Community-partnered research on subsistence char fisheries near Kugluktuk, Nunavut: novel insights from traditional knowledge and western science

by

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Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

While the research in this thesis is my own, and the work was largely and primarily completed by me, many collaborators contributed to the project and provided valuable input to Chapters 1-4 (details below). In recognition of the contributions of others and their co-authorship on the manuscript-style chapters in this thesis, I have thus used the pronoun "we" throughout Chapters 1-4. This was especially important in light of the fact that this work included Inuit authors and contributors.

Chapter 1: Weinstein SY, Gallagher CP, Hale MC, Loewen TN, Power M, Reist JD, Swanson HK (2023) An updated review of the postglacial history, ecology, and diversity of Arctic char (*Salvelinus alpinus*) and Dolly Varden (*S. malma*). Submitted February 2023 to *Environmental Biology of Fishes*. Revision requested.

Given the developments in char (*Salvelinus spp.*) research over the past several years, the advent of new technologies, and the fact that literature pertaining to Dolly Varden (*S. malma*) has not been reviewed since 1980, I and co-authors addressed the need for an updated review focusing on both Arctic char (*S. alpinus*) and Dolly Varden. This chapter was conceptualized by SYW and HKS, and was based on foundational work conducted in part by JDR. The original draft of this manuscript was written by SYW and reviewed and edited by HKS and MCH. CPG, TNL, and MP reviewed and edited subsequent drafts.

Chapter 2: Weinstein SY, Loewen TN, Reist JD, Gallagher CP, Hale MC, Swanson HK (2023)

Gill raker and pyloric caeca counts differ between Arctic char (*Salvelinus alpinus*) and Dolly Varden (*S. malma*) populations across their ranges. In Prep.

Meristic characters have often been used to distinguish *Salvelinus* fishes, but studies have generally focused on comparisons among or between populations that represent a small fraction of species' ranges; here, we investigated differences in meristic characters over the distributional ranges of Arctic char and Dolly Varden. Archived data used in this work were provided by TNL, JDR, CPG, and HKS. Additional samples were collected by SYW. This research was conceptualized by SYW and HKS. SYW conducted the data analyses and performed data visualization, with input and assistance from HKS. The original draft of this manuscript was written by SYW, and was then reviewed and edited by HKS. This manuscript is in preparation for submission to a journal, and has been sent to all coauthors for feedback.

Chapter 3: Weinstein SY, Hale MC, Reist JD, Loewen TN, Gallagher CP, Dumond A, Harris LN, Tallman RF, Bajno R, Martin ZA, Moore JS, Craig PM, Swanson HK (2023) Identification of sympatric anadromous Arctic char (*Salvelinus alpinus*) and Dolly Varden (*S. malma*) in the central Canadian Arctic. In Prep.

This chapter addresses several core questions, including what char species are present in the Coppermine River (located in the central Canadian Arctic), and are inferences consistent among conventional (e.g., meristics, morphology) and cutting-edge (genomics) techniques? The specific objectives of this study were developed by SYW, HKS, and MCH, as well as JDR, AD, and TNL. The research presented in this chapter builds on efforts initiated by JDR, RB, and LNH.

Samples were collected by SYW, JDR, TNL, CPG, LNH, RFT, JSM, ZAM, and HKS. SYW, HKS, and MCH formulated the methodology. Data curation, analysis, and visualization were done by SYW, HKS, and MCH. The SNP chip used in this paper was run at the Clinical Genomics Centre at Mt. Sinai Hospital, Toronto. HKS, TNL, and AD secured the funding necessary to complete this work. AD provided logistical and field support, and invaluable support in community engagement. PMC provided laboratory resources. SYW wrote the original manuscript draft, which was reviewed and edited by MCH and HKS. This manuscript is in preparation for submission to a journal, and all coauthors will have the opportunity to provide input and feedback before it is submitted.

Chapter 4: Weinstein SY, Dumond A, Loewen TN, Swanson HK (2023) Local knowledge documentation of Arctic char (*Salvelinus alpinus*) and Dolly Varden (*S. malma*) in the Coppermine River. In Prep.

As this project was community-partnered and driven by community concerns about the subsistence char fishery in the Coppermine River, it was crucial to include the knowledge and voices of fishers and elders in the community. Local knowledge interviews and interview validations were conducted in Kugluktuk by SYW. SYW also developed the interview guide and consent forms, transcribed the interviews, managed the Nunavut Research Institute permitting process, helped with the university permitting process, and wrote the original manuscript draft. AD facilitated the recruitment of participants, provided input on the interview guide, provided the space in which to conduct interviews, and managed honoraria payments. HKS and TNL acquired the funding for this work. HKS also contributed to development of the interview guide,

consent forms, and process, and with university permitting, as well as reviewing and editing manuscript drafts. This manuscript is in preparation for submission to a journal, and all coauthors will have the opportunity to provide input and feedback before it is submitted. Additionally, we will do a feedback session with community members prior to submission to ensure that we have appropriately represented the perspectives of interviewed knowledge holders.

Abstract

Arctic char (*Salvelinus alpinus*) and Dolly Varden (*S. malma*) are the two most closely related species in the genus *Salvelinus*. Both species show substantial intraspecific variation in ecology, life history, morphology, and postglacial history across their distributional ranges, which has presented substantial challenges for conservation and management. Not only do char play important ecological roles within ecosystems, but they are also culturally, economically, and recreationally important. Char, and char fisheries, are a foundational element of Inuit culture in many coastal communities in the Canadian Arctic, and are critically important to food security due to their abundance and availability for year-round harvest. Char are also vulnerable to climate-induced changes in hydrology and water temperature due to their life stage-specific dependency on multiple habitats. Despite their importance and vulnerability, the genetics, ecology, and demography of anadromous (i.e., sea-run) chars are understudied, which makes it difficult to anticipate the effects of climate change and other stressors on species persistence.

In the central Canadian Arctic, there is uncertainty surrounding the distribution of Dolly Varden, as well as interspecific relationships between Dolly Varden and Arctic char in systems where they may be sympatric. Furthering understanding of the diversity of char species present in the central Canadian Arctic will enable scientists and local community members to more accurately and efficiently identify and restore critical habitats, thereby ensuring the viability of the critically important subsistence char fisheries. Through the application of western science methods and the gathering of traditional knowledge in Kugluktuk, Nunavut, this thesis aims to address knowledge gaps and uncertainties regarding char diversity and the composition of *Salvelinus* fishes in ecosystems in the central Canadian Arctic.

