values were calculated and analysed statistically using a paired *t*-test of all life stages of each species individually in R-software (R Core Team, 2017, version 3.4.2.).

This study looked at HSI values used to describe two regional models of fish habitat associations, focusing on the depth, of three life stages of Lake Trout and Burbot. The analyses of these data took an alternate approach that followed the conceptual basis of the online R-based HEAT software applied in the Laurentian (Ontario) Great Lakes region; however, this study followed a semi-systematic evidence-gathering procedure. For example, using step 1-7 above, the depth class of 0-1m for Lake Trout young-of-the-year would record a reference weighting of 10 when a species at that life stage occupied 0.6 m on average in a given study and reported an 'after-impact' study design, in 3 lakes, with 12 fish collected. This reference weight of 10 would then be summed with other studies in the same habitat strata (0-1m) which were screened-in at a full text level to a hypothetical value of 18. The depth strata category as a whole would sum across all strata to a hypothetical value of 46. The HSI value could then be calculated proportionally across all depth classes from all reports for a Lake Trout young-of-the-year occurrence in the 0-1m depth class equal to 40% on average by dividing 18/46 for that particular class. The HSI value was then assigned to each depth strata category relative to the proportion values with 0-33% contributing to the low associations (1), 34-66% contributing to moderate associations (2), 67-100% as high associations (3), respectively. Nil (0) values in the dataset from literature indicated no association, rather than a lack of information (which was denoted as a missing value or N/A). These HSI values were then used for statistical analyses.

HSI values were compared between arctic and Laurentian (Ontario) Great Lakes regions for Lake Trout and Burbot. First, HSI values for each region were examined qualitatively by plotting histograms to assess distribution patterns, and summarizing known habitat association information. A paired *t*-test between regions, for each life stage was then used to quantitatively determine if there was a significant difference in the ice-free depth associations between the arctic and Ontario for Lake Trout and Burbot using the HSI values calculated (Table A3.5). All life stages from the Ontario HSI model were considered replicate values for the species by pairing them with the arctic HSI model for the same depth category and life stage. The suitability values of each habitat variable were plotted for each individual species across all life stages combined. All assumptions of the model were tested by assessing skewedness and kurtosis of the differences between pairs for normal distribution and outliers using D'Agostino's K-squared test.

3.3. Results

Qualitative and quantitative assessment of habitat associations and HSI results differed from one another in the number of species analysed. All 11 species were considered in the qualitative analyses, however Lake Trout and Burbot were the only identified candidate species for quantitative analyses based on availability of data.

3.3.1. CEE semi-systematic literature review

A total of 5,299 articles were collected from the Web of Science published between 2000-2019. All journal articles were screened at the title and abstract level. Only 52 articles were subsequently screened-in at the full-text level and used in data extraction

(Table 3.2). A summary table from these published studies were combined with known Nunavut/ Northwest Territories (Richardson *et al*., 2001) habitat association tables to supplement previous information with this review and then the total was compared with the Ontario dataset derived from Lane *et al*., (1996a, b, c) across the four core physical habitat variables of interest.

Table 3.2- Screening results from Web of Science for each of the 11 species surveyed using the search strategy.

Fish species common name	**Total Articles**	**Screened in at title/abstract level**	**Screened in at full text level**
Burbot	451	75	14
Ninespine Stickleback	240	34	2
Lake Trout	1023	61	9
Lake Whitefish	548	31	2
Round Whitefish	11	3	2
Slimy Sculpin	153	9	0
Arctic Char	2119	209	16
Arctic Grayling	153	52	3
Lake Cisco	146	10	3
Dolly Varden	179	24	2
Bull Trout	276	27	0
Total	*5299*	*535*	*52*

3.3.2. Quantitative analyses of Lake Trout and Burbot depth associations

Over half, 18 of 30, of the HSI values among both species across all life stages in the arctic region were represented by an absence of preference or a nil (0) value. There were only two high association categories for the arctic species, including adult/juvenile Burbot at +10 m depth and young-of-the-year Lake Trout at 10+ m depth. All other categories had HSI values between 0 and 1. Only 4 of 30 HSI values among both species and all life stages in the Ontario region were represented by an absence of preference or a nil (0) value. Over half, 18 of 30, of the HSI values in the Ontario region had high associations (HSI = 1). Similar to results for the arctic region, all other categories had HSI values between 0 and 1.

The paired *t*-test on the reported HEAT HSI values of depth associations in three life stages of Lake Trout (t_{14}= -3.9776, $p < 0.0001$) and Burbot (t_{14}= -4.7743, $p < 0.0001$) identified significant differences between regional datasets for each species. Higher HSI values, indicating stronger associations with depth, were identified across both species and most life stages in the Ontario Great Lakes region relative to the arctic region. Plots of paired comparisons for each life stage were created for Lake Trout (Figure 3.1) and Burbot (Figure 3.2). For the data as a whole, skewedness and kurtosis were significantly normal., z(skew)= .627, $p<.01$ and z(kurtosis)=-.106, $p<.05$.

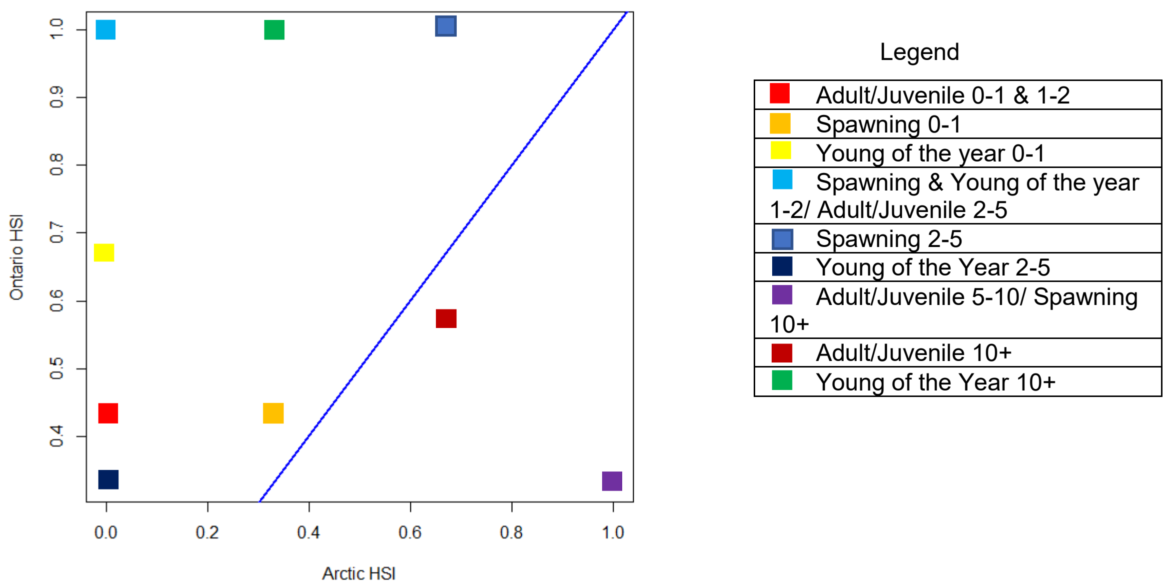

Figure 3.1 – Plot of paired Habitat Suitability Index values with depth for three Lake Trout life stages in two regions of Canada across depth categories. Circles below or to the right of the blue one-to-one line indicate observations with a higher association value for Arctic than for Ontario.

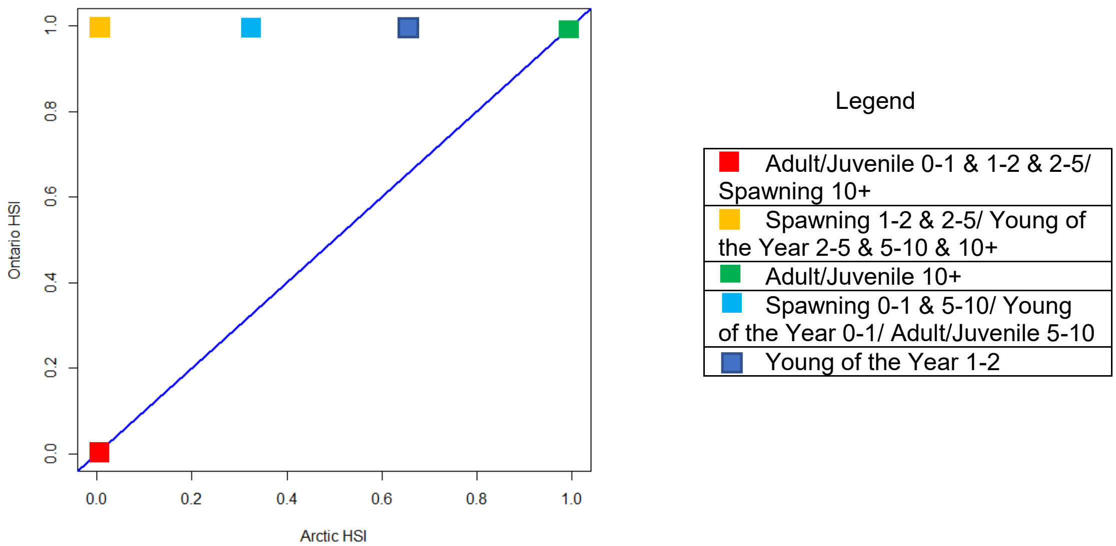

Figure 3.2 – Plot of paired Habitat Suitability Index values for three Burbot life stages with depth in two regions of Canada across depth categories. Circles below or to the right of the blue one-to-one line indicate observations with a higher value for the Arctic than for Ontario.

3.3.3. Qualitative habitat association descriptions by species

The semi-systematic literature review results that could not be configured into a statistical, quantitative-based analyses are summarized instead by species and habitat category searched. Literature sourced both north of 60 latitude was the focus and studies are discussed south of 60 latitude where data north of 60 was not available (Table 3.3).

Table 3.3 – Knowledge gaps in habitat requirements of fish species north of 60° from the semi-systematically reviewed literature (Web of Science for published and Fish-Out for unpublished).

	Depth			**Substrate**			**Vegetative Cover**			**Temperature**		
Species	*A/J**	*S**	*YOY**	*A/J*	*S*	*YOY*	*A/J*	*S*	*YOY*	*A/J*	*S*	*YOY*
Burbot	⊗*	⊗*	⊗*	⊗	⊗	⊗	⊗	⊗		⊗	⊗	⊗
Lake Trout	⊗*	⊗*	⊗*	⊗	⊗	⊗			⊗	⊗		
Arctic Char	⊗	⊗	⊗	⊗	⊗	⊗	⊗		⊗	⊗		⊗
Arctic Grayling	⊗	⊗	⊗	⊗	⊗		⊗	⊗	⊗		⊗	
Ninespine Stickleback	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗			
Slimy Sculpin	⊗	⊗	⊗	⊗	⊗	⊗			⊗			
Lake Whitefish	⊗	⊗	⊗	⊗	⊗	⊗	⊗		⊗			
Round Whitefish	⊗	⊗	⊗		⊗	⊗					⊗	
Bull Trout	⊗	⊗		⊗	⊗							
Dolly Varden	⊗	⊗		⊗	⊗							
Lake Cisco	⊗	⊗			⊗							

A/J= Adult/Juvenile; S= Spawning; YOY= Young-of-the-year; ⊗= Studies identified north of 60°; ⊗= Categories with data in each strata to facilitate analyses.

Burbot (*Lota lota*)

Burbot are one of the few species that spawns in the mid-winter, under the ice (Scott and Crossman, 1998). Freshwater populations can exhibit both lacustrine and riverine life histories, having resident subpopulations either completing their life cycle in a single lake or migratory, feeding and rearing mainly in lakes but spawning in rivers (McPhail and Lindsey, 1970; McPhail, 1997).

Depth associations

There is circumstantial evidence from Lake Simcoe, Lake Erie and Lake Manitoba that this species spawns in shallow water, on shoals less than one to three meters in depth (Clemens, 1951; Lawler, 1963; McPhail and Paragamian, 2000). In contrast, adult and juvenile Burbot north of 60° were found at depths of over ten meters (Guzzo *et al*., 2016; Kahilainen and Lehtonen, 2003), they spawned in five to ten meters of water (Cott *et al*., 2014; Martin and Cott, 2016) and the young-of-the-year occupied depths between zero to one meter in the ice-off season (Kjellman and Eloranta, 2002). Based on recent literature, Burbot generally occupy deeper areas of northern lakes, than they would south of 60° (Guzzo *et al*., 2016). Furthermore, while adult Burbot seek cooler, deeper waters in the summer, some individuals make diel movements into warmer, shallower water at night to feed (Cott *et al*., 2015). In conclusion, adult Burbot north of 60° are generally found in depths of five to ten meters of water during the ice-on periods of the year, and remain in this offshore zone, except to occasionally feed. During spawning/egg and young-of-the-year life stages, they are found in the littoral zone to feed during the open-water season before migrating back to deeper areas.

Substrate associations

At the beginning of their life cycle, as semi-buoyant eggs, Burbot sac fry are found primarily in the pelagic zone (Richardson *et al*., 2001; McPhail, 1960). Southern populations are known to spawn over gravel, sand or cobble substrates (Scott and Crossman, 1998) which tend to be limited to eskers in arctic and subarctic freshwater environments in Canada (Portt *et al*., 2015). Juveniles in the south are typically found over gravel bottoms and along boulder shorelines while water temperatures remain optimal for survival (McPhail, 1960). Seasonally, however, both juveniles and adults move offshore to deeper waters in the hypolimnion in early summer (Scott and Crossman, 1998). Populations north of 60° latitude have a general affinity for large, complex boulder substrate that provide a source of prey and shelter (Guzzo *et al*., 2016). European Burbot populations have also been observed over cobble or sandy-silt substrate (Fischer *et al*., 2001).

Vegetative Cover associations

Interstitial spaces in arctic and subarctic freshwater lakes are meaningful to this species beginning with the survival of semi-buoyant eggs that become demersal within a few days and settle into the matrix of the substrate (McPhail and Lindsey, 1970; Amundsen, *et al*., 2003). Once hatched, Burbot become photosensitive and seek shelter under stones, roots and amongst aquatic plants during the day (McPhail and Paragamian, 2000). The only form of complex structure in arctic and subarctic freshwater environments that could provide this form of shelter were larger substrate sizes or fissures. There is a lack of aquatic vegetation present in these environments, except for periphyton and flooded tundra vegetation. Burbot use the interstitial spaces of substrates during adult, juvenile and egg life stages (Guzzo *et al*., 2016; Cott *et al*., 2014; Cott *et al*., 2015). There was no published literature on the use of cover by young-of-the-year Burbot, however this is likely due to their pelagic activity.

Temperature associations

In temperate areas, Burbot are limited to the hypolimnion where there are optimal temperatures present for growth and reproduction (Scott and Crossman, 1998). Many arctic and subarctic lakes in the Kivalliq region, especially those that exceed five meters in depth, only undergo thermal stratification for two weeks in mid-July. The average temperature of lake environments in the Kivalliq region is approximately 2.5^{O}C annually, with a maximum temperature of 16-21^{O}C and a minimum temperature of 0.5^{O}C. In aquatic environments south of 60°, local spawning for Burbot is associated with the onset of water temperatures between 0.6 and 1.7 ^{O}C (Scott and Crossman, 1998). North of 60°, the optimal temperature during the adult and juvenile life stages ranges between 5 and 8

^{O}C (Guzzo *et al*., 2016; Donner and Eckmann, 2011) and is cooler for younger life stages; 4 ^{O}C (Kjellman and Eloranta, 2002) for young-of the year, and between 1.5 and 4 ^{O}C as an egg (Lahsteiner *et al*., 2012; Donner and Eckmann, 2011).

Lake Trout (*Salvelinus namaycush*)

Lake Trout are a widely distributed species, their range extending from the northern United States to northern Alaska and all throughout the Yukon, Northwest Territories and Nunavut; with both freshwater and anadromous morphs (Scott and Crossman, 1998). Throughout most of Canada, spawning occurs from late September north of 60° latitude, to early November in southern Ontario (McPhail and Lindsey, 1970).

Depth associations

In southern populations, spawning is known to occur as deep as 12 m and as shallow as 0.12 m throughout small, inland lakes. In the Great Lakes, spawning of Lake Trout can occur as deep as 36 m where the other habitat conditions are suitable (Scott and Crossman, 1998). In rare instances, spawning has been known to occur in rivers, as observed in Lake Superior (Loftus, 1958). North of 60°, adult and juvenile Lake Trout are typically found in the deepest areas of the lake around 20 m on average (Chavarie *et al*., 2018; McDermid *et al*., 2010). The spawning activity in arctic environments was observed in shallow areas next to steep drop-offs between one and six meters in depth where substrate was suitable (Callaghan *et al*., 2016; Faulkner *et al*., 2006; Muir *et al*., 2012). In Alexie Lake, Northwest Territories, the mean depth of tagged adult individuals during an acoustic telemetry study was 12 m (Guzzo *et al*., 2016). The adult individuals in this system occupied all depths, from less than one meter up to 30 m.

The quantitative analyses of depth of capture in this thesis indicated significant differences in depth patterns across regions. In southern Canada, depth-distributions of Lake Trout are well studied, and they are known to vary with the seasons (Scott and Crossman, 1998). For example, in autumn the mature adult individuals move into rocky shallows to prepare for spawning and then disperse freely throughout the water column in winter months; as surface waters warm in the spring, the species moves into cooler waters. All the research published on arctic populations are from the ice-off season, except for Guzzo *et al*., (2016) and as a result little is known about the overwintering habitat associations of fishes.