In Chapter 1, I provide a detailed overview of the postglacial history, ecology, and diversity of Arctic char and Dolly Varden. Arctic char and Dolly Varden have been studied extensively by scientists since the 1700s, and while several detailed reviews have been published on Arctic char over the past 40 years, Dolly Varden remain understudied. In addition, advances in the fields of genetics, ecology, and morphometrics have improved our understanding of the behavior, feeding, habitat requirements, postglacial histories, and intraspecific diversity within each of the two species. Chapter 1 focuses on placing findings from phylogenetic and morphometric studies from more recently published (through 2022) literature within the foundational context of earlier papers and reviews (since 1943) on Dolly Varden and Arctic char. Also included in this chapter are anticipated effects of climate change on the two species, and knowledge gaps and research priorities that, when addressed, will enable more informed conservation and management initiatives for these highly valued fishes. At the end of this chapter, I discuss how my research in chapters 2, 3, and 4 addresses known knowledge gaps.

Prior to the widespread use of genetics, closely related forms, morphs, and species of fishes were often differentiated using meristic characters. Analyses of meristic characters have provided researchers with a foundation upon which to build understanding of niche partitioning, sympatric speciation, and patterns of postglacial recolonization in taxa with complicated or contentious phylogenies, such as within the genus *Salvelinus*. In previous decades, meristic analyses have been used to investigate relationships between Arctic char and Dolly Varden, and to examine intraspecific diversity present within both species. Most individual studies have, however, focused on relatively small spatial scales. In Chapter 2, unpublished and previously published data from 374 populations and systems was collated to investigate whether two commonly used meristic characters – number of pyloric caeca and total number of gill rakers

along the first gill arch – differed consistently between fish identified as either Arctic char or Dolly Varden. Analyses of population mean data from across the North American and Russian Arctic and sub-Arctic indicated that fish visually and/or genetically identified as Arctic char or Dolly Varden were consistently different in these two meristic characters across their distributional ranges. Five years of data collected from the Coppermine River, in the central Canadian Arctic, indicated that there was a population-level increase over time (from 1961 to 2020) in fish that were meristically Dolly Varden.

In the central Canadian Arctic, scientists long thought that all char east of the Mackenzie River were Arctic char. Recently, however, limited mitochondrial DNA data, as well as documentation from fishers in Kugluktuk, NU regarding variation in fish appearance, have suggested the presence of both Arctic char and northern form Dolly Varden (*S. m. malma*) in river systems in the central Canadian Arctic. Northern form Dolly Varden is a COSEWIC-listed Species of Special Concern in Canada, and an accurate understanding of the species' range is critical to advance conservation and management efforts that are directed toward this important subsistence fish. In Chapter 3, data on morphometrics, individual meristics, and from the recently developed 87K *Salvelinus* SNP chip indicated presence of Dolly Varden in three systems east of the Mackenzie River; two systems, the Coppermine River and Darnley Bay, support sympatric anadromous Arctic char and Dolly Varden, while the third system, Tree River, supports solely Dolly Varden. Only one hybrid fish was detected in the analyses, in the Coppermine River; this may indicate that Arctic char and Dolly Varden maintain discrete spawning times and/or habitats, or that individuals of the two species either cannot or do not interbreed because of other unknown mechanisms or processes.

This project was community-partnered and driven by community concerns about the

Coppermine River subsistence char fishery, and it was crucial to include the knowledge and voices of fishers and elders in the community. In Chapter 4, a summary of local and traditional knowledge interviews is presented. Interviews were conducted in Kugluktuk, Nunavut, a hamlet that sits at the mouth of the Coppermine River. Seventeen elders and fishers discussed their char fishing experiences, changes they have noticed in the Coppermine River over time, their concerns regarding a changing environment, and any additional research they would like to see done in the area. Many fishers observed decreases in char abundance over the past decade or so, though the char population appeared to rebound in summer 2022, and several participants believe the declines are a result of climate change. Fishers confirmed catching both Arctic char and Dolly Varden in the Coppermine River, but do not refer to or discriminate between the two species in the same way that western scientists do. The reports of Dolly Varden in the Coppermine River by fishers interviewed here aligns with the contemporaneous genomic, morphometric, and meristic data presented in Chapter 3.

In Chapter 5, I synthesized the work presented in chapters 1-4. Together, the results of this thesis confirm that both Arctic char and Dolly Varden are present in the central Canadian Arctic, indicating that the Mackenzie River does not represent a range boundary for Dolly Varden, as had been previously believed by western scientists. The presence of Dolly Varden in systems east of the Mackenzie River is supported by genomics, morphometrics, meristics, and local Inuit knowledge, and this research confirms long-held speculations and assertions – often based on limited data or anecdotal information – regarding the distribution of Dolly Varden in the Canadian Arctic. This is also the first detailed description of genetic and morphological characteristics of sympatric anadromous Arctic char and anadromous Dolly Varden in the Canadian Arctic. Incorporating both Inuit knowledge and western scientific data allowed us to

gain a more comprehensive understanding of char diversity in the central Canadian Arctic, and will hopefully contribute to the ongoing community-based conservation and management of the Coppermine River subsistence char fishery.

Acknowledgements

I have to start by acknowledging my supervisor, Heidi Swanson, and unofficial co-supervisor/M.S. advisor, Matt Hale, for all of their support and encouragement over the past several years. Matt, I wouldn't be here without you. Actually, though, because I'd never heard of Heidi or Waterloo until the day you burst into the lab telling me that I had to email Heidi right away because she was looking for a PhD student on a project that'd be perfect for me. You weren't wrong. Anyway, thanks for continuing to put up with me even though I know I occasionally drive you crazy, and for helping me with all of the genetics things. Heidi, it's been a whirlwind of a time. Among many other things, thank you for helping me navigate a variety of situations, for saying yes to an appropriate number of my ideas, and for believing that I could in fact do this PhD even and especially when I didn't think it was possible. I've learned a lot during my time here, and I hope we have the opportunity to collaborate in the future.

I would also like to thank the members of my thesis/examining committee: Paul, for letting me use your lab equipment and for your support throughout my degree; Rebecca, for stepping in at the last minute so things could stay on track; and Chris and Simon for providing input that helped me think more critically about the different areas of my work.

This project would not have happened without the assistance of quite a few people. I am incredibly grateful to everyone who helped with sample collection and provided reference samples, especially to Colin Gallagher for sending reference Dolly Varden samples right as I was beginning to think we'd never find any. Tracey Loewen continuously found money for processing more genetics samples, which allowed for a more robust analysis and understanding of the char situation in the central Canadian Arctic. Yohannes at the Clinical Genomics Centre

processed all of my genomics data and answered very many of my questions throughout the process. Several members of the Swanson lab made this a memorable experience, especially Tara, during the first 2.5 years, who was always up for an adventure. Many other people both at Waterloo and beyond helped me with methodology and learning new techniques, especially when it came to my foray into social sciences, and I am appreciative of all of their assistance.

Koana to Amanda Dumond, Larry Adjun, the Kugluktuk Hunters and Trappers Organization, and all of the elders and fishers in Kugluktuk who welcomed me into the community, allowed me to sample their fish, and shared their knowledge with me. All char included in this work were caught by subsistence fishers, and this project would not have happened without the fishers' partnership and support. Fishers and people in Kugluktuk who contributed samples and/or time to this project include: McCotter Riffi (who can process a fish faster than anyone else I know), Adam Panioyak (I would have had half as many samples without his fishing prowess), Roger Hitkolok, Adrian Kudlak, Pocco Ilgok, Eric Kaiyogana, Allen Niptanatiak, Eric Hitkolok, Jonathan RT Nivingalok, Gordan Kokak, Robert Angivrana, Wesley Kamayok, Alex Kuliktana, Billy McWilliam, Jenny Klengenberg, Ryan Nivingalok, Russell Akeeagok, and Saveah Ilgok. I have to again acknowledge Roger, who never failed to make sampling a memorable time. Thanks for not letting me get eaten by a grizzly bear, your excitement whenever we caught a "weird" fish, always having a story to share, and liking me "even though" I'm American. Thank you as well to all of the char who gave their lives for science (and subsistence), especially the one tiny char that I still feel bad about sampling. The broader char project in Kugluktuk, of which my work represents a part, began in response to community concerns about the local subsistence fishery; I hope this work has a meaningful impact on the conservation of Coppermine River char.

Numerous funding sources made this research possible. This work was supported by ArcticNet, a Network of Centres of Excellence Canada. Funding for the research presented in chapters 1-4 was provided by the Fisheries and Oceans Canada Coastal Restoration Fund, an NSERC Discovery Grant, and a Northern Research Supplement awarded to my supervisor, Heidi Swanson, and an NSERC Vanier Canada Graduate Scholarship that I was awarded. I received additional scholarships throughout my PhD from the University of Waterloo and the American Fisheries Society. In addition to funding, I am grateful for all of the professional development opportunities I have had during my PhD, which have broadened my knowledge and appreciation of all of the ongoing global char research. Beyond the scientific aspects of those opportunities, they have also allowed me to meet many other PhD students from around the world with similar interests and motivations, several of whom have become friends and sources of encouragement.

Thank you to everyone who has mentored me throughout my scientific journey, and who helped me see this as a viable career path for myself. I wouldn't have made it, though, without the support of my family and friends, especially my parents and sisters, who have been excited for me when things were going well, listened to me complain when they weren't, helped me make decisions when I was feeling unsure, and been there for me every step of the way.

Finally, I am pretty proud of myself for [almost] finishing this degree. On top of the normal stresses of grad school, I contended with two missed field seasons due to the pandemic, tremendous delays in sample processing during the lab supply shortage, and many of the challenges that come with international student life. There were several moments when I seriously questioned all of my life choices. I made it through, though, and I'm excited about the work that I've done in this thesis.

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List of Abbreviations

PCA: Principal component analysis

LDA: Linear discriminant analysis

COSEWIC: Committee on the Status of Endangered Wildlife in Canada

DFO: Fisheries and Oceans Canada

SNP: Single nucleotide polymorphism

mtDNA: Mitochondrial DNA

Two fish in hot water

by Martin PM

I'm leaving to go up North.

But there is no such "up North"!

Imagine that for decades you were used to catching enough Arctic Char to feed your family.



But in the **last 10 years** you have caught less and less...



In addition, what scientists believed to be one species of char...



...was in fact **two.**



The "new" species was even the most abundant one!





Ten years ago, when Inuit fishers began catching fewer fish, they asked scientists to work with them to help address this threat to their subsistence fishing.

Spencer Weinstein is a PhD student in aquatic ecology at the University of Waterloo. She is one of the scientists Inuit fishers are working with.





Scientists have long thought that the only char present in Coppermine River, where Kugluktuk fishers catch chars, was Arctic Char.

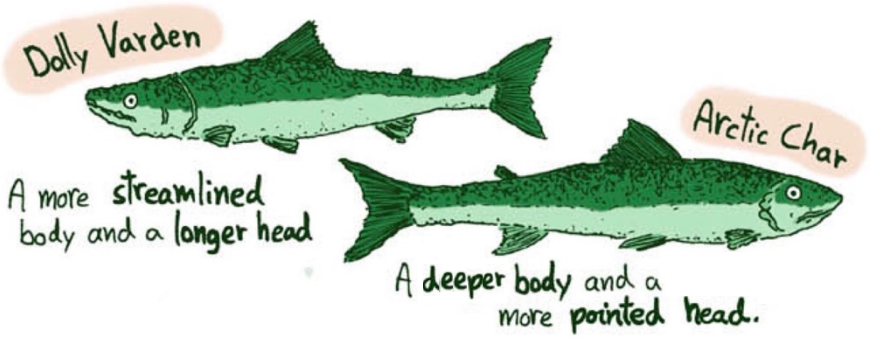
But, there's new DNA evidence showing that Dolly Varden is instead present much further east than we thought.



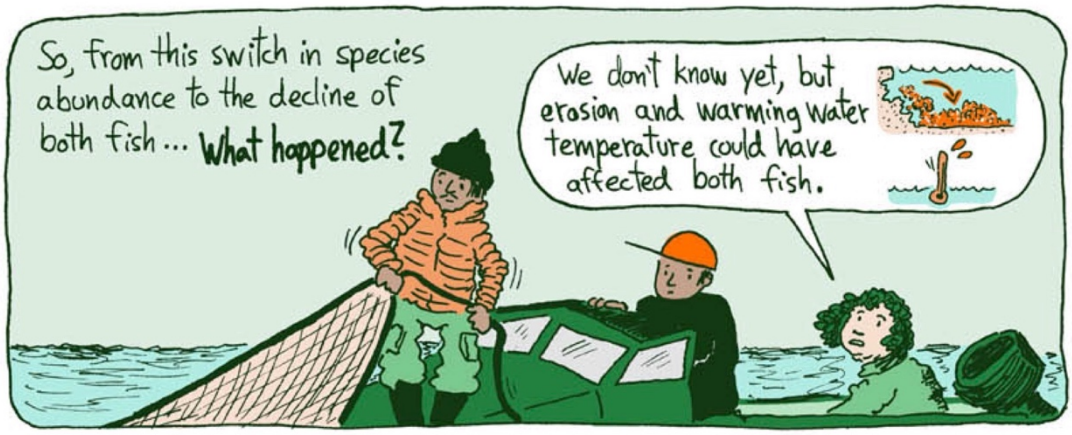
Fishers knew there were different kinds of char. They often referred to some of the longer, skinnier fish as Dolly Varden.