Substrate associations

Lake Trout create a redd to reproduce and as a result they are known to have a high affinity in southern populations for boulder or rubble substrate in inland lakes during spawning (Scott and Crossman, 1998). Binder *et al*., (2018) recorded Lake Trout spawning in northern Lake Huron consistently over five years in areas where gravel and cobble substrate met larger boulder in a 'reef-like' arrangement. Although Lake Trout may avoid areas with sand, silt and mud, several authors have observed or recorded spawning over these substrate types (Goodyear *et al*., 1982; Beauchamp *et al*., 1992; Minns *et al*., 2008). In Alexie Lake, Northwest Territories, Lake Trout spawning was observed at several sites with substrate ranging from 3-15 cm (cobble/rubble) immediately next to a drop-off location that had silt-sand adjacent to a boulder crib present in each location (Callaghan *et al*., 2016). Another study in the Lac de Gras area of Northwest Territories noted the dominance of boulder substrate in egg deposition areas (Faulkner *et al*., 2006). Furthermore, site observations at the Amaruq mine camp in the

Kivalliq region of Nunavut during August 2018 indicated that Lake Trout were staging on medium-sized cobble and rubble (personal observation, Hannah Hancock, August 24, 2018). For adult substrate associations outside of the spawning period, Lake Trout in Alexie Lake were reported to have a lower requirement for substrate complexity relative to Burbot and Northern Pike (Guzzo *et al*., 2016).

Vegetative Cover associations

Vegetation is not known to play an important role in the life cycle of Lake Trout in southern areas and as a result the cover preferences of this species are very similar across space and are associated with coarser bottom substrates. Eggs are laid and settle into the cracks amongst boulders, where they incubate in the interstitial spaces for four to five months (McPhail and Lindsey, 1970). Relative to Burbot and Northern pike, Lake Trout are known to occupy significantly less complex substrate and a pelagic position in the water column, ranging from nearshore to offshore areas (Guzzo *et al*., 2016). This is the only published account of cover requirements for Lake Trout north of 60°.

Temperature associations

In general., Lake Trout throughout their range are generally found to prefer 10 ^{O}C water (Scott and Crossman, 1998). They are known to make excursions above the thermocline in temperate climates despite unfavourably warm temperatures (Martin, 1954). The preferences of adult and juvenile life stages of Lake Trout north of 60° latitude were reported as between 1 ^{O}C and 10 ^{O}C (Mackenzie and Post, 2006a; Mackenzie and Post, 2006b). However, there is no published literature on the temperature preferences of the young-of-the-year, spawning and egg life-stages.

Lake Whitefish (*Coregonus clupeaformis*)

Lake Whitefish can be found across Canada from coast to coast to coast, as far south as southern Lake Michigan to the most northern tip of Alaska (Scott and Crossman, 1998). Throughout their range, Lake Whitefish are found within freshwaters, however in the Hudson Bay region and Arctic Ocean drainages they enter brackish waters (McPhail and Lindsey, 1970). South of 60° latitude this species is one of the most commonly studied fishes, mainly because it has long been considered an important commercial resource in the Laurentian Great Lakes region (Lawler, 1965). North of 60°, the species is understudied in lacustrine environments with only depth preferences of the adult and juvenile life stages reported in the published literature since 2000. Scott and Crossman (1998) noted this species spawns in November and December in the Laurentian Great Lakes region. Previously, the furthest north where patterns were reported in the published literature is Lake Manitoba where spawning occurred between October 19 and 25, 1953 (Lawler, 1965).

Depth associations

Richardson *et al*., (2001) reported a comprehensive outline of the specific depth distribution of Lake Whitefish across all four life stages. Several studies indicated that spawning took place in shallow water areas less than 5-8m deep when the temperatures reach 8°C (Bryan and Kato, 1975; Anras *et al*., 1999; Scott and Crossman, 1998). Young-of-the-year then migrate to shallow surface waters, less than 1 m within the general vicinity of the spawning area (Goodyear *et al*., 1982). There were accounts of juvenile Lake Whitefish movement in relation to the isotherm, following the 17°C isocline in their first year of life (Reckahn, 1970; Lindsay and Woods, in review). In northern waters, this species may only spawn every second or third year (Scott and Crossman, 1998). Adults and juveniles were found at depths of over 10m for most of the year and have been found at depths in excess of 100m (Olk *et al*., 2016; McPhail and Lindsey, 1970).

Substrate and Vegetative Cover associations

There were no published accounts of substrate or cover preferences for Lake Whitefish since 2000. Scott and Crossman (1998) note that this species often spawns over hard or gravel bottom, but sometimes over sand. Eggs were released over the substrate and settle into the matrix of crevices, where they incubate for several months before hatching sometime from March to May (Harper, 1948). Richardson, *et al*. (2001) concluded that juveniles were often found over boulder, cobble and gravel substrates in association with vegetation and woody debris (Bryan and Kato, 1975). This cannot be the case for this region due to the lack of these habitat features, however Richardson *et al*., (2001) also suggest that during all other life stages, this species generally does not show preferences for substrate. In addition, they are primarily bottom dwelling, although they have been found in pelagic zones of lakes (Harper, 1948).

Temperature associations

There was one published account of temperature preferences in Lake Whitefish since 2000 which identified their home range to be within 7°C to 10°C with a peak at 11.1°C and observations in February at 1°C (Madenjian *et al*., 2006). Laboratory studies cited by Scott and Crossman (1998) in Great Slave Lake indicated spawning occurred mainly between late September and early October (Rawson, 1949). Another study concluded that the species will not spawn until temperatures reach below 7.8°C and that eggs would experience 99% mortality at over 10°C, with optimal ranges tested under experimental conditions between 0.5° - 6.1°C (Rawson, 1951).

Lake Cisco (*Coregonus artedi*)

Lake Cisco has an arctic distribution limited to Nunavut and the Northwest Territories in Great Bear Lake at its furthest northwestern range, extending to eastern Quebec and as far south as southern Lake Ontario (Scott and Crossman, 1998). This species has a lacustrine life history, however some anadromous individuals have been recorded in the Ungava region of James Bay (Morin *et al*., 1981). The biology and ecology of this species were more well-known than that of any other morphotypes of Cisco. Spawning takes place one to two weeks after Lake Whitefish spawn in the fall, although the exact date depends on water temperature (Scott and Crossman, 1998).

Depth associations

Three sources of published literature on Lake Cisco north of 60° since 2000 report on the adult and juvenile life-stage depth associations. The depth of capture ranged from 35-55 m on average (Muir *et al*., 2014; Muir *et al*., 2013; Blackie *et al*., 2012). Adult Lake Cisco are most commonly found at depths from 10-60m throughout the year because they prefer cooler waters in the hypolimnion of lakes south of 60° latitude (Dryer, 1966). In inland lakes, spawning usually takes place in shallow water 1-2 m deep (Scott and Crossman, 1998). In the Great Lakes, spawning has been documented offshore at 9-12 m (Smith, 1964) and in benthic regions at 65m (Dryer and Beil, 1964). In Great Slave Lake, Cisco are most common within the top 30m of the water column, and become less frequent at greater depths (Rawson, 1949). Richardson *et al*., (2001) noted that at the time very little was known about the habitat requirements of young Lake Cisco and this remains the case with the current review.

Substrate and Vegetative Cover associations

There were no published sources of literature on the substrate and cover preferences of Lake Cisco north of 60° since 2000. Scott and Crossman (1998) note the species were known to spawn over any substrate type, however, it is often cited over gravel. The eggs of the Lake Cisco incubate over the winter for approximately 12 weeks and hatch the following spring just before ice breakup (Richardson, *et al*. 2001). The deepwater life cycle of this species may be the reason there is limited literature on these topics.

Temperature associations

There were no published sources of literature on the temperature preferences of Lake Cisco north of 60° since 2000. In Wisconsin, Cahn (1927) observed spawning at temperatures between 4-5°C just before ice-on. However, they noted that spawning would occur even if these temperatures were not reached. Laboratory experiments have indicated that incubation temperature for this species was most ideal at 5.6°C (Colby and Brooke, 1970). In Minnesota lakes the lethal temperature was observed to be at 24°C (Jacobsen *et al*., 2008). In arctic and subarctic lake environments, these temperatures are not reached until mid-fall and as a result the incubation time in the species may persist longer in cooler climates.

Round Whitefish (*Prosopium cylindraceum*)

In North America, the species distribution was identified by Scott and Crossman (1998) across all three Canadian territories, with three smaller populations south of 60° in southern Ontario and central Quebec. They exhibit lacustrine, riverine and ad-fluvial life history types predominantly in freshwater environments, however they have also been found in brackish waters (McPhail and Lindsey, 1970; Goodyear *et al*., 1982). Spawning occurs primarily in lakes and on occasion in streams throughout October north of 60° (Lawrence and Davies, 1978). They were commonly found in cold, clear water above 37m depth however, they were known to use turbidity for cover when it is present in the environment (Stewart *et al*., 2007). Although most of their range exists north of 60°, only two literature sources were published on their physical habitat requirements since 2000.

Depth associations

Post-2000 literature on physical habitat requirements of Round Whitefish found adult and juvenile individuals in the fall at depths of five meters on average but up to 37 m maximum (Lim *et al*., 2018). Richardson *et al*., (2001) comprehensively discussed the depth preferences of the entire life cycle of the species. Spawning typically occurs in shallow water (Normandeau, 1969; Bryan and Kato, 1975) but has been recorded at depths from 5-10 m (Haymes and Kolenosky, 1984). Juveniles have been encountered from 1.5 - 4.5 m (Normandeau, 1969; McPhail and Lindsey, 1970). Depth preferences of adult species were not reported in the Richardson *et al*., (2001) literature review.

Substrate and Vegetative Cover associations

There were no published records of substrate and cover habitat preferences in Round Whitefish since 2000. Scott and Crossman (1998) cited spawning studies across the Great Lakes at variable depths, however it is consistently found over gravel substrate in that region. On the border of 60° latitude, at Nueltin Lake between Manitoba and the

Northwest Territories, an upstream migration related to spawning activity was noted in late October (Harper, 1948). Richardson *et al*., (2001) reported that adults were often found in association with boulders in the north.

Temperature associations

There was only one published record of optimal temperature ranges for Round Whitefish north of 60° since 2000. Stewart *et al*., (2007) concluded that the species was commonly found in cold, clear water between 0 to 18°C. Richardson *et al*., (2001) does not present any temperature information for this species. Scott and Crossman (1998) noted that in the Great Lakes region Round Whitefish are known to spawn at 4.5°C on average. A population local to Lake Superior was studied over-winter and hatching success was based upon optimal development at 2.2°C on average for 140 days (Bailey 1963).

Ninespine Stickleback (*Pungitius pungitius*)

Ninespine Stickleback exhibit a circumpolar distribution in fresh and brackish waters throughout the northern hemisphere (Scott and Crossman, 1998). In Canada, the species occurs in all provinces and territories. On occasion, this species has been known to spawn multiple times in one season between May to late July and no evidence has been collected of autumn spawning (Scott and Crossman, 1998). There was more published literature on the marine variant of this species and as a result significant data gaps exist in the knowledge of physical habitat associations of the freshwater morphotypes.

Depth associations

There was one published account of depth preferences in adult and juvenile freshwater Ninespine Stickleback north of 60° since 2000 that noted their presence in 1.5 m of water on average near Iqaluit, Nunavut (Gallagher and Dick, 2011). Richardson *et al*., (2001) reports spawning behaviour in relatively shallow water up to depths of 40 m in some areas (McPhail and Lindsey, 1970).

Substrate and Vegetative Cover associations

There were no published sources of literature on the substrate and cover preferences of Ninespine Stickleback north of 60° since 2000. This species is well known for unique habitat requirements during spawning events in temperate latitudes with the construction of a tunnel-shaped nest by males with vegetation, detritus and woody debris which is bound together with a thread-like kidney secretion (Scott and Crossman, 1998; McPhail and Lindsey, 1970). Eggs incubate for 4 - 7 days before hatching, upon which time the young are moved into a nursery area, which the males construct from the nest material and create just above the nest (McPhail and Lindsey, 1970; Morrow, 1980). The low-lying vegetation, periphyton and detritus present in shallow, warmer, ephemeral ponds of Nunavut and the Northwest Territories, with connecting channels to larger lakes, may facilitate this type of nursery and spawning activity in arctic and subarctic lakes (Portt *et al*., 2015).

Temperature associations

There were no published sources of literature on the temperature preferences of Ninespine Stickleback north of 60° since 2000, in Scott and Crossman (1998) or Richardson *et al*., (2001).

Slimy Sculpin (*Cottus cognatus*)

Slimy Sculpin has both lacustrine and riverine life history types, however they are typically found in rivers, streams and creeks (McPhail and Lindsey, 1973; Richardson *et al*., 2001). They are widely distributed across Canadian freshwater systems with no evidence of anadromous populations. Richardson *et al*., (2001) reported spawning in May, however there is very little known about the biological requirements for reproduction of this species – especially in arctic and subarctic ecosystems. There were no published literature accounts for Slimy Sculpin from studies north of 60° since 2000 for the physical habitat variables researched for this study.

Depth associations

There were no published sources of literature on the depth preferences of Slimy Sculpin north of 60° since 2000. This species is benthic and as such it spends the majority of its life cycle on the lake bed (Scott and Crossman, 1998). According to Richardson *et al*., (2001), spawning typically occurs in less than 1.5m of water, young-of-the-year are encountered in 0.5 to 1.5m of water and adult Slimy Sculpin can be found at depths from 0.5 to 210m. This large range indicates the spawning and nursery depths cannot be determined with confidence. Within Nunavut, the species were encountered in areas with current and wind action in waters greater than 10m deep (McPhail and Lindsey, 1970).

Substrate and Vegetative Cover associations

There were no published sources of literature on the substrate and cover preferences of Slimy Sculpin north of 60° since 2000. Spawning was well known to occur over sand, gravel and cobble in littoral embayment areas of lakes as males select nest sites in the interstitial spaces of the substrate (McPhail and Lindsey, 1970).

Thermal associations

There were no published sources of literature on the substrate and cover preferences of Slimy Sculpin north of 60° since 2000. The species was known to be acclimated at a mean temperature of 20°C and have been reported in 13°C to 25°C waters south of 60° (Symons *et al*., 1976; Otto and Rice, 1977).

Arctic Char (*Salvelinus alpinus*)

Arctic Char has the most northerly distribution of any freshwater fish and exhibits anadromous life history (Scott and Crossman, 1998). It has a circum-polar distribution and is in the most northern areas of Canadian waters. Anadromous Arctic Char are more commercially significant than inland, freshwater char and as a result the marine morphotypes are better studied (Scott and Crossman, 1998). In arctic waters, Arctic Char spawn in September or October in lakes, or in quiet pools of rivers (McPhail and Lindsey, 1970). Scott and Crossman (1998) also indicate populations of Char permanently dwelling in Canadian lakes have received little attention, especially in the Barrenlands region of the arctic and subarctic.

Depth associations

Scott and Crossman (1998) report this species spawning at depths of 1-4.5m in arctic waters. Similarly, Richardson *et al*., (2001) notes spawning activity in 0.5-2m south of 60° latitude. The results of the semi-systematic literature review indicate spawning activity of this species occurs at depths of 1.5-4.0m (Sorum *et al*., 2011; Amundsen *et al*., 2010; Svenning, *et al*., 2007). Literature sources published before 2000 suggest juveniles are most often found in deep, benthic habitats of lakes at depths >5m (Bjoeru and Sandlund, 1995; Naesje, 1995; Richardson *et al*., 2001). Depth preferences of young-of-the-year are not well distinguished, however they have been found in 12-20m of water on average throughout Europe (Amundsen and Knundsen, 2009; Svenning *et al*., 2007) and in >4m of water in North America (Sinnatamby *et al.*, 2012) in recent literature. Richardson *et al*., (2001) suggest Arctic Char usually occupy the pelagic zone of lakes during the summer and make seasonal shifts to benthic/littoral habitat in the fall, when zooplankton are less abundant. Since 2000 there have been 12 published accounts of Arctic Char that present depth data for the adult life stage. There was no consensus among the literature based on the weight of evidence associated with each source to indicate Arctic Char are associated a specific depth zone (Eloranta *et al*., 2017; Dick *et al*., 2009; Saksgard and Hesthagen, 2004).

Substrate associations

As a species in the salmonid family, Arctic Char create a nest in clean gravel for spawning, however they are cited by Scott and Crossman (1998) as being uniquely known for burying their eggs beneath the gravel over winter. Richardson *et al*., (2001) note young-of-the-year char and juveniles use their substrate in a similar manner, as refuge from predators, and they tend to have a strong affinity for large cobble, rubble and boulder (L'Abee-Lund *et al*., 1992). As juveniles, Arctic Char may become pelagic, however as the species matures most individuals will shift from benthic to pelagic habitat to prey upon zooplankton in the open-water season (Reist *et al*., 1997; Bjoeru and Sandlund 1995). Since 2000 there have been three published accounts of substrate use by

Arctic Char. Adults and juveniles were found using gravel in the offshore zone (Sorum *et al*., 2011) and in the pelagic zone over silt substrate (Amundsen and Knudsen 2009). Young-of-the-year were identified in a Norwegian lake as using boulder substrate (Bystrom *et al*., 2009) and spawning/egg masses were noted on gravel substrate by one study (Sorum *et al*., 2011). Of note, all published accounts of substrate use by freshwater-resident Arctic Char have come from European sources since 2000.

Vegetative Cover associations

Richardson *et al*., (2001) identifies several sources that suggest the benthic life stages of this species (which include all except for mature adult) were heavily dependent upon the presence of large, complex, boulder substrate to provide cover from predation by large-bodied fishes. This may also be the reason they tend to cover their fertilized egg masses with gravel, to provide cover from predation. Three sources published since 2000 suggest all life stages may use the interstitial spaces among boulder substrate as cover (Eloranta *et al*., 2017; Amundsen and Knudsen, 2009; Bystrom *et al*., 2004).