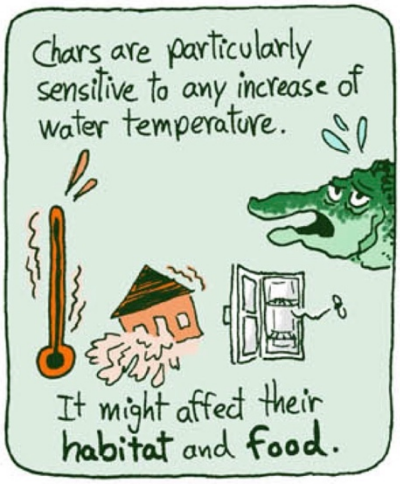


Flesh color may vary from dark to light red.



Some evidence shows that, 50 years ago, Arctic Char was probably the most present in Coppermine River.







Understanding how Arctic Char and Dolly Varden will react to climate change differently will help the community protect this critically important food source.





Food security, and cultural well-being for the generations to come: that's the aim of the collaboration between Kugluktuk Inuit fishers and scientists.



Chapter 1

General Introduction

This chapter is an adapted version of the following paper, submitted to *Environmental Biology of Fishes* in February 2023, and currently in revision:

Weinstein SY, Gallagher CP, Hale MC, Loewen TN, Power M, Reist JD, Swanson HK. 2023. An updated review of the postglacial history, ecology, and diversity of Arctic char (*Salvelinus alpinus*) and Dolly Varden (*S. malma*).

1.1 Introduction

Across their Holarctic ranges, Arctic char (*Salvelinus alpinus*) and Dolly Varden (*Salvelinus malma*) exhibit tremendous variation in morphology, ecology, and life history (Dunham et al. 2008; Klemetsen 2010; Klemetsen 2013; Muir et al. 2016; Reist et al. 2016; Markevich et al. 2018). Both species are culturally and economically important to Indigenous peoples and local fishers in Canada, Alaska, Greenland, Scandinavia, Russia, and Japan (Priest and Usher 2004; Nuttall et al. 2005; Helgason et al. 2006; Prno et al. 2011; Gallagher et al. 2013), and support highly valued recreational, commercial, and subsistence fisheries across their ranges (e.g., Castañeda et al. 2020). In many remote northern coastal communities, where resources are limited and imported food remains expensive relative to southern areas with better infrastructure and access, chars remain an important component of food security (Hammar 1987; Power et al. 2008; Klemetsen 2010; Roux et al. 2011; Elmer 2016).

First scientifically described in the 1700s (Arctic char by Linnaeus in 1758 and Dolly Varden by Walbaum in 1792), the biology, ecology, and diversity of these fishes have been studied extensively in the ensuing centuries. As a result of differentiation and variation within and among populations of char – largely in response to variable and still evolving northern environments – there has long been uncertainty with regard to the delineation of subspecies, lineages, forms, and morphs of both Arctic char and Dolly Varden (e.g., McPhail 1961; Behnke 1980; Morrow 1980). Consistent with previous authors (e.g., McPhail 1961; Reist et al. 2013; Taylor 2016), we therefore recognize that Arctic char and Dolly Varden form a species complex, with 'typical' behaviors exhibited only over small geographic scales or among populations that occupy ecologically similar habitats. Throughout this manuscript, the term 'char' will be used to refer to both Arctic char and Dolly Varden.

The first detailed reviews of Arctic char and Dolly Varden were each published over 40 years ago (Armstrong and Morrow 1980 (Dolly Varden); Johnson 1980 (Arctic char)). While literature about Arctic char has been updated and supplemented several times since the publication of these foundational reviews (Jonsson and Jonsson 2001; Klemetsen et al. 2003; Kershner et al. 2019), updated literature on Dolly Varden has been more limited (e.g., Behnke 1984; Kowalchuk et al. 2010). This is particularly true in North America, where Arctic char have received more scientific study. There is a need for an updated review of Dolly Varden, as well as of relationships between Dolly Varden and Arctic char, given that the species share a close evolutionary history and that, as cold water-adapted species, both are vulnerable to climate-induced changes.

Arctic char are found throughout the circumpolar Arctic, while Dolly Varden occur across the northern Pacific Rim (Figure 1.1), and many morphs and subspecies have been

designated throughout the species' ranges (Tables B.1-B.3). Use of Arctic char delineations by subspecies appear to have generally decreased in the literature over time in favor of delineation by glacial lineage, as indicated by mtDNA haplotypes (Brunner et al. 2001), which may increase consistency in understanding and language use among researchers. In this review, we refer to subspecies due to their prevalence in the older char literature. Commonly designated Arctic char subspecies include *S. a. alpinus* (continental Europe; Russia; Iceland), *S. a. salvelinus* (central Europe), *S. a. oquassa* (Maine; Quebec; New Brunswick) *S. a. erythrinus* (Canadian Arctic; Alaska; Russia), and *S. a. taranetzi* (Russia). Subspecies and forms of Dolly Varden, as well as closely-related Dolly Varden-like chars, include *S. m. malma* (northern form Dolly Varden; Asia; Alaska north of the Alaska Peninsula; Canadian Arctic), *S. m. lordi* (southern form Dolly Varden; Alaska south of the Alaska Peninsula; Washington State; British Columbia; Yukon), *S. m. krascheninnikovi* (southern Asian Dolly Varden; Russia (Kamchatka; Primorye; Kuril Islands; Sakhalin Islands); Hokkaido), *S. m. miyabei* (Hokkaido), and *S. m. kuznetzovi* (stone char; Kamchatka River basin).

Within and among populations, Arctic char and Dolly Varden exhibit many distinct life history strategies: individuals can be anadromous, landlocked, stream- or lake-resident, adfluvial, or isolated (i.e., obligate residents, even if the populations are riverine) due to natural barriers (e.g., waterfalls) or distance from the marine environment (Armstrong and Morrow 1980; Behnke 1980; Johnson 1980; Reist and Sawatzky 2010). Where the two species occur sympatrically in freshwater systems, Arctic char more commonly occupy lacustrine habitats, whereas Dolly Varden more commonly occupy riverine habitats (Taylor et al. 2008; Hart et al. 2015; May-McNally et al. 2015; Arostegui and Quinn 2019). Both species display sympatric morph diversity across their ranges, though such divergence may to be more common in Arctic

char due to the relative stability of lake systems (we recognize, though, that Dolly Varden are comparatively understudied; Melnik et al. 2020).