Temperature associations

Scott and Crossman (1998) cited the onset of spawning activity at 4°C, optimal incubation between 0°-2.2°C and mortality of eggs above temperatures of 7.8°C. Richardson *et al*., (2001) do not cite any temperature preferences for the freshwater resident morph. Recently published sources suggest the adult life stage can thrive anywhere from 5-13°C on average, young-of-the-year prefer 5°C on average and there were no new sources that cited spawning or egg incubation temperature preference (Sinnatamby *et al*., 2012; Siikavuopio *et al*., 2014; Larsson, 2005).

Arctic Grayling (*Thymallus arcticus*)

Arctic Grayling has many unique characteristics for a species in the salmonid family. They are distributed across a Holarctic pattern mostly in freshwater and very rarely in brackish or salt water conditions as documented in Asia (Scott and Crossman, 1998). They also exhibited lacustrine, ad-fluvial and riverine life history types (McPhail and Lindsey, 1970). Regardless of their life history, spawning takes place immediately following ice-off in cold rivers and streams (Richardson *et al*., 2001). This migration, which can take place anywhere from April to June north of 60°, depending on the latitude and annual climate (Rawson, 1950; Bishop, 1971). Courtship activity was most common during the day during warmer temperatures and no actual nest or redd was prepared (Richardson *et al*., 2001). All published literature that presents relevant physical habitat data on this species since 2000 focuses on the life stages that require riverine habitat which is mostly limited to spawning activity. Richardson *et al*., (2001) cited no information on Grayling spawning in lakes throughout Nunavut and the Northwest Territories, however Alaska Grayling have been observed spawning in littoral areas of deep lakes (Krueger, 1981).

Depth associations

Scott and Crossman (1998) only cite one study that analysed depth preferences of this species in lake habitat during a gill net study on Great Slave Lake at no greater than 3.05m (Bishop, 1971). Richardson *et al*., (2001) notes juvenile and young-of-the-year Arctic Grayling are found at depths ranging from 0.20-0.46m (Krueger, 1981). They also cite adult species as shallow-water dwellers inhabiting <3.0m in most lakes (McPhail and Lindsey, 1970). Three literature sources published since 2000 provided similar depth associations of 0.15-0.6 m among all life stages in riverine habitat (Baker *et al*., 2017; Jones and Tonn, 2004; Jones *et al*., 2003).

Substrate and Vegetative Cover associations

Arctic Grayling mature at approximately 9 years and 410mm on average (Scott and Crossman, 1998; Miller, 1946). Due to their relatively small size at maturity, this species is cited in both past and present literature using interstitial spaces throughout their entire life cycle (Baker *et al*., 2017; Jones and Tonn, 2004; Jones *et al*., 2003). Furthermore, Scott and Crossman (1973) noted that the vigorous vibration and clasping behaviour that takes place during spawning often disturbs the substrate and covers the eggs with debris.

Temperature associations

Although the onset of spawning activities in this species was highly correlated with the ice-off of streams and nearshore areas of lakes, the temperature preferences of this species are not well documents in past and present literature. Hatching temperature was the only well-studied aspect of the Grayling life cycle that is cited by Scott and Crossman (1998) from 7-11°C in tributaries of Great Slave Lake. Jones *et al*., 2003 presented the only published account of Grayling temperature preferences at an average of 5°C during onset of spawning activity in the tributaries of Lac de Gras, Northwest Territories.

Bull Trout (*Salvelinus confluentus*)

Bull Trout have been designated as their own species, separate from Dolly Varden, since Scott and Crossman (1998) was published. Fisheries and Oceans' research scientists confirmed their presence in several locations in the Mackenzie River valley (Reist *et al*., 2002; Mochanacz *et al*., 2013), however they are not known to occur in Nunavut

(Richardson *et al*., 2001). They exhibit riverine and ad-fluvial life history types. There have been no published accounts of physical habitat preferences in Bull Trout since 2000.

Depth associations

There were no published sources of literature on the depth preferences of Bull Trout north of 60° since 2000. Only mature adults will migrate to lake habitat; they have been identified primarily within 3m of the bottom, at depths of 22.5-40m (Connor *et al*., 1997).

Substrate and Vegetative Cover associations

There were no published sources of literature on the substrate or vegetative cover preferences of Bull Trout north of 60° since 2000. All existing literature on Bull Trout substrate preferences is classified as Dolly Varden habitat preferences and as a result these findings are reported below.

Thermal associations

There were no published sources of literature on the thermal preferences of Bull Trout north of 60° since 2000. All existing literature on Bull Trout thermal preferences is classified as Dolly Varden habitat preferences and as a result these findings are reported below.

Dolly Varden (*Salvelinus malma*)

Dolly Varden were found in isolated populations on the western coast of North America, as far south as northern California, and to the north coast of Alaska (Scott and Crossman, 1998). They are known to be common in central Yukon and some localities in the Northwest Territories but have not been encountered in Nunavut as yet (McPhail and

Lindsey, 1970). A vast majority of Dolly Varden exhibit anadromous and riverine life history; there has been confusion about speciation of lacustrine life history types among salmonid populations in western Canada for decades (Richardson *et al*., 2001) however there are more recent records of landlocked populations in the Northwest Territories and Russia (Markevich *et al*., 2018; Ghamry *et al*., 2016). Spawning takes place in typical salmonid fashion, during the fall between September to early November near spring seeps or river mouths (McPhail and Lindsey, 1970). Males aggressively defend their redd, which is typically 305mm deep and 6.1m apart from one another (Scott and Crossman, 1998). The Dolly Varden is the only species at risk involved in this literature review. The western Arctic populations have been designated as 'special concern' since 2011 (COSEWIC, 2011).

Depth associations

There were no published sources of literature on the depth preferences of the Dolly Varden freshwater morph in Scott and Crossman (1998) or Richardson *et al*., (2001). Markevich *et al*., (2018) cited spawning activity of Dolly Varden in a lake habitat within 0.5m of water on average.

Substrate and Vegetative Cover associations

There were no published sources of literature on the substrate and cover preferences of the Dolly Varden freshwater morph in Scott and Crossman (1998) or Richardson *et al*., (2001). Ghamry *et al*., (2016) noted an affinity for cobble substrate during the spawning and nursery period of the Dolly Varden life cycle.

Temperature associations

There were no published sources of literature on the temperature preferences of the Dolly Varden freshwater morph since 2000, in Scott and Crossman (1998) or Richardson *et al*., (2001).

3.4 Discussion

This study highlighted three main findings. First, that most literature regardless of the region did not often include studies which were specifically designed to differentiate habitat suitability, or from which sufficient detail regarding habitat suitability could be obtained. Second, that the Collaboration for Environmental Evidence approach sets a very high standard that ask causational yes-or-no questions rather than scientific observations from field surveys often presented in ecological research. Finally, that a need exists for wider scale systematic assessments of differential habitat use, possibly using the Broadscale Monitoring protocol with a combination of hydro-acoustic surveys and physical habitat observations in different ecoregions in conjunction with bathymetric surveys, substrate mapping and basic limnological conditions in order to inform HEAT models (i.e. temperature, dissolved oxygen, turbidity and light) and impact decision making overall.

3.4.1 Habitat suitability of northern populations

The hypothesis that HSI values will have greater depth associations south of 60° latitude than north of 60° was supported and therefore they are more likely to be encountered at all life stages, across all depths in Ontario versus the arctic. Results of the quantitative analyses that described two paired *t*-tests looking at depth of Lake Trout and Burbot indicated there was a significant difference across the two study regions for both species;

stronger depth associations in Ontario versus arctic. The differences described by the quantitative analyses were much lower than the statistical alpha value of 0.05 for both species. Differences of this magnitude indicate that assuming southern Ontario distributional patterns in applications of HEAT in northern environments very likely results in incorrect assessments. Depth shapes distributional patterns more in the south versus the north which should be expected due to the lack of thermal structure north of 60° compared to south of 60°. Lake Trout was a good candidate species to occupy different depth strata south of 60° in response to the thermal structure of their environment. The application of literature that is not sourced from the same climatic conditions where a population was experiencing an impact cannot be expected to accurately predict the ecological outcome of development activities in that region. The findings of this study place emphasis on the importance of locally-sourced knowledge, scientific studies and other complementary measures to assess how best to compensate for the authorized development activities. Results of the qualitative analyses indicate the importance of filling identified knowledge gaps that exist in physical fish habitat associations north of 60° latitude. There was no literature to inform the young-of-the-year life stage of Lake Cisco and no literature at all to inform any life stages of Slimy Sculpin, Dolly Varden and Bull Trout.

The strength of association between physical habitat features with different fishes are used to calculate net gains and losses associated with development activities in HEAT. This interpretation of fish habitat facilitates a basic understanding of the ways in which fishes interact with their environment, essentially based upon where they are likely to be found on the landscape. In southern localities, significant pressures from urbanization have caused habitat destruction and species extirpations (Seilheimer *et al*., 2007), and the availability of physical habitat areas with the proper features, functions and attributes that facilitate major life processes of fishes are of limiting quantity. As a result, the frequency of habitat modelling by an analysis of depth, substrate and vegetation or cover preferences in the HEAT output data is quite common. In the arctic region, the same pressures are not present and as a result the quantity of available habitat which was limiting for southern populations (on which HEAT models are currently based) may not be limiting for fishes in northern regions. Other work has demonstrated that the limiting habitat feature in arctic lacustrine ecosystem appears to be associated with prey availability of a given habitat type (Milne, *in prep*., 2019). The aquatic invertebrate communities, predominantly Blackflies and Mosquitoes, were known to molt in ephemeral events from their juvenile life stage in the water column to dry land, forcing fishes to flood littoral zones to feed (Downes, 1965). When temperatures reach appropriate levels to cease dormancy, Blackfly and Mosquito larvae activate their transition from lacustrine to terrestrial environments where they will begin to grow before returning to their aquatic habitat for mating (Downes, 1965). There are very large populations of such insects in arctic climates. As a result, their gelatinous egg masses serve as an excellent food source ahead of spring emergence for fishes. It would be advisable for the HEAT model to consider including parameters such as ecosystem productivity to enhance the accuracy of model results.

Furthermore, the search results of the CEE-SR procedure on published literature sourced from the Web of Science may be further expanded to include literature on riverine species to determine if any publications were missed in the analyses of this study. Average values were extracted for analyses for the purposes of this study, however it would enhance the accuracy of the HEAT model analyses if distributional catch data was available for each physical habitat variable.

3.4.2. Habitat suitability of southern populations

There are several sources of published summary data regarding fish habitat preferences, including Scott and Crossman (1998) and Lane *et al*., (1997) and online databases that collect the same information. These published resources have been used to build the base tables of the current, online HEAT model which has been used by professional environmental consultants and resource managers to assess the impacts of development projects in the Laurentian Great Lakes region and beyond. Although the published summaries cite primary, peer-reviewed, scientific literature to support the findings of their habitat suitability index values, they did not utilize the same quantitative approach employed by this study to calculate the arctic habitat suitability index values. The difference in the methodologies may have provided a source of variation in the results– nonetheless – both regional approaches provided a source of habitat suitability index values for comparison. Further studies may include analysis of the Richardson *et al*., (2001) literature tables as they too follow the same format used for the HEAT model elsewhere. A systematic method of developing HSI values was presented in this thesis as a template for how comparisons might be completed moving forward.

3.4.3. Observed differences across latitude in Canada

Unlike the results published in the second chapter of this thesis, there were significant differences detected among Lake Trout depth preferences across regions. The differences observed in Lake Trout and Burbot HSI values were the only data available to make a statistical determination, and suggest that regionally-specific information would aid in creating a more accurate model of lacustrine physical habitat associations in the arctic. If the HEAT model was to be used as a national toolkit it would be advised that the data tables reflect different ecoregions in which the model might be applied. The refinement of data sources such as the Fish-Out database to contribute directly to knowledge of fish habitat associations by including basic ecological data about the environment in which fishes are caught would be useful. This local baseline knowledge could serve as historical and pre-construction data that could be referenced during environmental assessments of inevitable development activities north of 60° latitude. Currently, these ecosystems contribute to fleeting, cold, freshwater fish habitat for fish populations in summer that will only become rarer in the face of climate change and other pressures over the 21st century.

3.4.4. Data gaps in fish habitat associations north of 60°

Future research is required to fully explore the fish habitat associations among arctic populations that would greatly benefit the accuracy of impact assessments. HEAT provides a general modelling framework from the Laurentian Great Lakes region with the potential to be applied as a national tool to areas such as the Canadian arctic. The following recommendations come from this study in order to improve the overall accuracy north of 60° latitude:

1) Update literature base tables to include locally sourced data;
2) Use a quantitative method, such as that employed in this thesis, to determine the weight of evidence provided by sourced data;

3) Incorporate depth as core habitat parameters for arctic models because these variables likely drive observed regional variation.

As a final thought, arctic fish habitat science has many uncharted frontiers that present a vast opportunity for future quantitative research.

4. Chapter 4 – Conclusions

The rapid rate of rising temperatures and highly destructive nature of development activities north of 60° latitude has been unprecedented over the past decade. Arctic marine environments are the focus of a great deal of research that was screened out during the systematic review process of this thesis. Studies in salt water suggest fishes are experiencing increased abundances, expanded distributional ranges and increasing temperatures twice as fast as the global average (Hoegh-Guldberg and Bruno, 2010; Doney *et al*., 2011). Arctic ecosystems are expected to have the largest invasion of non-native species, modelled at an intensity 5 times the global average (Cheung *et al*., 2009; Fossheim *et al*., 2015). Information production, acquisition and analyses in this region might therefore give valuable insight into proper fisheries management.

The findings of this thesis suggest both through comparison of both catch data (due to lack of sufficient data) and HSI comparisons, that region-specific models are needed. The depth of occupancy analysis conducted in Chapter 2 indicated that Lake Trout use depth similarly across regions of Canada. In contrast, Habitat Suitability Index analyses in Chapter 3 based on summaries of published and available data indicated that both Lake Trout and Burbot at all life stages have significantly greater associations with depth in southern regions than they do in the arctic. The conflicting evidence suggests that more data will be required to make a final determination about the feasibility of regional models in evaluating impacts to fish habitat. Nonetheless, the HSI analyses followed a more robust method with greater sample sizes and as a result the significant differences detected in this chapter are important to overall recommendations for future work. Expected shifts in ecosystem structure will change the ecological interactions of fishes and therefore developing a baseline understanding of these sensitive areas is highlighted by the findings of this study.

This study also suggests that the current HEAT base tables can be improved upon by incorporating data that is sourced from specific ecoregions. Stakeholders actively engaged in arctic development activities are one of the main sources of access to these remote areas. As a result, opportunities to inform the overall scientific understanding of fish habitat associations are essential in these areas where infrastructure exists. Beyond opportunities with developers are those to consult with Indigenous communities in a meaningful, mutually beneficial fashion. Relationships of this nature take several years to develop, however engagement in consultation may yield a great deal of knowledge due to the intimate relationship which these peoples have with the natural environment.

The results of this thesis also highlight the data gaps in the existing published and unpublished literature sources north of 60° for basic ecological fish habitat associations in lacustrine environments. It will not be possible to conduct a community analyses of fishes in the primary or secondary watersheds of the Kivalliq region using the HEAT model to it’s full capacity based on information from the Great Lakes because some of the keystone predators, such as Arctic Char and Arctic Grayling, are not present in the current online environment (i.e., these species are not present in Great Lakes watersheds, where HEAT was developed). As such, tertiary watersheds should be targeted to obtain the most accurate fish lists for analysis in HEAT. The analysis presented in this thesis were heavily impacted by the lack of available data sourced from the pan-arctic research. The approach that was used could be expanded to include species from other habitat types, such as rivers and literature sourced before 2000 to ensure all sources of data are assessed using the same protocol. These findings can be used in decision making when assessing impacts in freshwater, arctic fish communities to determine the accuracy of the model provided. Ultimately, arctic models should be interpreted with caution and the base literature sources should be provided along with the model results to demonstrate 'no-net-loss' of fish habitat (Minns, *et al*. 1999).

Key recommendations that arise from the results of this study concern the Collaboration for Environmental Evidence Systematic Review (CEE-SR) protocol and the Fish-Out database. Although the benefits of systematic literature reviews in decision making are clear, the CEE-SR protocol could benefit from softening the structure of search strategies and critical appraisal to accommodate the incorporation of more streamlined, rapid studies that contain relevant information but do not follow the BACI-style designs. For example, a similar methodology as what was used to develop HEAT in the south could be applied to make more clear comparisons across regions in the modelling software. Similarly, the Fish-Out database does not conveniently provide comparable habitat data with fish community information to facilitate any meaningful analyses due to the methods for deploying the gill-net sets which has lacked standardization or proportionality relative to surface area of specific depth intervals, for example, to facilitate this type of analysis. It would enable a more robust analyses if one method could be adopted across the two regions.

The application of generic fish habitat models, such as HEAT, in arctic ecosystems has only recently been explored. The results of this study show that the current version of HEAT should be updated to include region-based literature. To expand HEAT to regions beyond the Laurentian Great Lakes, updates will likely have to be made that contribute to region-specific versions, however a larger sample size of lakes from north of 60° latitude should be compared against those south of 60° when comparable habitat data becomes available. The evidence synthesis methods proposed for the analyses of HSI values will help to develop a baseline protocol for HEAT literature analyses in future studies that improves the spatial application of the existing software. This research notes that more studies are required to uncover local habitat associations and micro-distributions of freshwater fish species in the Kivalliq region of Nunavut and throughout the Canadian arctic region.

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Appendix I- Temperature profiles and fish density estimates from the Broadscale Monitoring database

This appendix presents temperature profile data and density estimates of Lake Trout and Burbot at 5 meters depth intervals from 0 to the maximum depth of each lake. Data is presented here for all 6 lakes randomly selected for analysis in this study. In Mameigwess Lake the temperature profiles varied from 9 ^{O}C to 16 ^{O}C. The density of Lake Trout and Burbot reached a maximum value of 11 and 5 per net set, respectively, in 6 to 10 metres of water (Appendix I- Figure A1.1). This temperature recorded at this depth was the coolest water temperature, whereas the temperature was the warmest in the deepest portion of the lake. The temperature profile in Daniels Lake varied from 5 ^{O}C to 9 ^{O}C. The density of Lake Trout and Burbot reached a maximum value of 13 and five per net set, respectively, in 6 to 10 meters of water (Appendix I- Figure A1.2). This point in the data was the second warmest, with the thermocline observed between 11 to 15 metres of water, with cooler temperatures observed from 16 to 50 metres. The Cry Lake temperature profiles ranged from 14 ^{O}C to 5 ^{O}C. The density of Lake Trout and Burbot reached a maximum value of 11 and 5 per net set, respectively, in 6 to 10 metres of water (Appendix I- Figure A1.3). This point in the data was the second warmest and no stratified thermocline was observed. In Castle Lake the temperature profiles varied from 21 ^{O}C to 4 ^{O}C. The density of Lake Trout reached a maximum value of 9 per net set, in 6 to 10 metres of water and Burbot reached a maximum value of six in 11 to 15 metres of water (Appendix I- Figure A1.4). In Tinto lake the temperature profile varied from 24 ^{O}C to 5 ^{O}C. The density of Lake Trout reached a maximum value of 3 per net set, in 6 to 10 metres of water and Burbot reached a maximum value of 1 in 16 to 20 metres of water (Appendix I- Figure A1.5). In Kamikau Lake the temperature profile varied from 21^{O}C to 6^{O}C. The density of Lake Trout and Burbot reached a maximum of 1.5 per net set, in 11 to 15 metres of water (Appendix A1.I- Figure 6).

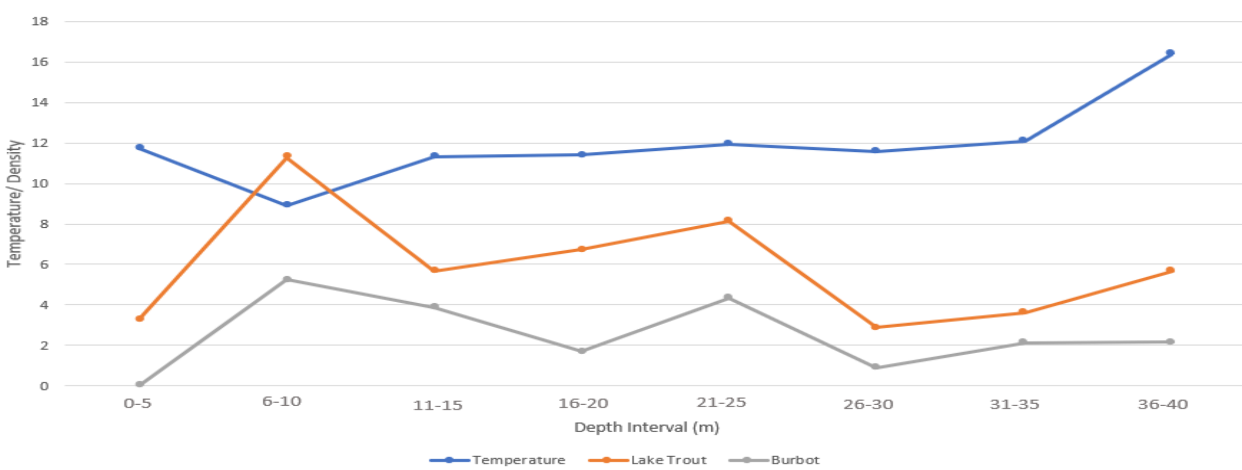

Figure A1.1 – Temperature profile and density per net set of Lake Trout and Burbot in Mameigwess Lake.

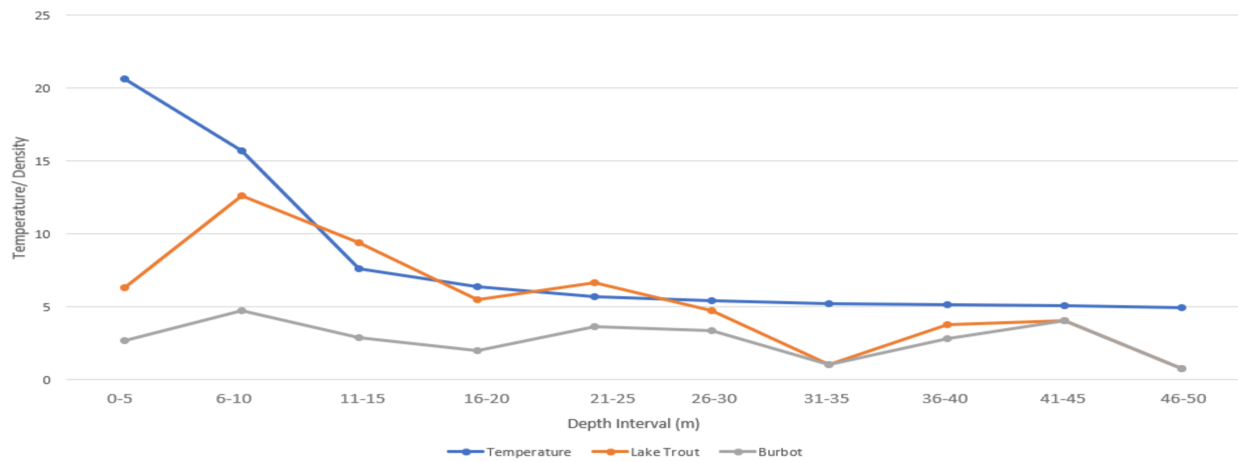

Figure A1.2 – Temperature profile and density per net set of Lake Trout and Burbot in Daniels Lake.

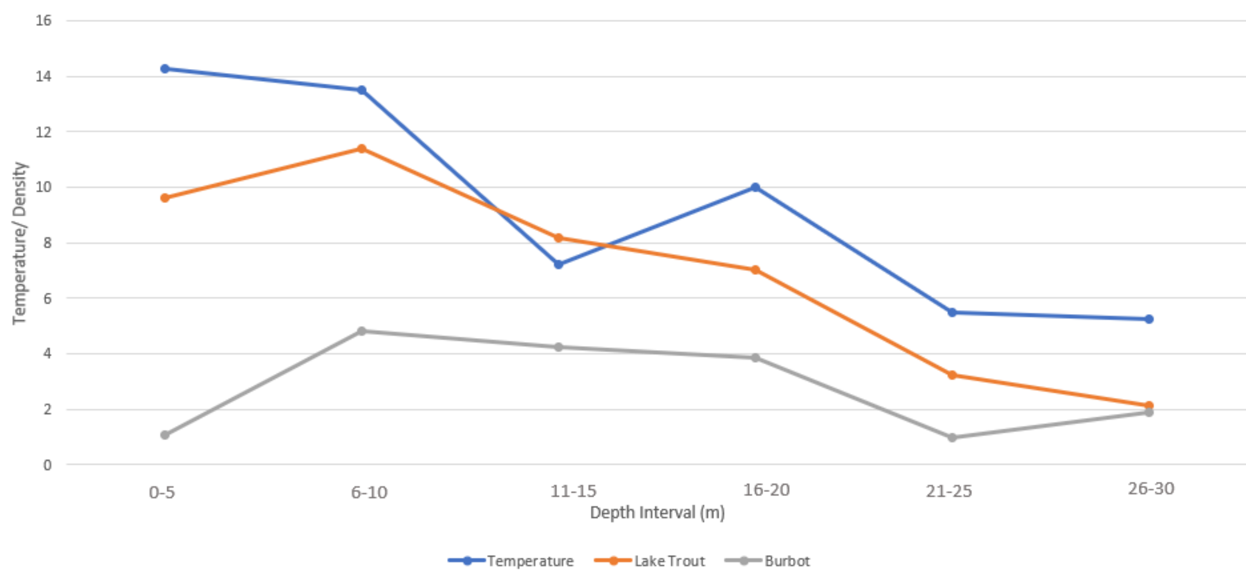

Figure A1.3 – Temperature profile and density per net set of Lake Trout and Burbot in Cry Lake.

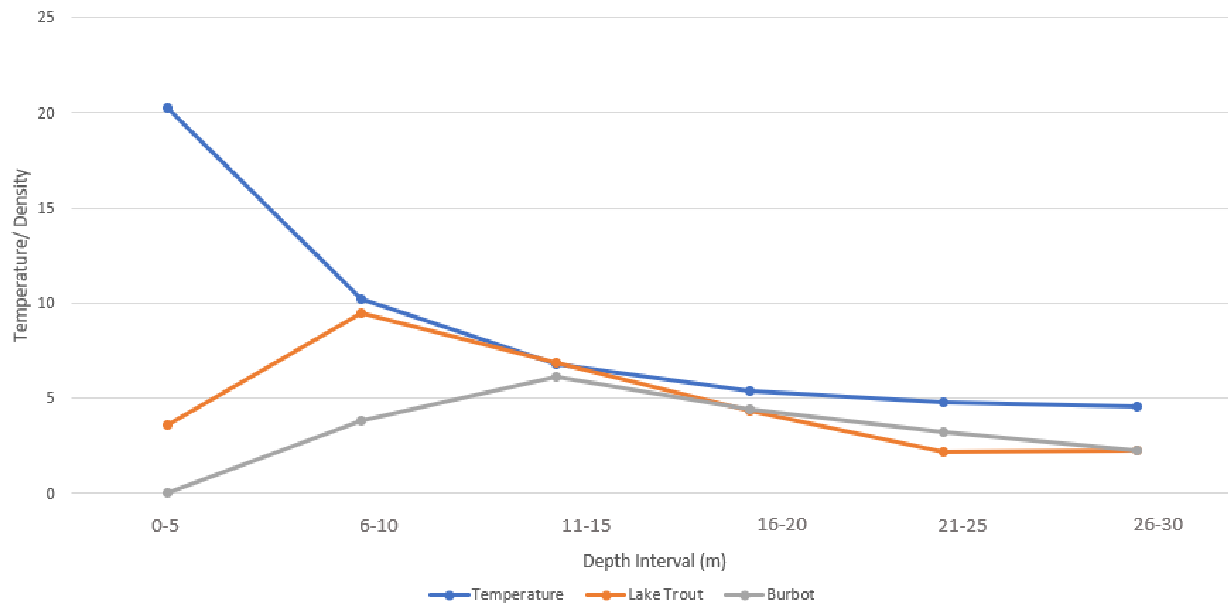

Figure A1.4 – Temperature profile and density per net set of Lake Trout and Burbot in Castle Lake.

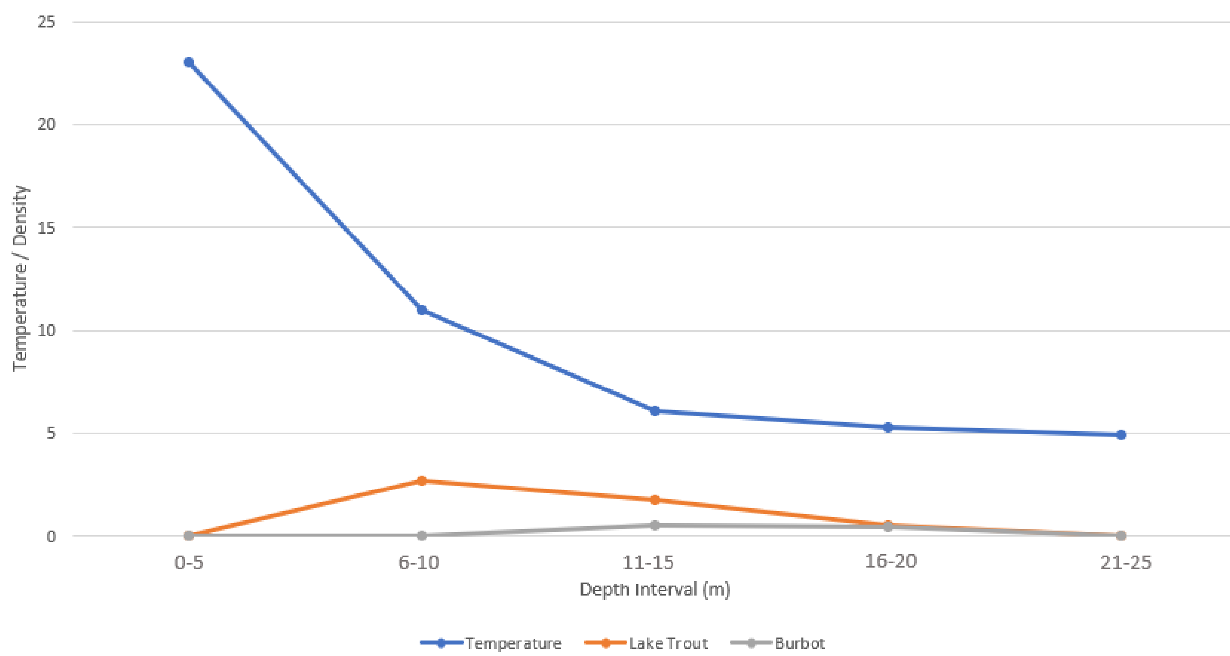

Figure A1.5 – Temperature profile and density per net set of Lake Trout and Burbot in Tinto Lake.

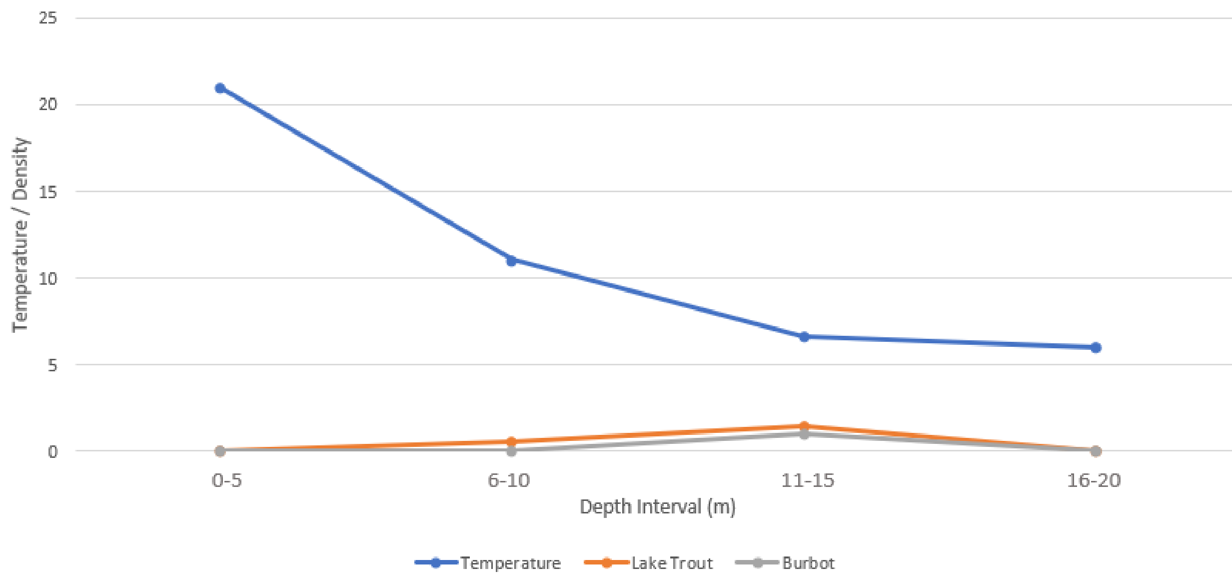

Figure A1.6 – Temperature profile and density per net set of Lake Trout and Burbot in Kamikau Lake.

Appendix II- Depth of occurrence and temperature distribution north and south of 60° latitude

These appendices present a compilation of the raw depth data that was provided for this study from several different sources, including Milne *in prep*. (2019), proportion of occurrence estimates from the Fish-Out database, and proportion of occurrence estimates from the Broadscale Monitoring database. Data from these figures were used to inform the statistical analyses in Chapter 2 of this study. They were developed using the methods described in Chapter 2 and the proportion of occurrence equations. Thermal habitat data presented in the Fish-Out database and the Broadscale Monitoring database for are presented for comparison.