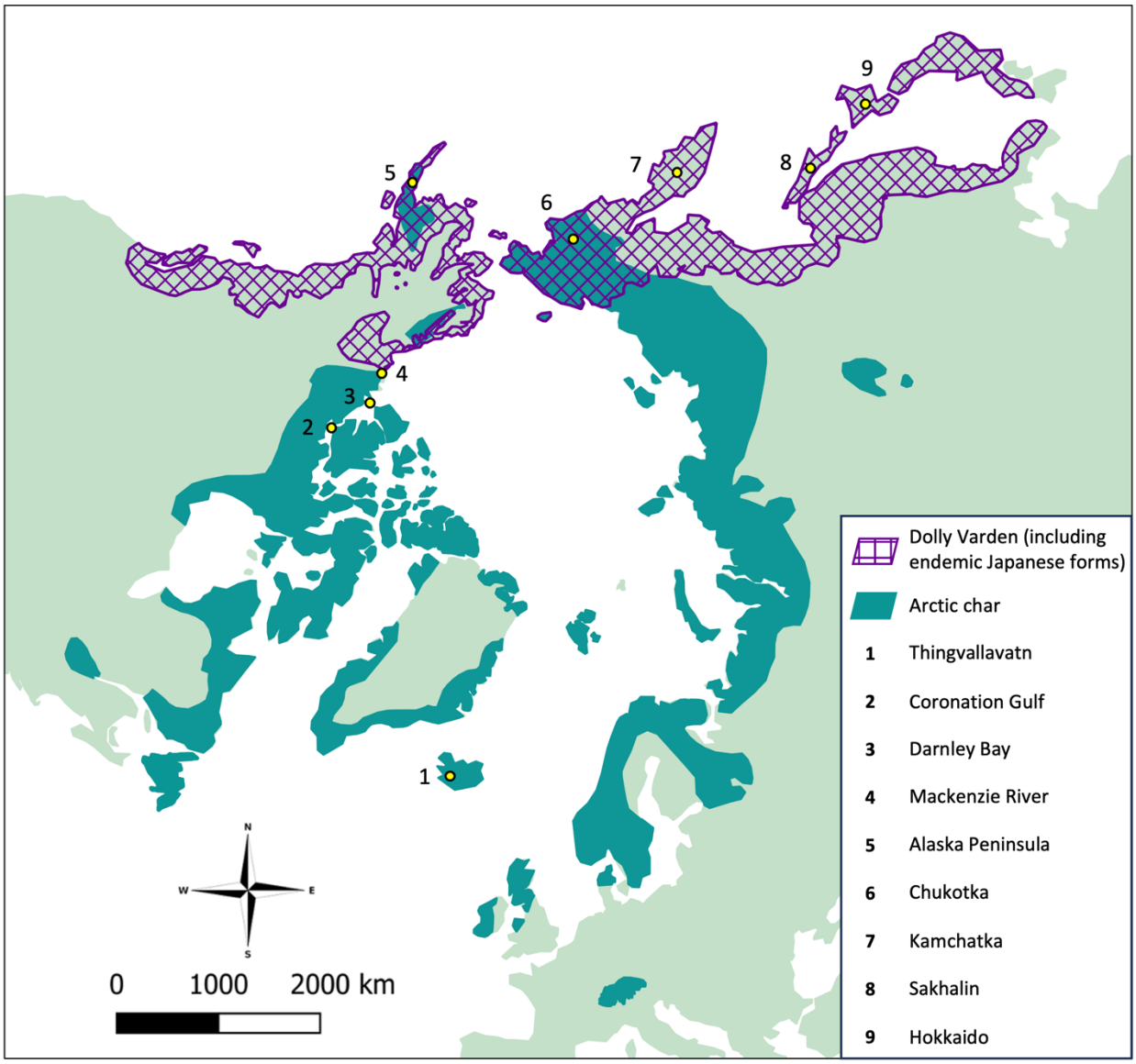


Figure 1.1: *Generally accepted distributions of Arctic char and Dolly Varden, including the Dolly Varden-like fishes found in Japan. A selection of significant placenames are indicated. Adapted from Reist et al. (2013) and Whiteley et al. (2019).*

Limited data for many remote and isolated populations of Arctic char and Dolly Varden has exacerbated problems associated with applying general knowledge to local fisheries management, and has made effective, data-based management difficult to achieve in many

locations. Dolly Varden have been substantively researched in Japan (e.g., Ishii et al. 2002; Koizumi et al. 2006; Yamamoto et al. 2014; Yamamoto et al. 2021), the Russian Far East (e.g., Oleinik and Skurichina 2007; Tiller 2013; Esin 2015; Gruzdeva et al. 2017) and the western Canadian Arctic (i.e., west of the Mackenzie River) and Alaska (e.g., Armstrong 1984; Bond and Quinn 2013; Gallagher et al. 2013; Courtney et al. 2015; Taylor and May-McNally 2015), but are understudied in the Canadian Arctic east of the Mackenzie River. In Canada, the northern form Dolly Varden (*S. m. malma*) is a COSEWIC (Committee on the Status of Endangered Wildlife in Canada)-listed Species of Special Concern due to declines in abundance and geographically limited spawning and overwintering habitats (COSEWIC 2010); however, there is limited population-scale data and an incomplete knowledge of the biology, ecology, behavior, and distribution of Dolly Varden in the Canadian Arctic (COSEWIC 2010; Gallagher et al. 2013). The Species of Special Concern designation has highlighted the need for data-driven management and conservation initiatives for Dolly Varden in Canada, especially in the face of climate change; it is currently difficult to form management and recovery plans for Dolly Varden because distributional and diversity data are still lacking and/or uncertain and/or in conflict.

In this review, we highlight the diversity of Arctic char and Dolly Varden, the ecological and cultural importance of both species, and urgent knowledge gaps regarding diversity and conservation across their ranges. While management of fisheries is not often specific to particular morphs, understanding origins and ecological differences among morphs can inform predictions about effects of climate change and variability in population vital rates. Our objectives are threefold:

1. To review the body of knowledge regarding Arctic char and Dolly Varden, including both foundational and updated reviews, with particular focus on

post-glacial history, ecology, and diversity;

2. To contextualize current and projected effects of climate-induced changes on Arctic char and Dolly Varden; and,
3. To provide recommendations for future research that will inform conservation and management needs.

We recognize that these objectives are not exclusive, and that advances have been made in other areas of char research – especially related to trophic ecology – that merit further review; however, such topics are beyond the scope of this review.

1.2 Methods and Approach

We performed a literature review in Web of Science (All Databases) with the search string ("Arctic char*" OR "Dolly Varden" OR "Salvelinus alpinus" OR "Salvelinus malma") AND (distribut* OR spawn* OR overwinter* OR phylogen* OR morph* OR migrat* OR "climate change" OR "post*glacial" OR "postglacial" OR "life history" OR harvest*). This search returned 3,079 papers, of which 2,212 were removed due to lack of relevance to our stated objectives after scanning the titles and abstracts. Given the unresolved taxonomy of *Salvelinus* fishes, and in particular the Asian Dolly Varden and Dolly Varden-like fishes, we retained papers on other taxa such as *S. levanidovi* and *S. leucomaenis*, which may or may not represent distinct species. Of the remaining 867 papers – a subset of which are cited herein – 516 discussed Arctic char, 163 discussed Dolly Varden or Dolly Varden-like chars, 35 discussed both species, and the remainder focused on broad aspects of char biology and ecology and environmental change. Additionally, we searched the references of selected papers to ensure that this review adequately covered the depth and breadth of the char literature relevant to our topics.