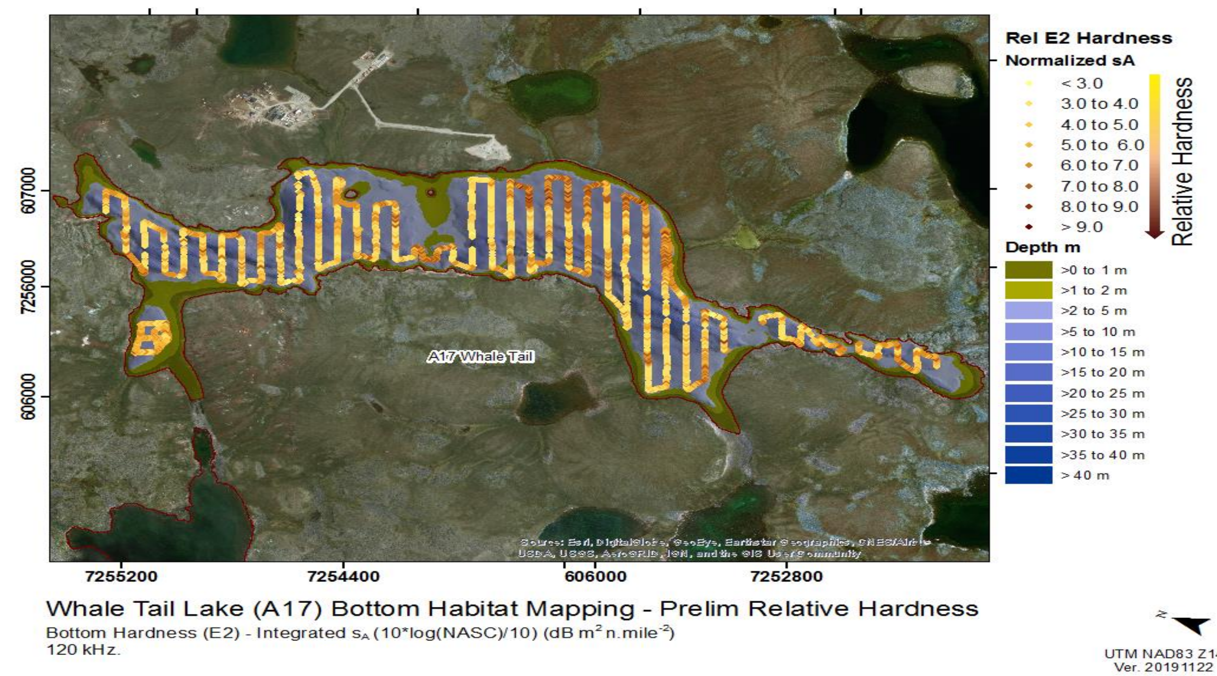

Figure A2.1 – Bottom habitat mapping results from the down-scan hydroacoustic BioSonics instrument with bathymetric depth measurements for Whale Tale Lake at the Amaruq mine property in the Kivalliq region of Nunavut (Milne, *et al*. 2018).

Habitat associations of the Fish-Out database

Mean catch rates did not decline over time and catch per unit effort was not calculated, but rather the raw catch data was provided. This is a limitation of the Fish-Out database and should be addressed by future research. Therefore, the proportion of occurrence was the focus of the depth of capture results.

Depth distribution of species in arctic lakes

Third Portage Lake catch did not decline from the onset of the Fish-Out on August 6, 2010 to August 30, 2010, so data from all net sets were included in the analysis. The bottom depth ranges on individual net sets varied considerably but most had ranges between 0 and 5 metres. The net height was assumed to be one metre for these analyses.

Lake Trout were more abundant at shallower depths with a dip circa 7.5 meters. Burbot were less abundant in the shallow areas but peaked at 7.5 meters (Figure A2.2 and A2.3).

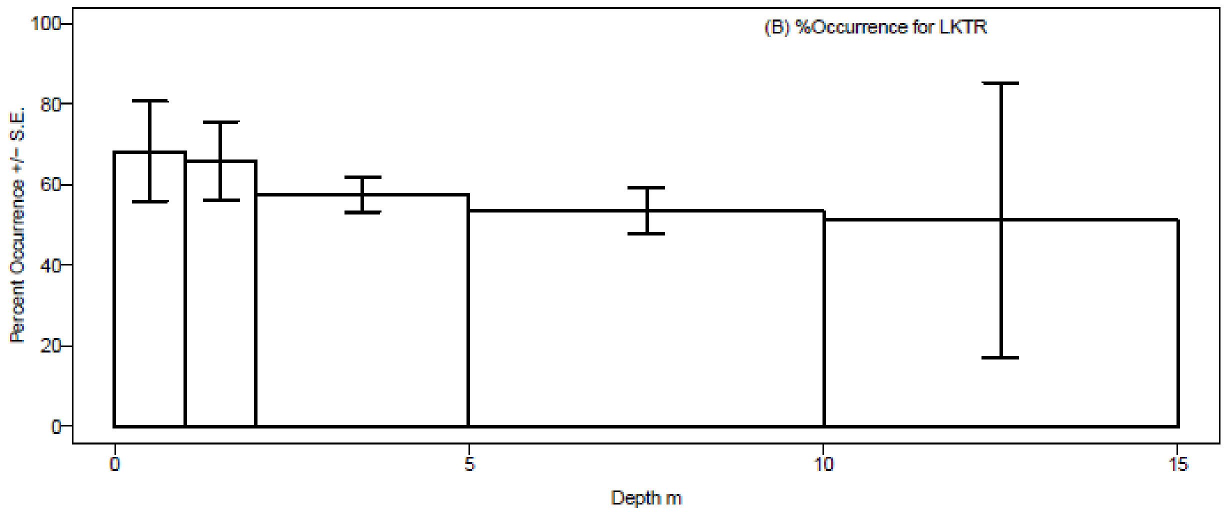

Figure A2.2 – Percent occurrence of Lake Trout from Third Portage Lake.

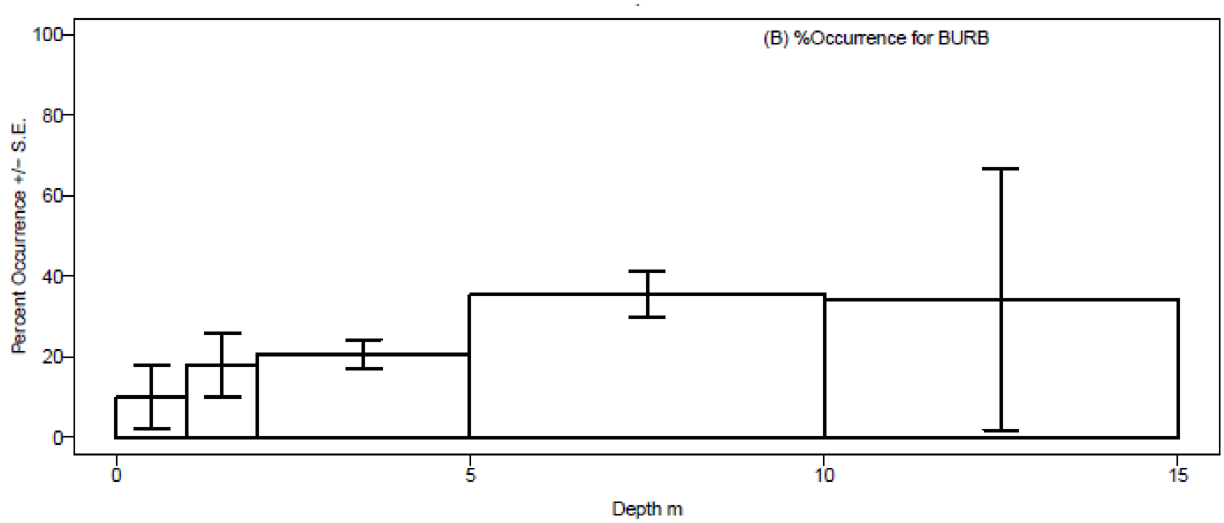

Figure A2.3 – Percent occurrence of Burbot from Third Portage Lake.

Second Portage Lake catch did not decline from the onset of the Fish-Out on August 23, 2008 to September 25, 2008, so data from all net sets were included in the analysis. The bottom depth ranges on individual net sets varied considerably but most had ranges between 10 to 20 metres. The net height was assumed to be one metre for these analyses. Arctic Char and Round Whitefish were more abundant at shallower depths with a dip circa 10m. Burbot were less abundant in the shallower areas but showed a peak coincident with Char and Whitefish decreases. Lake Trout were found in all the observed depth intervals (zero to 40m) evenly. Arctic Grayling were not identified in a large enough sample size of the net sets to express any meaningful pattern (Figure A2.4 to A2.7).

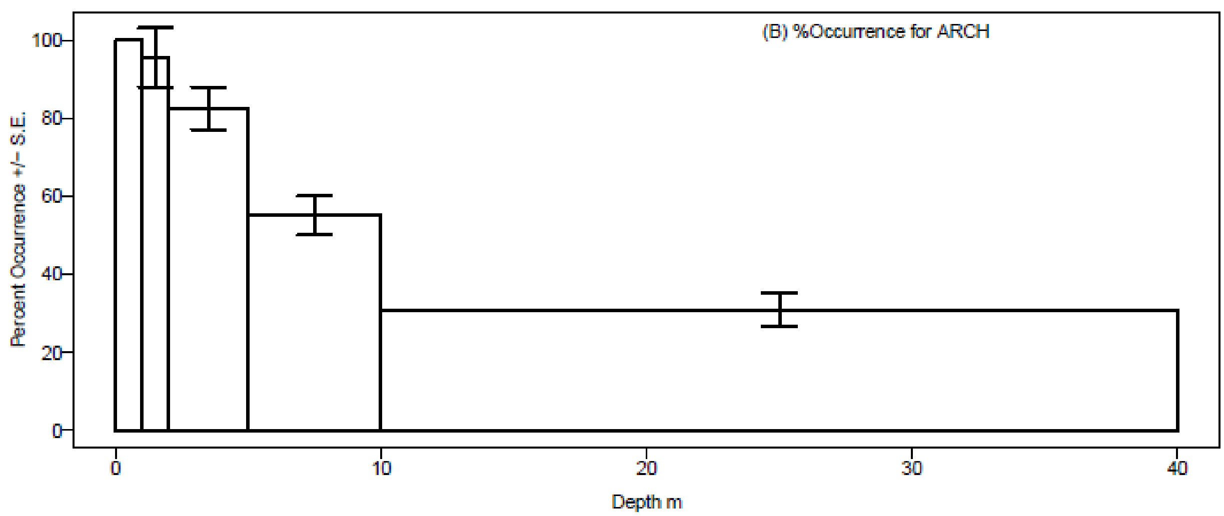

Figure A2.4 – Percent occurrence of Arctic Char in Second Portage Lake.

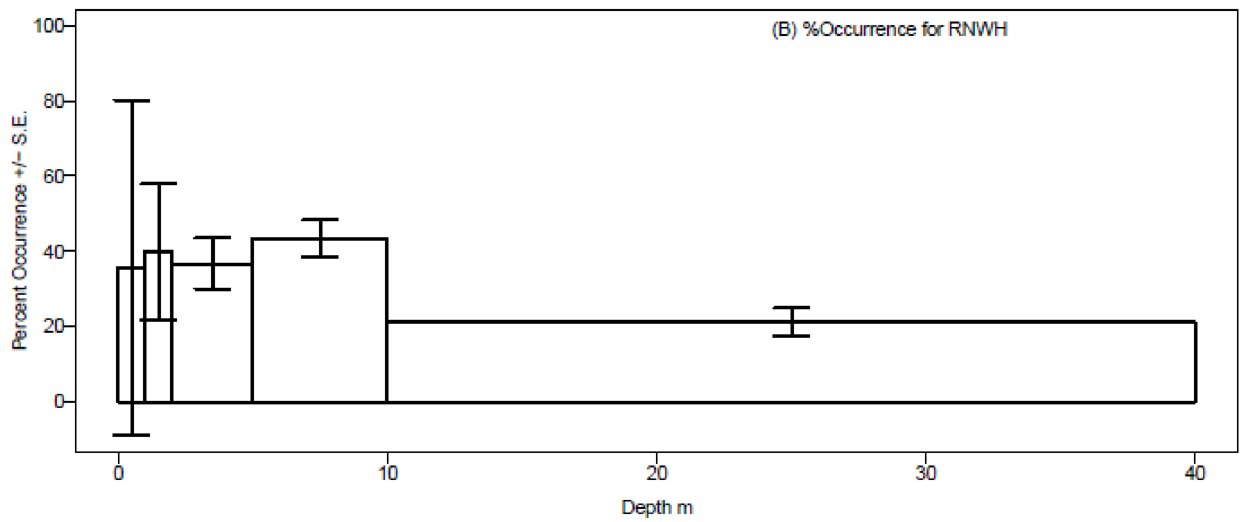

Figure A2.5 – Percent occurrence of Round Whitefish in Second Portage Lake.

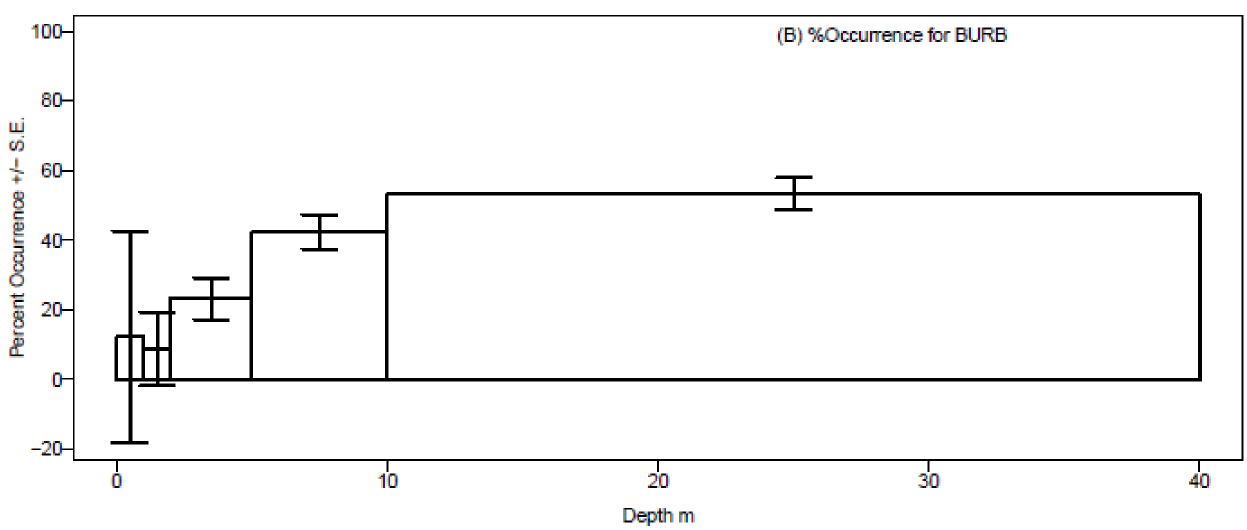

Figure A2.6 – Percent occurrence of Burbot in Second Portage Lake.

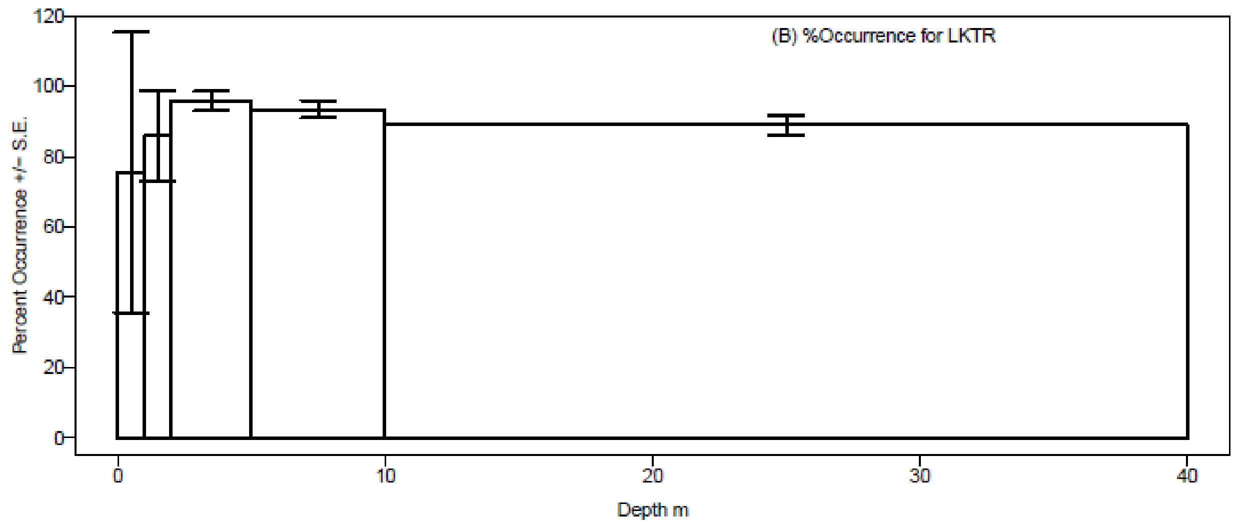

Figure A2.7 – Percent occurrence of Lake Trout in Second Portage Lake.

Sable Lake catch did not decline in catch rates over time so data from all net sets were included in the analysis. The bottom depth ranges on individual net sets varied considerably but most had ranges between 5 to 15 metres. There were no net sets between 0 to 2 metres. The net height parameter was assumed to be one metre for these analyses. Lake Trout and Slimy Sculpin were the only observed species for this lake. Both species occurred most frequently in two to five metres of water, however, catch rates for Slimy Sculpin were negligible (Figure A2.8 and A2.9).

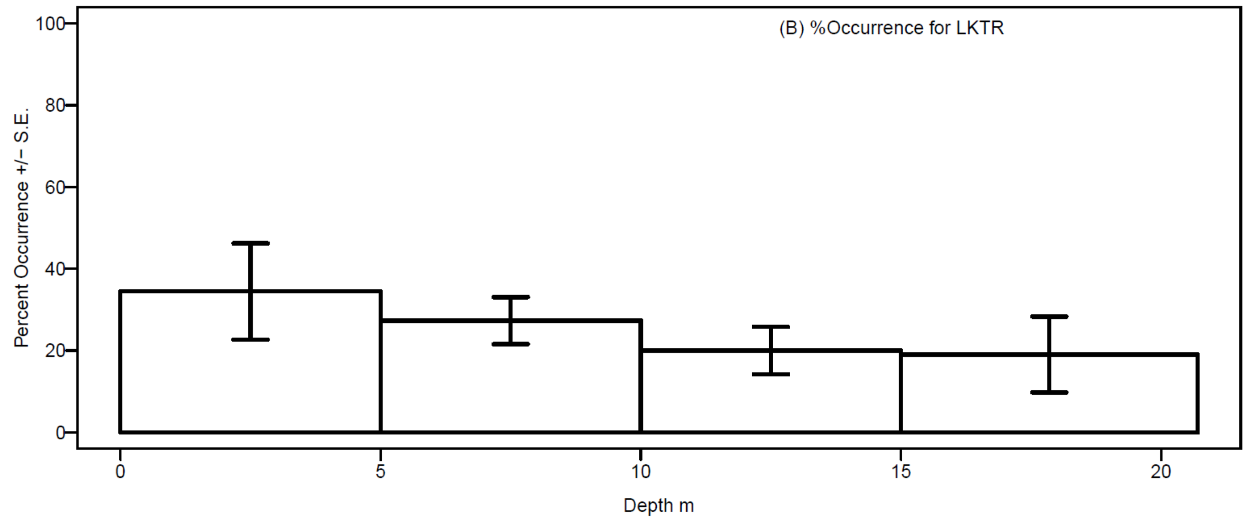

Figure A2.8 – Percent occurrence of Lake Trout in Sable Lake.