We also searched Canada's Federal Science Libraries Network for gray literature, including reports published by Fisheries and Oceans Canada and by the Alaska Department of Fish and Game, and for papers that were originally published in languages other than English and that were translated as part of the Canadian Translation of Fisheries and Aquatic Sciences and Fisheries Research Board of Canada Translation Series. Finally, we included seminal contributions published in conference proceedings and books such as *Charrs: Salmonid fishes of the genus* Salvelinus (Balon 1980), *Freshwater fishes of Canada* (Scott and Crossman 1973), and *Trout and char of the world* (Kershner et al. 2019). We acknowledge that we are likely missing some relevant gray literature from Europe and Asia that has not been translated or that was not returned from any of our searches, as well as graduate theses and reports produced by consultants for local resource management boards. Given that Arctic char and Dolly Varden exhibit substantial variation across small spatial scales, this is not an exhaustive review of all Arctic char and Dolly Varden populations.

1.3 Discussion

1.3.1 Postglacial history, phylogenetics, and distribution of Salvelinus fishes

Arctic char, Dolly Varden, and forms thereof diverged from a common ancestor an estimated 0.8 – 2 million years ago (Grewe 1990; Oleinik et al. 2004; Oleinik and Skurichina 2007; Oleinik et al. 2013; Yamamoto et al. 2014). Most *Salvelinus* species, including Arctic Char and Dolly Varden, occupy formerly glaciated areas. Approximately 10,000 years ago, following the recession of the Laurentide and Cordilleran ice sheets, many taxa, including *Salvelinus* fishes, began a large-scale colonization of northern environments (Johnson 1980; McCormick 1994; Brunner et al. 2001; Shafer et al. 2010). This colonization occurred on temporally and

spatially variable scales from multiple glacial refugia across North America and Siberia (Behnke 1984; Hammar 1989; Wilson et al. 1996; Moore et al. 2015; Reist et al. 2016), and resulted in inter- and intra-specific radiations and in individuals becoming adapted to local environments (Brunner et al. 2001; Elmer 2016; Wilson et al. 2019). Many systems were colonized repeatedly, by way of both transient waterways and higher sea levels that were prevalent during glacial retreat (Brunner et al. 2001). Fluctuations in water levels facilitated fish movement and allowed for widespread colonization of systems that were previously – and have since been – isolated (Alekseyev et al. 2009; Kapralova et al. 2011; Reist et al. 2016; Esin and Markevich 2018).

Inter- and intra-specific diversity in chars were fostered by cyclical periods of contact and isolation during glacial advances and retreats that occurred throughout the Pleistocene (Johnson 1980; Grewe et al. 1990). During these glacial cycles, tremendous local and regional diversity evolved; both Arctic char and Dolly Varden display phenotypic and genetic differentiation within and between populations, and many forms and morphs of chars are endemic to one or a limited number of systems (Taylor et al. 2008; Kowalchuk et al. 2010; Reist and Sawatzky 2010; Esin and Markevich 2018). The timing and duration of isolation, which were affected by glacial cycles, likely influenced the degree of lineage divergence (e.g., Hewitt 1996) and whether lineages proceeded independently or merged to some degree when again in sympatry; processes of both divergence – which range from complete (i.e., species-level) to incomplete (i.e., subspecies and/or taxonomic forms) – and introgression between lineages are ongoing. Superimposed upon the diversity facilitated by glacial cycles during the Pleistocene is diversity driven by environmental heterogeneity, competition, newly formed post-glacial environments, and other ecological variables (e.g. Skúlason et al. 2019).

Given that Arctic char and Dolly Varden exhibit many ecological, biological, and

phenotypic similarities, as well as substantial intraspecific variability, debate over whether they merit distinct species status prevailed for much of the 20th century. The identification of reproductively isolated, sympatric populations of Arctic char and Dolly Varden originally allowed for the species to be differentiated using the biological species concept (DeLacy and Morton 1943; McPhail 1961); for example, in several lakes systems in Alaska where Arctic char and Dolly Varden are sympatric (e.g., Becharof Lake, Lake Aleknagik, and Iliamna Lake), Arctic char and Dolly Varden have been thought to maintain largely discrete spawning times and/or habitats (McPhail 1961; Taylor et al. 2008). While mitochondrial and nuclear DNA analyses have identified low levels of introgression and hybridization between Arctic char and Dolly Varden where the two species are known to exist in sympatry, including in the Chukchi and Bering seas (Behnke 1972) and in parts of Alaska and Yukon (Taylor et al. 2008; Taylor and May-McNally 2015; May-McNally et al. 2015), much of this contact was likely historical, as there is evidence of introgression and hybridization in systems where contemporary Arctic char and Dolly Varden populations display different life histories and where the two species do not commonly appear to produce (Taylor et al. 2008). Similar evidence of introgression and hybridization can be seen between other *Salvelinus* species, including Arctic char and lake trout (*S. namaycush*) in Québec (Wilson and Bernatchez 1998) and in the Canadian Arctic (Wilson and Hebert 1993), as well as between Dolly Varden and bull trout (*S. confluentus*) in British Columbia (Baxter et a. 1997), including in systems that currently only support one of the two species. The occurrence of even limited natural hybridization between Arctic char and Dolly Varden suggests that the biological species concept cannot be exclusively used to differentiate the two species, and that genetic, morphometric, and life history data must be considered as well.

Species and subspecies designations are often subjective within *Salvelinus*, and clear

morphological or genetic guidelines for taxonomic designations are lacking; for example, Arctic char in the United Kingdom and Ireland were once classified as 15 distinct species (Igoe and Hammar 2004; Maitland et al. 2007). As Behnke (1980) noted, "there will not be general agreement on the number of species recognized in the genus". The taxonomy of *Salvelinus* fishes has been called "confused" (McPhail 1961; Behnke 1984), and Brunner et al. (2001) recognized that "phylogenetic relationships are controversial." Taxonomy is complicated by the fact that many char variants are found in only one lake or distributed over a small geographic scale, and because, across their full ranges, Arctic char and Dolly Varden may not be reciprocally monophyletic (Phillips et a. 1999). Though the phylogenetic relationships between the two species have not been fully resolved, genetic analyses suggest that northern form Dolly Varden diverged from Arctic char before southern form Dolly Varden did (Phillips et al. 1999; Kowalchuk et al. 2010). Given inconsistencies in the literature in terms of definitions of species, subspecies, and morphs, designations must be interpreted within the limitations of the study or system (see Lecaudey et al. (2018) for a summary of variations in phylogenetic tree topologies across studies when different genetic markers or morphological features are used), and researchers may refer to the same population of char by different names.