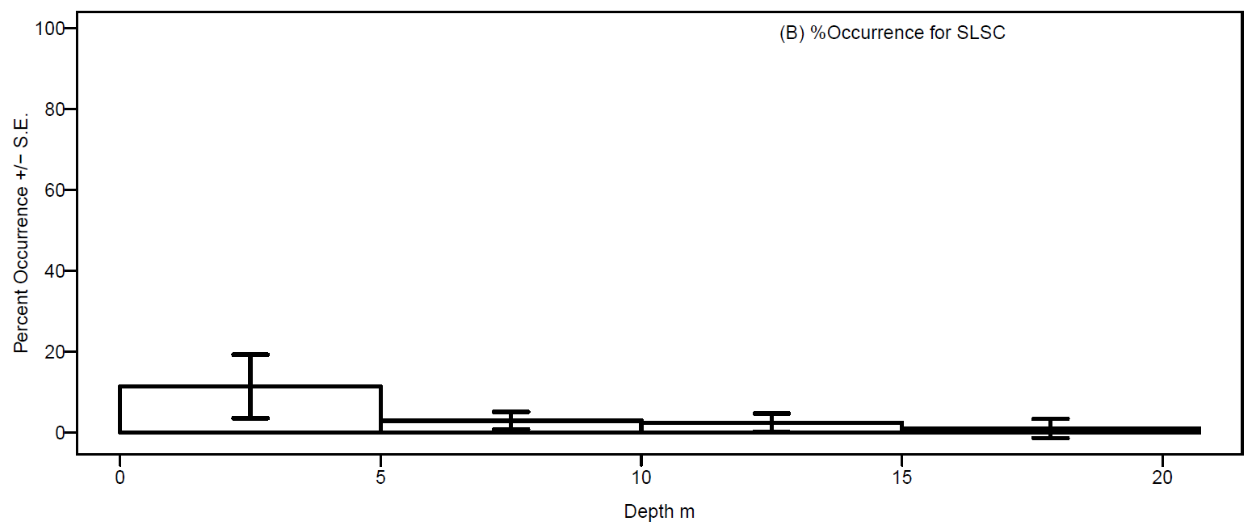

Figure A2.9 – Percent occurrence of Slimy Sculpin in Sable Lake.

Two Rock Lake catch data over time did not indicate any declines in catch rates over time so data from all net sets were included in the analysis. The bottom depth ranges on individual net sets varied between 2 and 10 metres. The net height parameter was assumed to be one metre for these analyses. Lake Trout and Round Whitefish were only observed for this lake. Both species occurred most frequently in the two metres depth of water column (Figure A2.10 and A2.11).

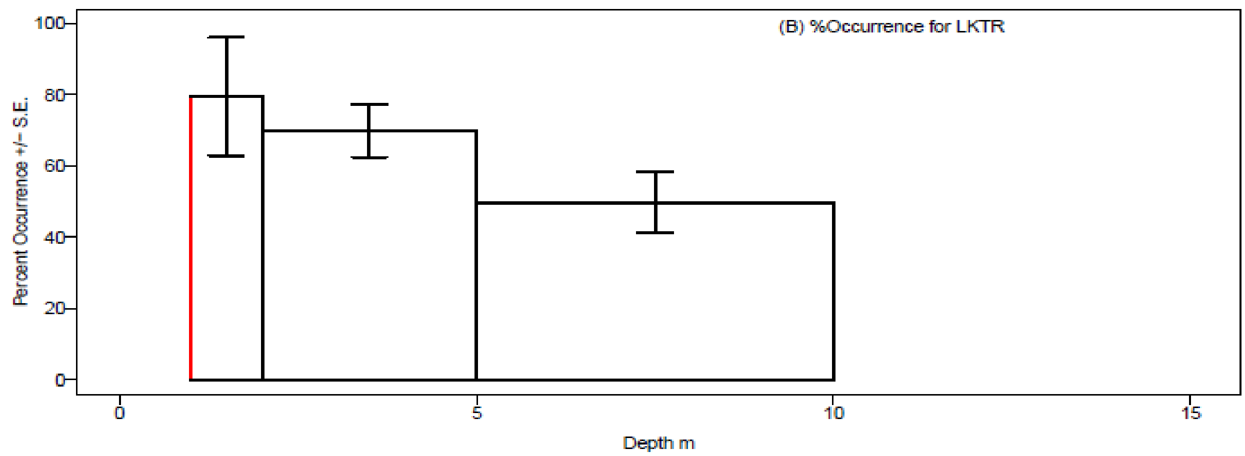

Figure A2.10 – Percent occurrence of Lake Trout in Two Rock Lake.

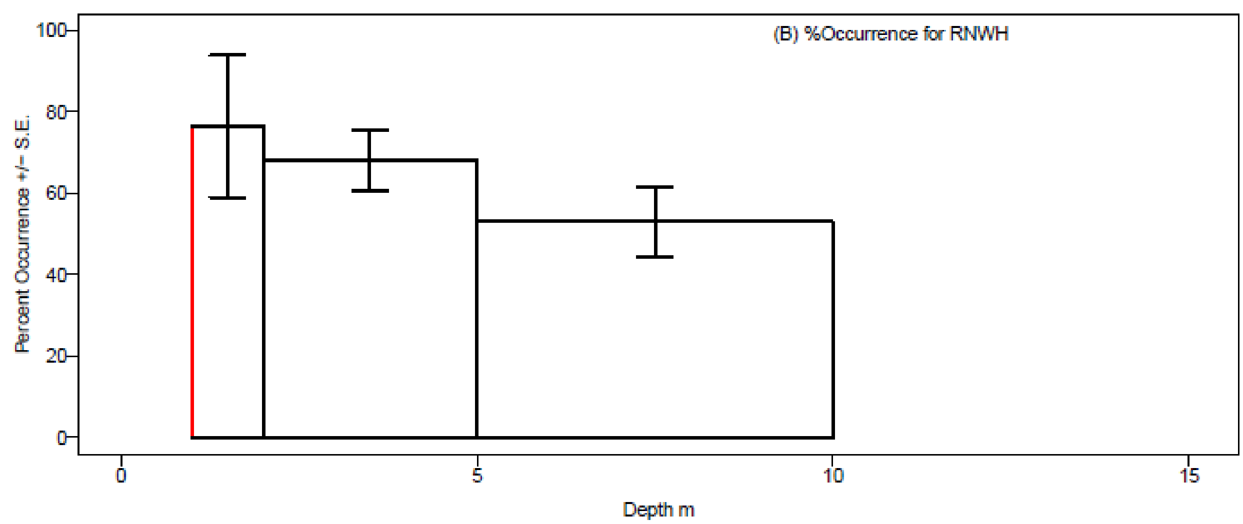

Figure A2.11 – Percent occurrence of Round Whitefish in Two Rock Lake.

Thermal habitat associations in the Fish-Out lakes

The thermal habitat associations of populations north of 60° was not captured by the Fish-Out database because the standardized protocol does not specify the location of temperature measurements relative to the net sets. The thermal data currently provided by the Fish-Out database reports on surface water temperature at the net set, rather than the temperature at the depth the net set is located. As a result, a statistical analysis was not possible under the current Tyson, *et al*. (2011) protocol and highlights a knowledge gap. Nonetheless, a temperature profile was obtained by Milne, et al. (2018) and it can be inferred from this data that the lack of depth preferences in Arctic environments can perhaps be associated with the lack of stratification present in a majority of the thermal regimes present in inland lakes during the open water season.

Habitat associations in Broadscale Monitoring lakes

Broadscale monitoring catch records from Castle, Cry, Mameigwess, Daniels, Kamikau and Tinto lakes along with associated lake dimensions and thermal measurements were used in this study. Theanalyses included two fish species and their percent occurrence from each lake.

Depth preferences of Lake Trout and Burbot in northwestern Ontario

In Castle, Cry and Mameigwess the number of net sets were sufficient to satisfy the net threshold (N.Thresh) of 10, however in Daniels, Kamikau and Tinto Lakes the net sets were not in sufficient number and as a result the threshold of net sets for these lakes was set to 5. All datasets did not decline in catch rates over time so data from all net sets were included in the analysis. These data were analyzed using 5 metre depth intervals.

In Castle Lake, individual net depths ranged from 0 to 35 metres, however most of the were captured between 0 and 5 metres. Lake Trout were captured in 75% of the nets set between 5 to 10 metres of water, and 25% of the net sets between 0 to 5 metres of water. Burbot was captured in 25% of the net sets between 5 to 10 metres and was not encountered in any other regions of Castle Lake (Figure A2.12 to A2.13).

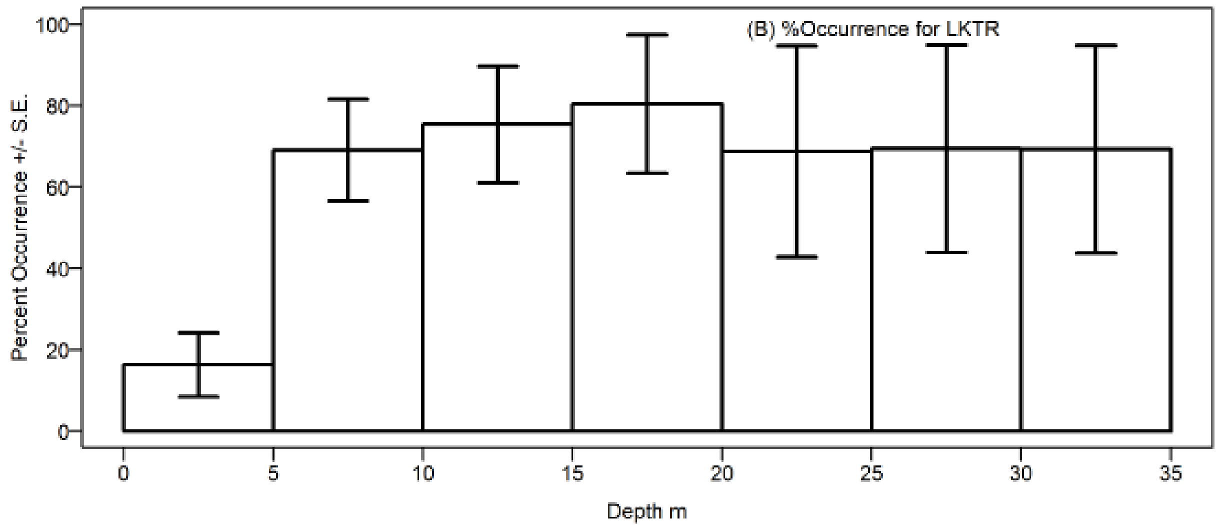

Figure A2.12 – Percent occurrence of Lake Trout in Castle Lake.

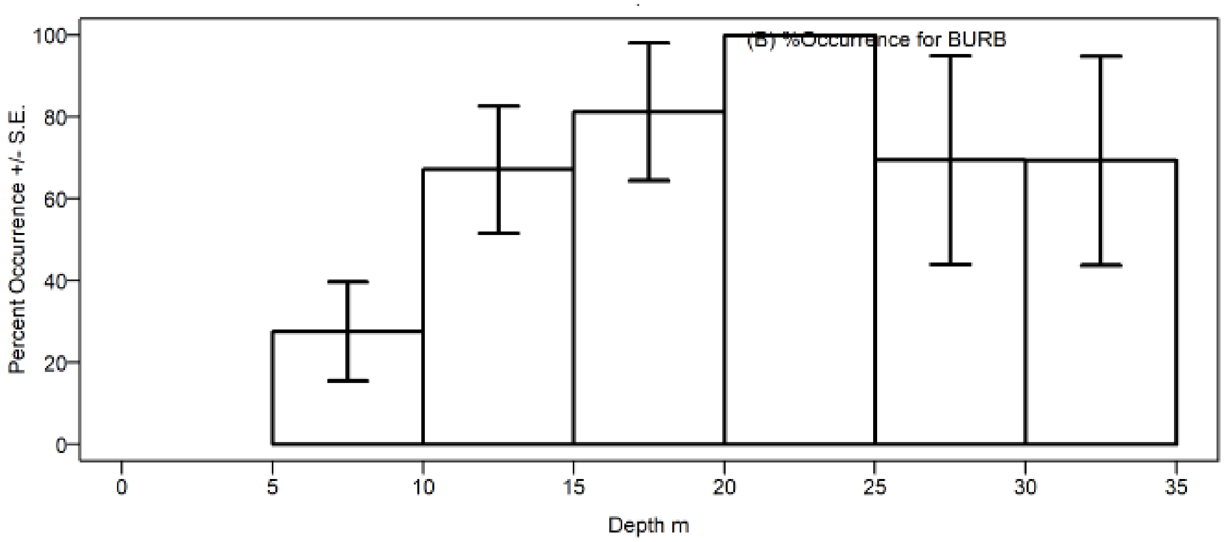

Figure A2.13 – Percent occurrence of Burbot in Castle Lake.

In Cry Lake, the individual net depths ranged from 0 to 49.4 metres. In this case most of the fish were captured between 0 and 10 metres. Lake Trout were caught in approximately 100% of the net sets between 10 to 15 metres of water, and the species was also encountered in less abundance from 0 to 10 and 15 to 20 metres. Burbot was caught in 55% of the net sets between 10 to 15 meters of water, and the species was also encountered in less abundance from 0 to 10 and 15 to 20 metres (Figure A2.14 and A2.15).

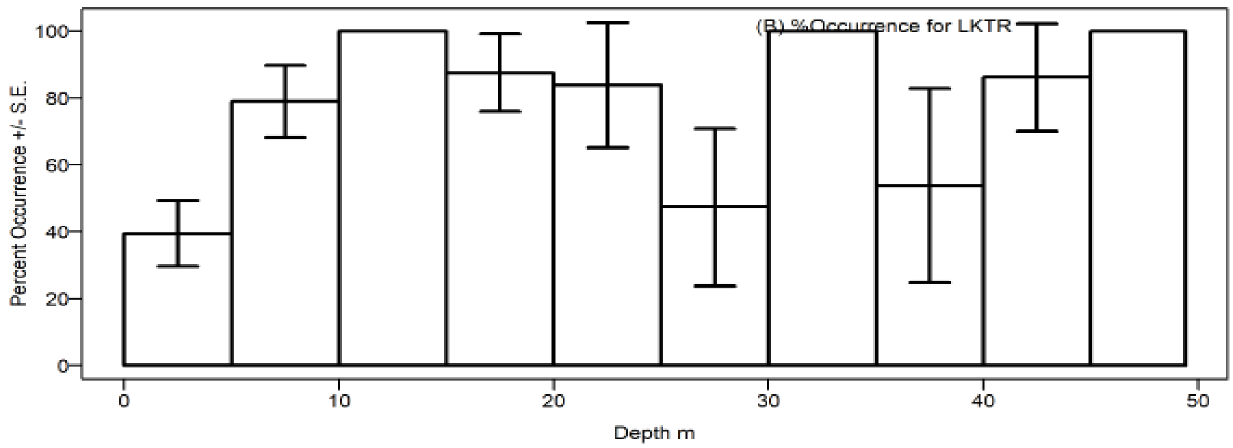

Figure A2.14 – Percent occurrence of Lake Trout in Cry Lake.

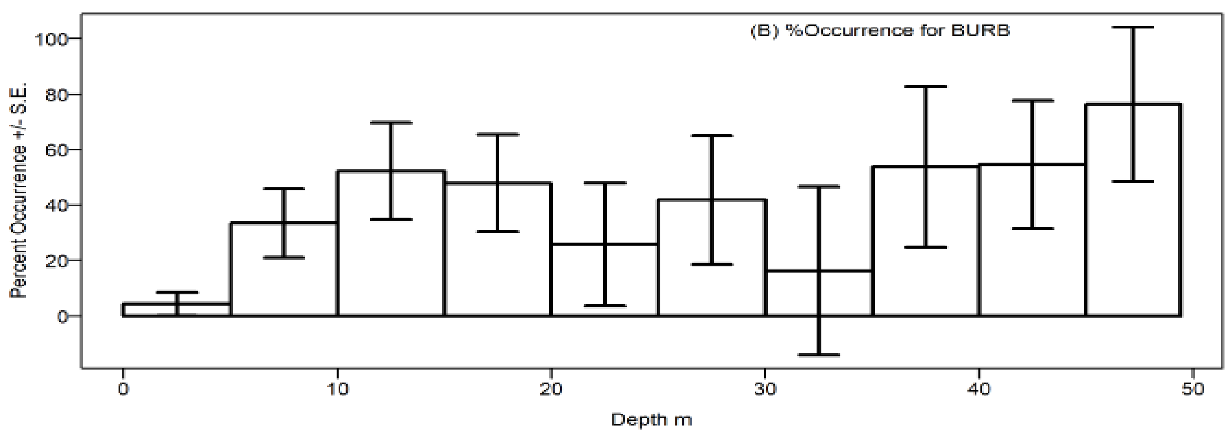

Figure A2.15 – Percent occurrence of Burbot in Cry Lake.

In Mameigwess Lake, the individual net depths ranged from 0 to 48.1 metres. However, most of the Burbot was caught between 0 and 5 metres. Lake Trout was caught in 60% of the net sets between 10 to 15 metres of water, 20% of the net sets between 5 to

10 metres and less than 5% of the net sets between 0 to 5 metres. Burbot was only encountered in 30% of the net sets, all between 10 to 15 metres of water (Figure A2.16 and A2.17).

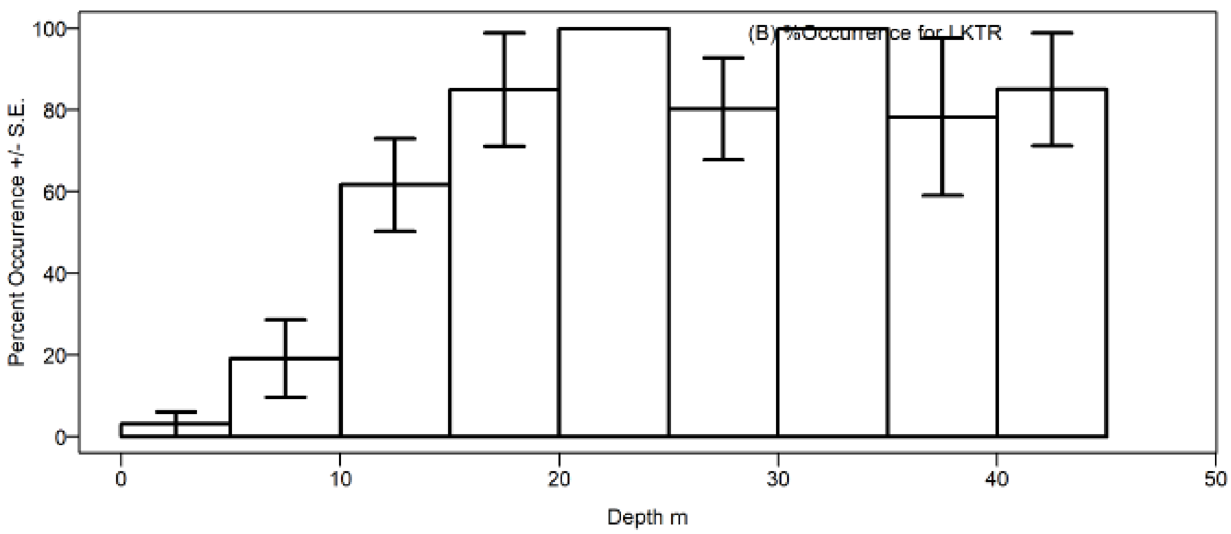

Figure A2.16 – Percent occurrence of Lake Trout in Mameigwess Lake.

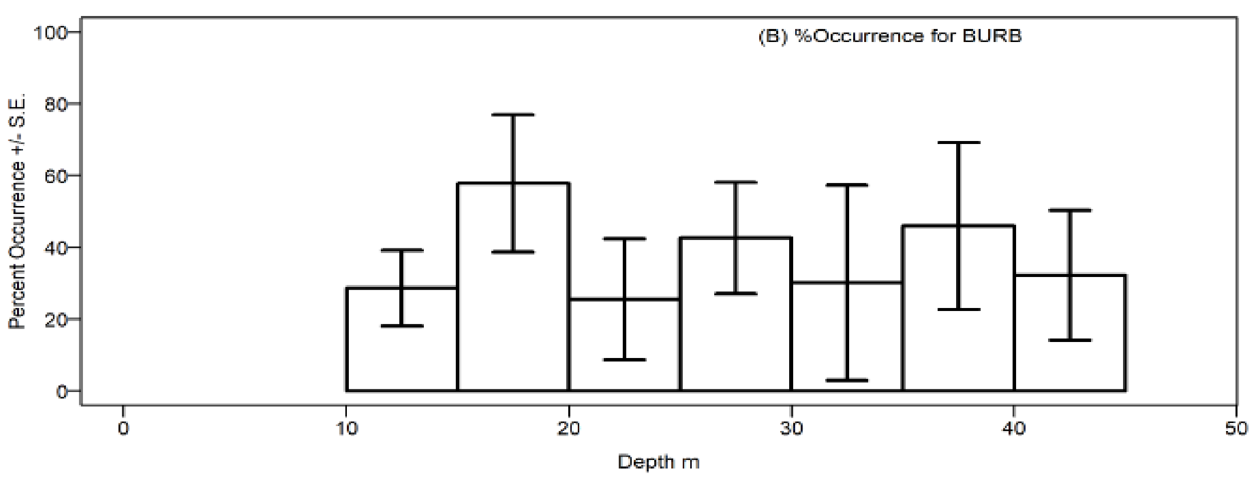

Figure A2.17 – Percent occurrence of Burbot in Mameigwess Lake.

In Daniels Lake, the individual net depths ranged from 0 to 73.2 metres water depth. The majority of the Lake Trout captured were between 5 to 15 metres. They were caught evenly in 100% of the net sets between 15 to 40 metres of water. This species was also encountered in less abundance between 0 to 15 metres and 40 to 50 metres. Burbot was captured most frequently in 100% of the nets set between 30 to 35 metres of water. This species was also encountered in less abundance between 0 to 30 metres and 35 to 55 metres (Figure A2.18 and Figure A2.19)

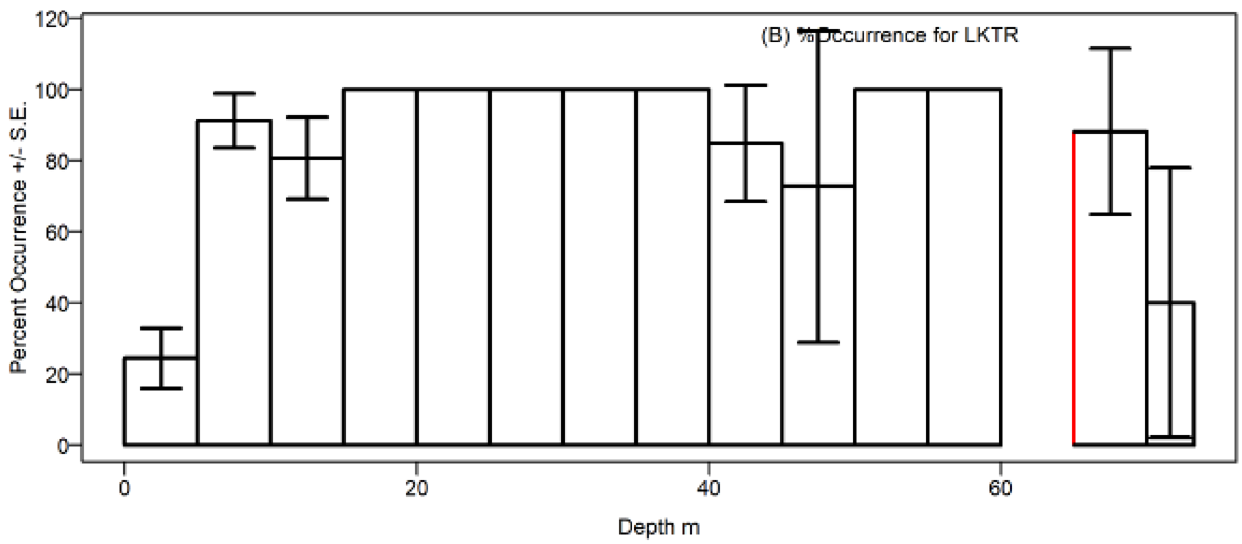

Figure A2.18 – Percent occurrence of Lake Trout in Daniels Lake.

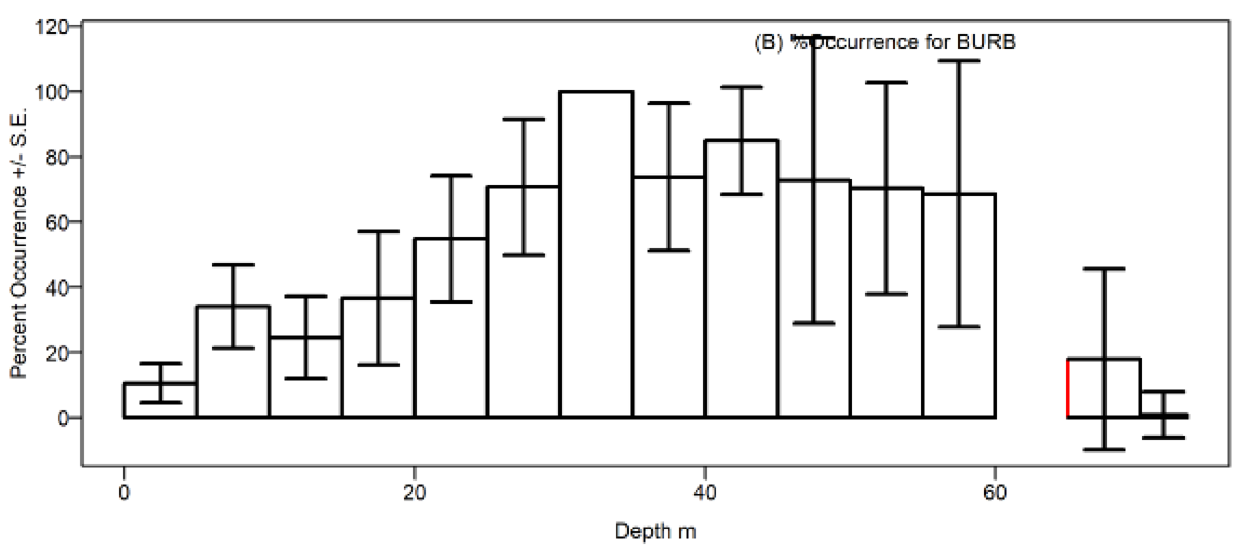

Figure A2.19 – Percent occurrence of Burbot in Daniels Lake.

In Kamikau Lake the individual net depths ranged from 0 to 20.1 metres, however most of the data was captured between 0 to 10 metres. Lake Trout was captured only in 10% of the nets set between 5 to 10 metres of water. Burbot was not encountered in this lake (Figure A2.20 and A2.21).

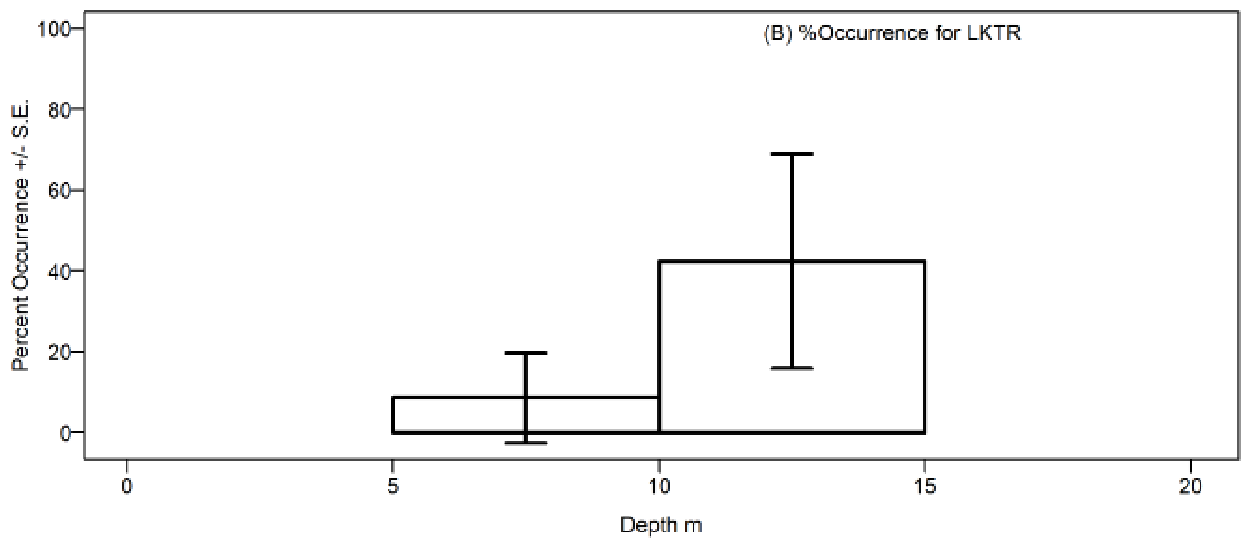

Figure A2.20 – Percent occurrence of Lake Trout in Kamikau Lake.

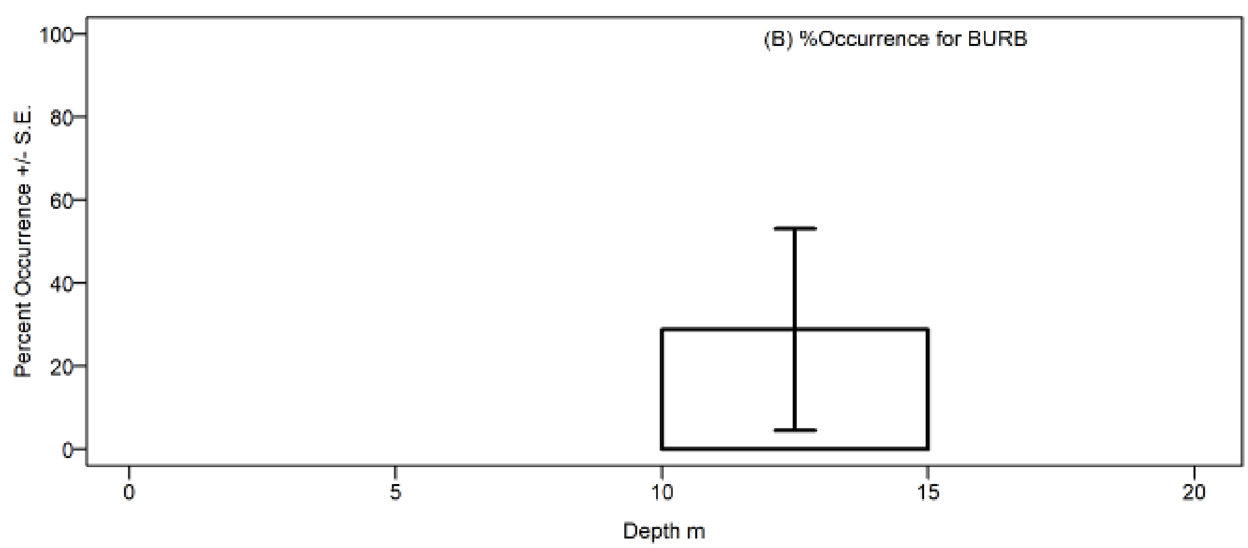

Figure A2.21 – Percent occurrence of Burbot in Kamikau Lake.

In Tinto lake the individual net depths ranged from 0 to 31.5 metres, however most of the data was captured between 0 to 10 metres. Lake Trout was captured in 40% of the net sets between 10 to 15 metres of water, and the species was also encountered in approximately 38% of the net sets between 5 to 10 metres and in less than 5% of the net sets between 0 to 5 metres. Burbot was only captured in approximately 15% of the net sets between 10 to 15 metres of water (Figure A2.22 and A2.23).

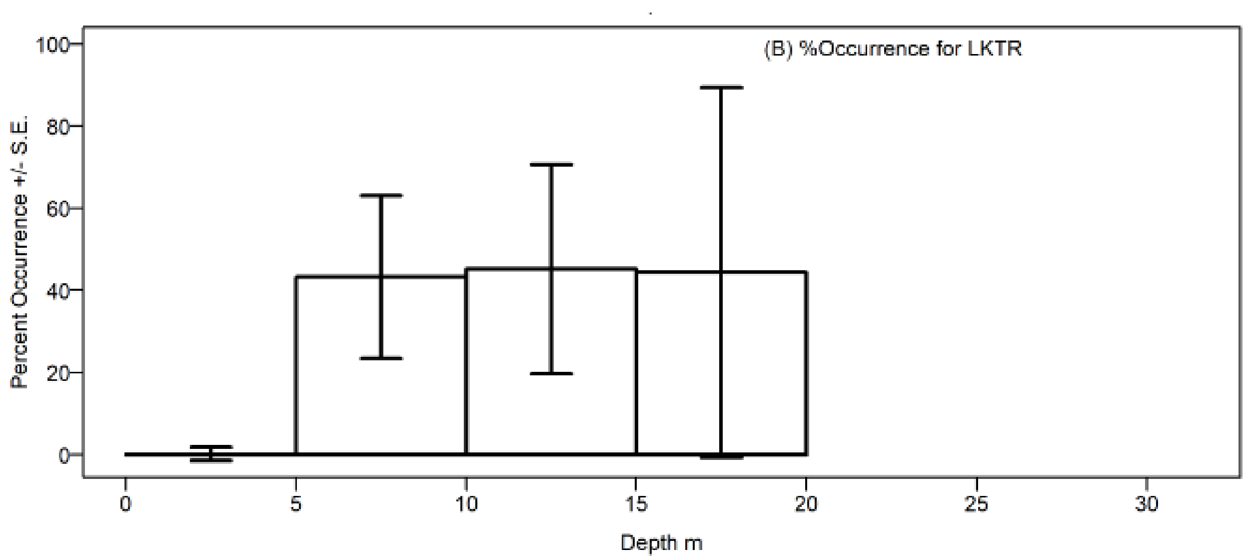

Figure A2.22 – Percent occurrence of Lake Trout in Tinto Lake.