In North America, the identity of chars both west and east of the Mackenzie River has long been a topic of debate. West of the Mackenzie River (Figure 1.1), uncertainty had prevailed for decades as to the species identification of riverine chars. Identified by McPhail (1961) as a form of Arctic char that he referred to as the Bering Sea-western Arctic form, Morrow (1980) subsequently determined that those fish were indistinguishable from northern form Dolly Varden (*S. malma malma*) in terms of both meristics and ecology. However, ambiguity amongst scientists remained (see Reist et al. 1997), and in the literature populations of riverine char west

of the Mackenzie River continued to be referred to as both Arctic char and Dolly Varden. Eventually, Reist et al. (1997) used meristic characteristics to identify riverine and anadromous chars west of the Mackenzie River as Dolly Varden, and lacustrine chars west of the Mackenzie River and all chars east of the Mackenzie River as Arctic char.

Since at least as far back as 1980 (Armstrong and Morrow 1980; Behnke 1980), the Mackenzie River has been suggested as a distributional boundary for Dolly Varden. While it is possible that there is no suitable habitat for Dolly Varden east of the Mackenzie River or that northern form Dolly Varden are unable to co-exist with anadromous Arctic char (Reist et al. 1997), it appears increasingly unlikely that the Mackenzie River is a firm distributional boundary for Dolly Varden (e.g., Somorjai 2001; Reist and Sawatzky 2010; Byers et al. 2019; McNicholl et al. 2020). Anecdotal data from community members, as well as unpublished scientific data, suggest that Dolly Varden are present (sometimes in sympatry with Arctic char) in several clear-water, high-gradient rivers in the Canadian Arctic east of the Mackenzie River, specifically around Darnley Bay and the Coronation Gulf (Figure 1.1; Reist and Sawatzky 2010; McNicholl et al. 2020). Reist and Sawatzky (2010) present three possible explanations for the presence of Dolly Varden-like fish in waterbodies east of the Mackenzie River: 1) a contact zone exists between Arctic char and Dolly Varden; 2) Dolly Varden mtDNA haplotypes found east of the Mackenzie River reflect postglacial introgression, and alleles have been maintained within Arctic char populations following a past contact event; or, 3) the Dolly Varden-like fish represent a distinct form of Arctic char that morphologically and genetically resemble Dolly Varden (Reist and Sawatzky 2010). Research that will contribute to understanding the presence of Dolly Varden-like fish east of the Mackenzie River is ongoing.

1.3.1.1. Arctic char

Arctic char is both the northernmost freshwater fish species and the most abundant large-bodied fish species in Arctic freshwater ecosystems (Scott and Crossman 1973; Klemetsen et al. 2003; Power et al. 2008). Contemporary Arctic char populations are found in and around Alaska, the Canadian Arctic, the northeastern United States (i.e., New England) and eastern Canada, Greenland, the United Kingdom, parts of mainland Russia (including Siberia) and the islands to the north (including Transbaikalia, Chukotka, and Kamchatka), sub-Arctic and Arctic islands (including Iceland, the Faroe Islands, Svalbard, and Bear Island), and continental Europe – including lakes throughout the Alps that were colonized during glacial retreat and now support isolated landlocked populations (Figure 1.1; Johnson 1980; Esin and Markevich 2018).

Analyses of mitochondrial DNA (mtDNA) haplotypes suggest that Arctic char survived the last glacial maximum in at least five glacial refugia: one each in Siberia, Beringia, Acadia, the North American Arctic, and the Atlantic (Brunner et al. 2001; Oleinik and Skurichina 2007; Moore et al. 2015). Following glacial retreat, secondary contact between established populations of anadromous chars from glacial refugial lineages was facilitated by reduced ocean salinity, (Moore et al. 2015; Oleinik et al. 2017); analyses of range-wide mtDNA haplotype diversity have identified, for example, genetically diverse contact zones between the Bering and Arctic lineages of Arctic char in Kamchatka (Oleinik et al. 2017), between the Arctic and Atlantic lineages in Greenland (Jacobsen et al. 2022), and between the Arctic, Atlantic, and Acadian lineages in Labrador (Salisbury et al. 2019). Genetic data shows that, following glacial retreat, some regions were recolonized by fish from one glacial refugium, while other systems were recolonized by fish from multiple refugia (Wilson et al. 2004; Alekseyev et al. 2009; Oleinik et al. 2017). Northern Europe, for example, appears to have been colonized by char from only the

Atlantic refugial lineage (Wilson et al. 2004), whereas Arctic char in Siberia appear to have been colonized by fish from other refugia to both the west and the east (Alekseyev et al. 2009; Oleinik et al. 2017). While some Arctic char populations in the Alps (also referred to as a distinct species, *Salvelinus umbla*; see Tiberti and Splendiani 2019) and Scandinavia were introduced into lakes (Rasmussen et al. 2019), other populations likely colonized systems using ephemeral waterways during the last glacial retreat. When these waterways became impassable, individuals would have been stranded and, even if capable of anadromy, forced to adopt a landlocked life history (Johnson 1980).

1.3.1.2 Dolly Varden

Dolly Varden is a Pacific species that is believed to have originated in systems isolated by the presence of the Bering land bridge (Savvaitova 1980). Dolly Varden-like fishes have adopted a wide array of behavioral and life history adaptations in rivers in eastern Asia, which makes elucidating phylogenetic relationships challenging and suggests that Asia (i.e., the Sea of Japan and/or the Sea of Okhotsk) was a center of speciation for Dolly Varden and, possibly, Arctic char as well (Oleinik et al. 2007; Yamamoto et al. 2014; Melnik et al. 2020). An origin in the western Pacific is further supported by estimated divergence timing of mtDNA haplotypes, with Dolly Varden lineages in the west identified as being older than lineages in the east (Yamamoto et al. 2014).

Contemporary Dolly Varden populations are found in western Canada and, likely, in the central Canadian Arctic, as well as in Alaska, Japan, Korea, northeastern China, and throughout much of eastern Russia, including in Siberia, Transbaikalia, Chukotka, Sakhalin, and Kamchatka (Figure 1.1; Armstrong and Morrow 1980; Behnke 1980). Dolly Varden in the central Canadian

Arctic east of the Mackenzie River, the Korean Peninsula, and China appear to be particularly understudied compared to populations in other regions.