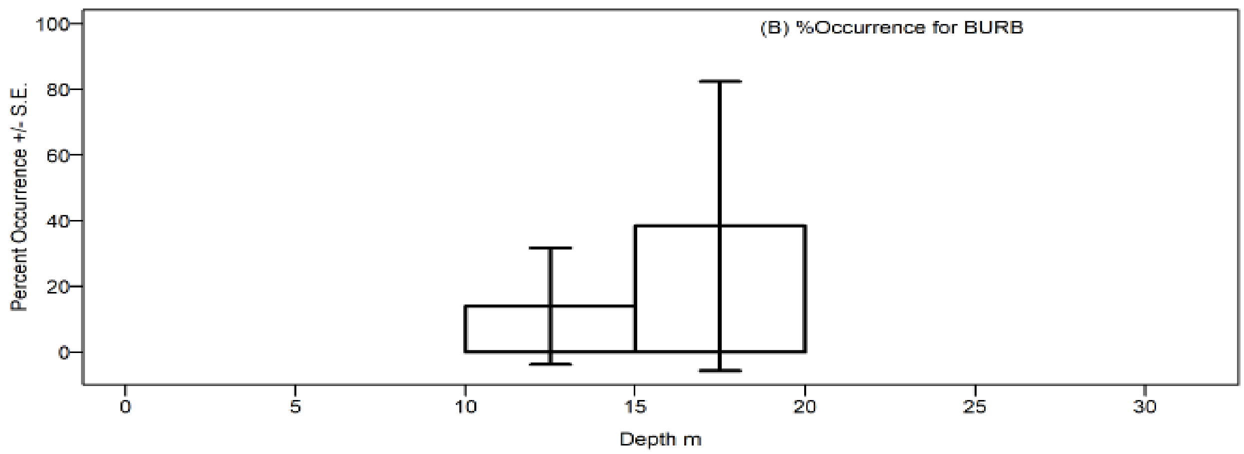

Figure A2.23 – Percent occurrence of Burbot in Tinto Lake.

Thermal habitat associations of Lake Trout and Burbot in northwestern Ontario

Temperature profiles were collected in each lake mid-summer to capture thermal stratification at 5 metre depth intervals at the time of fish sampling. These measurements were taken in Cry Lake over 3 years; Castle Lake, Daniels Lake and Mameigwess Lake over 2 years; and only on 1 occasion in Kamikau and Tinto lakes. These values were averaged and compared to the density of Lake Trout and Burbot across individual net sets based upon the depth preference analyses. The highest density of each species, to compare trends across Lake Trout, were recorded along with the temperature at depth (Figure A2.24). The highest density of Burbot was also recorded along with the temperature at that depth (Figure A2.25).

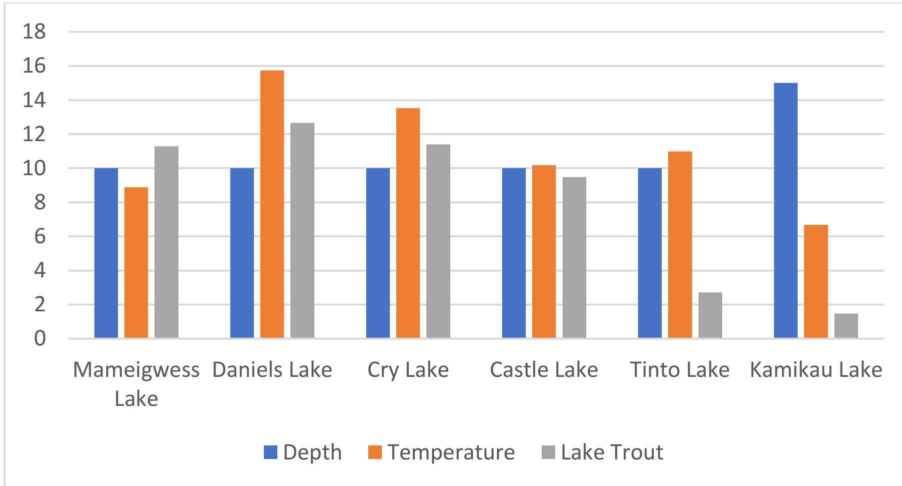

Figure A2.24 – Highest density of Lake Trout in six lakes across northwestern Ontario in the Dryden and Thunder Bay regions with temperature measurements at depth (^{O}C).

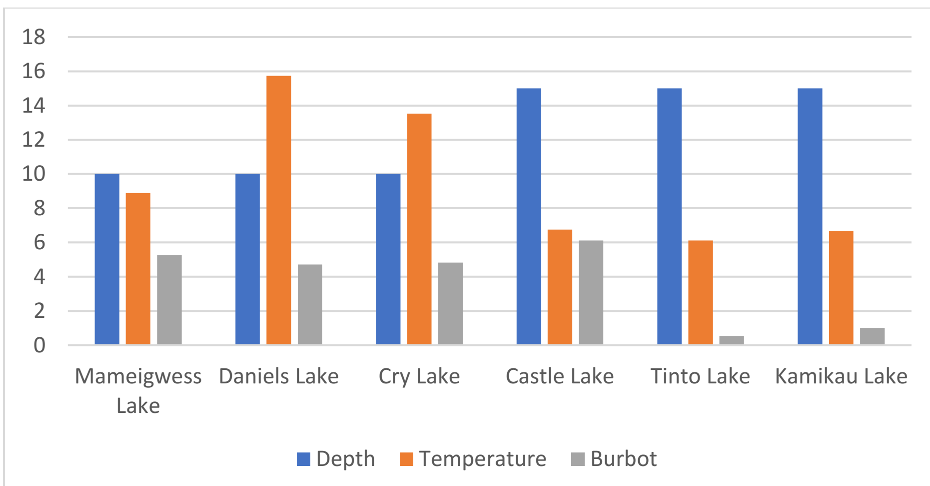

Figure A2.25 – Highest density of Burbot in six lakes across northwestern Ontario in the Dryden and Thunder Bay regions with temperature measurements at depth (^{O}C).

Appendix III- Quantitative methodology used to develop HEAT model

This appendix provides an example of steps 1-7 described in section 3.2.1.1.4 of Chapter 3 to demonstrate the proposed methodology for quantifying the weight of literature sources relative to one another. The example provided here were the steps used to determine which habitat suitability index (HSI) values were appropriate for the depth associations of Lake Trout for three separate life stages. This species was chosen because it presented the only case in all 11 species researched from the Kivalliq region to meet the quantity of evidence threshold sought by this study.

Habitat Ecosystem Assessment Tool (HEAT) model with Ontario data

The data tables that inform the HEAT model currently used in the Laurentian Great Lakes region were data derived from local populations and literature (Lane, *et al*. 1996a, b, c). The habitat suitability values were output and used in this thesis' analysis were only depth and substrate (i.e. vegetative cover was not used to create the HSM output). The depth HSI values for eight species are presented in Table A3.1) for the Ontario populations. They were output from www.habitatassessment.ca.

Table A3.1 – Depth HSI values from the online Ontario Great Lakes' HEAT model.

	Water Column Depth (m)				
Life Stage and Common Name	0-1	1-2	2-5	5-10	10+
Adult/ Juvenile Arctic Char	0.42	0.42	1.00	1.00	0.57
Adult/ Juvenile Burbot	0.00	0.00	0	1.00	1.00
Adult/ Juvenile Lake Cisco	0	0	0	1.00	1.00
Adult/ Juvenile Lake Trout	0.42	0.42	1.00	1.00	0.57
Adult/ Juvenile Ninespine Stickleback	1.00	1.00	1.00	1.00	1.00
Adult/ Juvenile Round Whitefish	0.28	0.28	0.28	1.00	1.00
Adult/Juvenile Lake Whitefish	0.28	0.28	0.28	1.00	1.00
Adult/ Juvenile Slimy Sculpin	1.00	1.00	1.00	1.00	1.00
Spawning Arctic Char	0.44	1.00	1.00	1.00	1.00
Spawning Burbot	1.00	1.00	1.00	1.00	0
Spawning Lake Cisco	1.00	1.00	1.00	1.00	1.00
Spawning Lake Trout	0.44	1.00	1.00	1.00	1.00
Spawning Ninespine Stickleback	1.00	1.00	1.00	1.00	1.00
Spawning Round Whitefish	1.00	1.00	1.00	1.00	1.00
Spawning Lake Whitefish	1.00	1.00	1.00	1.00	1.00
Spawning Slimy Sculpin	1.00	1.00	1.00	1.00	1.00
Young-of-the-year Arctic Char	0.66	1.00	0.33	0.33	0.33
Young-of-the-year Burbot	1.00	1.00	1.00	1.00	1.00
Young-of-the-year Lake Cisco	0	1.00	1.00	1.00	1.00
Young-of-the-year Lake Trout	0.66	1.00	0.33	0.333	0.33
Young-of-the-year Ninespine Stickleback	1.00	1.00	1.00	1.00	1.00
Young-of-the-year Round Whitefish	1.00	1.00	1.00	1.00	1.00
Young-of-the-year Lake Whitefish	1.00	1.00	1.00	1.00	1.00
Young-of-the-year Slimy Sculpin	1.00	0	1.00	1.00	1.00

Habitat Ecosystem Assessment Tool (HEAT) model with arctic data

The data tables that inform the HEAT habitat suitability model currently used north of 60° latitude in Canada were informed by expert opinion. Similar methods utilized south of 60° latitude. For the purposes of this study, data was compiled from peer-reviewed publications, technical documents, previous literature reviews and evidence-based methods. To compare directly with Ontario values, the habitat suitability values were limited to depth. The depth values for eight species are presented (Table A3.2) for the arctic populations.

Table A3.2 – Depth habitat suitability index values of the arctic HEAT model collected and compiled in this study.

	0-1	1-2	2-5	5-10	10+
Adult/ Juvenile Arctic Char	0.33	0.33	0.33	0.67	0.67
Adult/ Juvenile Burbot	0	0	0	0.33	1.00
Adult/ Juvenile Lake Cisco	0	0	0	0	1.00
Adult/ Juvenile Lake Trout	0	0	0	0.33	0.67
Adult/ Juvenile Ninespine Stickleback	1.00	0	0	0	0
Adult/ Juvenile Round Whitefish	0	0	0.67	0.67	0
Adult/Juvenile Lake Whitefish	0	0	0	0.667	0.33
Adult/ Juvenile Slimy Sculpin	0	0	1.00	0	0
Spawning Arctic Char	0	0.67	0.33	0	0
Spawning Burbot	0.33	0	0	0.33	0
Spawning Lake Cisco	0	0	1.00	0	0
Spawning Lake Trout	0.33	0	0.67	0	0.33
Spawning Ninespine Stickleback	1.00	0	0	0	0
Spawning Round Whitefish	1.00	0	0	0	0
Spawning Lake Whitefish	0	0	1.00	0	0
Spawning Slimy Sculpin	0	0	1.00	0	0
Young-of-the-year Arctic Char	0.33	0.33	0	0	0.67
Young-of-the-year Burbot	0.33	0.67	0	0	0
Young-of-the-year Lake Trout	0	0	0	0	1
Young-of-the-year Ninespine Stickleback	0	0	1.00	0	0
Young-of-the-year Round Whitefish	0	1.00	0	0	0
Young-of-the-year Lake Whitefish	0	0	0	1.00	0
Young-of-the-year Slimy Sculpin	1.00	0	0	0	0

The methodology utilized to determine the Habitat Suitability Index values applied the quantitative approach described by Webb, *et al*. (2013). The average reported habitat value was then recorded as in the example provided for Burbot (Table A3.3 and A3.3 cont'd).

Table A3.3 – EcoEvidence protocol applied to Burbot literature 1-10 from north of 60° latitude for physical habitat preferences that inform the Habitat Ecosystem Assessment Toolkit.

Paper No.	1	2	3	4	5	6	7	8	9	10
Author (years)	Guzzo, et al (2016)	Cott, et al. (2015)	Cott, et al. (2014)	Martin and Cott (2016)	Lahsteiner, et al. (2012)	Kahilainen and Lehtonen (2003)	Amundsen, et al. (2003)	Kjellman and Eloranta (2002)	Fischer, et al (2001)	Berg, et al. (2013)
Title	Resource partitioning among top-level piscivores in a sub-Arctic lake during thermal stratification	Diel bank migration of Burbot (Lota lota)	Song of the burbot: under-ice acoustic signaling by a freshwater gadoid fish	The under-ice soundscape in Great Slave Lake near the city of Yellowknife, Northwest Territories, Canada	The effect of temperature on embryonic and yolk-sac larval development in the burbot Lota lota	Piscivory and prey selection of four predator species in a whitefish dominated subarctic lake	Ontogenetic niche shifts and resource partitioning in a subarctic piscivore fish guild	Field estimations of temperature-dependent processes: case growth of young burbot	The use of passive integrated transponder systems (PIT) triggered by infrared-gates for behavioural studies in nocturnal., bottom-dwelling fish species	High prevalence of infections and pathological changes in burbot (Lota lota) from a polluted lake
Study design	2	2	1	1	1	1	1	1	1	1
Ref units	3	3	0	0	0	0	0	0	0	0
Impact units	0	0	0	0	3	3	3	3	0	0
Response replicates	6	6	6	0	6	0	6	0	0	0
Weight of Evidence	11	11	7	1	10	4	10	4	1	1
AJ- Depth	16.2	14.13 +/- 0.39 (night), 16.25 +/- 0.35 (day)	9.5	9.5		15	11			20
AJ- Substrate	90% Boulder; 10% Cobble	50% Silt, 50% Boulder (day); 50% Cobble, 50% Boulder (night)	50% Sandy-silt, 50% Cobble-gravel						90% Cobble, 10% Gravel.	
YOY- Depth								0.5		
YOY- Substrate										
ES- Depth			9.5	9.5				0.5		
ES- Substrate			50% Sandy-silt, 50% Cobble-gravel							

Table A3.3 cont'd – EcoEvidence protocol applied to Burbot literature 11 to 16 from north of 60° latitude for physical habitat preferences that inform the Habitat Ecosystem Assessment Toolkit.

Paper No.	11	12	13	14	15	16
Author (years)	Kley, et al (2009)	Donner and Eckmann (2011)	Fischer (2000a)	Fischer (2000b)	Fish-Out data	Richardson, et al. (2001)
Title	Influence of substrate preference and complexity on co-existence of two non-native gammarideans	Diel vertical migration of larval and early-juvenile burbot optimises survival and growth in a deep, pre-alpine lake	An experimental test of metabolic and behavioural responses of benthic fish species to different types of substrate	Test of competitive interactions for space between two benthic fish species, burbot Lota lota, and stone loach Barbatula barbatula	N/A	Life history characteristics of freshwater fishes occurring in NWT and NU, with a major emphasis on lacustrine life history
Study design	1	1	1	1	1	1
Ref units	0	0	0	0	3	3
Impact units	3	3	2	3	0	0
Response replicates	4	4	6	6	6	6
Weight of Evidence	8	8	9	10	10	10
AJ- Depth					15	10+
AJ- Substrate	%100 Cobble		100% Cobble (day); 50% Cobble, 50% Gravel (night)	90% Boulder; 10% Cobble		Boulder
YOY- Depth						2
YOY- Substrate						Cobble
ES- Depth						1
ES- Substrate						Gravel

A continuation of the EcoEvidence protocol was then applied to determine if there were a sufficient weight of evidence assigned to a given category, in the same format as the HEAT model, to support a given hypothesis regarding the habitat association of a specific life stage of a specific species as per step 7 of the EcoEvidence-based methodology (Table A3.4). An example is provided for depth distribution of three life stages of Burbot in the arctic region based on the literature review results.

Table A3.4 – Habitat suitability value calculation of Burbot from sum of weight of evidence by HEAT depth intervals.

	0-1	1-2	2-5	5-10	10+	Total	Proportion	Conclusion	Suitability values	Reference diversity
Adult-Depth	**0**	**0**	**0**	**8**	**46**	**54**	**85% 10+, 15% 5-10**	**Support for hypothesis**	**10+=3, 5-10=1**	**7**
YOY-Depth	**5**	**10**	**0**	**0**	**0**	**15**	**33% 0-1, 66% 1-2**	**Insufficient**	**0-1= 1, 1-2=2**	**2**
Egg-Depth	**14**	**0**	**0**	**8**	**0**	**22**	**37% 5-10, 63% 0-1**	**Insufficient**	**0-1=2, 5-10=1**	**3**

Comparison of Ontario and arctic HEAT model

Lake Trout and Burbot were the chosen species to compare depth preferences as derived from existing habitat suitability index (HSI) values from the Habitat Ecosystem Assessment Toolkit (HEAT) (Table A3.5). The Ontario HSI values were extracted from the online version of the HEAT model, which uses base tables and R code to translate the information cited in Lane *et al*. (1996a, b and c). The Arctic HSI values were reported from a compilation of the CEE-SR and EcoEvidence protocols presented here, and those using base tables and R code that inform the model cited from a series of published and unpublished literature sources published since Richardson, *et al*. (2001), including the findings of the Richardson, *et al*. (2001) habitat preference base tables.

Table A3.5 – A comparison of Habitat suitability base tables for the adult/juvenile, spawning and young-of-the-year life stages of Burbot and Lake Trout depth preferences in Ontario, derived from the online HEAT toolkit and Canadian arctic region dataset derived for this study.

	0-1		1-2		2-5		5-10		10+	
	Ont.	**Arctic**	**Ont.**	**Arctic**	**Ont.**	**Arctic**	**Ont.**	**Arctic**	**Ont.**	**Arctic**
Adult/ Juvenile Burbot	0	0	0	0	0	0	1.00	0.33	1.00	1.00
Adult/ Juvenile Lake Trout	0.43	0	0.43	0	1.00	0	1.00	0.33	0.57	0.67
Spawning Burbot	1.00	0.33	1.00	0	1.00	0	1.00	0.33	0	0
Spawning Lake Trout	0.44	0.33	1.00	0	1.00	0.67	1.00	0	1.00	0.33
Young-of-the-year Burbot	1.00	0.33	1.00	0.67	1.00	0	1.00	0	1.00	0
Young-of-the-year Lake Trout	0.67	0	1.00	0	0.33	0	0.33	0	0.33	1