There are at least three subspecies of Dolly Varden (Tables B.1-B.2), though an understanding of the true extent and scale of Dolly Varden diversity is limited. The three known and broadly accepted subspecies are: 1) the northern form, *S. malma malma*, found in Russia, from the eastern coast of Chukotka south to Kamchatka and the Gulf of Amur (McPhail 1961; Oleinik et al. 2011) and in North America north of the Alaska Peninsula and east to the Mackenzie River in Canada (Behnke 1980; Morrow 1980); 2) the southern form, *S. m. lordi*, in North American systems south of the Alaska Peninsula to Washington state (Behnke 1980; Morrow 1980); and, 3) *S. m. miyabei* in landlocked lakes on the Japanese island of Hokkaido (Phillips et al. 1999; Ishii et al. 2002; Oleinik et al. 2004; May-McNally et al. 2015). A fourth possible subspecies, *S. m. krascheninnikovi* or *S. m. curilus*, which is found across the Asian islands and mainland, is also referred to as *S. curilus*, a distinct species (Oleinik et al. 2007; Esin and Markevich 2018; Yamamoto et al. 2021). Based on physical and ecological characteristics, DeCicco and Reist (1999) proposed the presence of an intermediate Bering Sea form of Dolly Varden in western Alaska, from the northern-draining rivers of the Alaska Peninsula north to the south-draining rivers of the Seward Peninsula; however, the existence of such an intermediate form remains uncertain (see: Kowalchuk et al. 2010).

There are several other closely related Dolly Varden-like chars in eastern Russia and Japan, including the stone char (*S. kuznetzovi* or *S. m. kuznetzovi*). The stone char is endemic to the Kamchatka River Basin, and has been characterized as a morph, a subspecies, and a species by different authors (Oleinik et al. 2019; Melnik et al. 2020). The stone char shares a close evolutionary history with both Dolly Varden and the white-spotted char (*S. leucomaenis*).

Analyses of mitochondrial DNA suggest that hybridization and introgression, which may be unidirectional (i.e., between larger migratory females and smaller resident males), have occurred between several Dolly Varden-like fishes, including between the predominantly stream-resident *S. curilus* and anadromous *S. m. malma* on Sakhalin Island, Russia (Yamamoto et al. 2021), *S. m. malma* and *S. taranetzi* in Lake Grand in Russia's Okhotsk-Kolyma watershed (Oleinik et al. 2021), and *S. m. malma* and *S. leucomaenis* in rivers draining into the Sea of Okhotsk (Radchenko 2004).

Dolly Varden survived the last glacial maximum in at least two major glacial refugia – Beringia and the Pacific Northwest south of the ice sheets in North America – and these refugia likely contained additional minor refugia (Redenbach and Taylor 2002; Yamamoto et al. 2014). In North America, southern form Dolly Varden may have survived the last glaciation south of the ice sheet (i.e., in a Pacific Northwest refuge) while northern form Dolly Varden persisted in Beringian refugia in unglaciated parts of Alaska (McPhail 1961; Reist et al. 1997); division between northern- and southern-form Dolly Varden may have additionally occurred within Beringia (Groening 2008). Northern and southern form Dolly Varden continue to be found on opposite sides of the Alaska Peninsula, with a contact zone along the Alaska Peninsula (Taylor and May-McNally 2015).

1.3.2 Life history, spawning, and overwintering ecology

Herein, we use 'life history' to refer to traits, patterns, and behaviors associated with residency and anadromy, and we use 'morphs' in the context of the niche partitioning that can occur within populations of char that exhibit landlocked or lake-resident life histories and result in phenotypic differences. Within and among populations, both Arctic char and Dolly Varden

can adopt a variety of life history strategies. Individuals can be anadromous, landlocked (primarily Arctic char), stream- (Dolly Varden) or lake- (Arctic char) resident (i.e., individuals that are sympatric with anadromous fish during spawning), adfluvial (uncommon in Dolly Varden; likely more prevalent in Asian than North American populations), or isolated (by barrier or by distance; typically used when describing Dolly Varden; Tables B.1-B.3; Harris et al. 2015; Kowalchuk et al. 2010; Sawatzky and Reist 2021). Genetic diversity differs among life history types: isolated populations exhibit the least amount of genetic diversity, stream- and riverine-resident populations are intermediate, and anadromous populations have the most genetic diversity (Gyllensten 1985; DeWoody and Avise 2000; Gomez-Uchida et al. 2009; Harris et al. 2015).

As has been described in detail elsewhere (e.g., Jonsson and Jonsson 1993), migration is in part driven by differential food availability in fresh water vs. saltwater (i.e., facilitating anadromy) and streams vs. lakes (i.e., facilitating the adfluvial life history). Anadromy, which appears to confer more of a benefit in northern systems than in mid-latitude and southern systems (Maekawa and Nakano 2002), represents a life history tradeoff – it is energy intensive and daily mortality rates can be high (e.g., Brown et al. 2019), particularly for first- and second-time migrants who can experience mortality rates 10-15 times higher than those of freshwater residents (Jensen et al. 2019). In systems where river water levels fluctuate interannually, years of low water levels may be correlated with increased mortality among migrant individuals (Svenning and Gullestad 2002). However, successful migrants (i.e., individuals who are able to effectively osmoregulate, avoid predation, and return to fresh water) have access to higher quality marine food sources, are able to grow larger than resident individuals, and are more fecund than their freshwater-resident counterparts (Jonsson and Jonsson 1993). For males, who

do not (from a fecundity perspective) benefit as much as females from migration, individuals can remain resident and adopt a 'sneaker' strategy, remain small, and mate with larger, highly fecund anadromous females (Jonsson and Jonsson 1993). Resident chars occurring sympatrically with anadromous chars can also form genetically distinct populations (Salisbury et al. 2018; Doenz et al. 2019; O'Malley et al. 2019; Salisbury et al. 2020).

Where they co-occur in continuous lake-stream systems in Alaska, Arctic char and Dolly Varden make differential use of lake and stream habitats, respectively, throughout their lives, including during spawning (e.g., May-McNally et al. 2015). There is also evidence to suggest that the species are morphologically adapted to different food sources (DeLacy and Morton 1943; Dennert et al. 2016). Research in an Alaskan system found that Arctic char consumed a wider variety of prey than did Dolly Varden, and that the variety of prey consumed increased with increasing fish size (Dennert et al. 2016). These differences in prey preference likely contribute to distinct morphological characteristics between the species, with Dolly Varden having smaller heads and mouths than Arctic char (Dennert et al. 2016). Morphological differences between Arctic char and Dolly Varden tend to be apparent from the juvenile stage, indicating that the species may avoid competition in sympatric rearing habitats by occupying distinct trophic niches (Dennert et al. 2016; Melnik et al. 2020). Similar inter-specific differences are observed when Dolly Varden (*S. m. malma*) are sympatric with other Dolly Varden-like fishes, such as stone char; in these systems, stone char are ambush predators whereas Dolly Varden are generalist benthivores with smaller heads and mouths (Melnik et al. 2020).

Limited hybridization between the species has been thought to reflect distinct spawning habitats, with Arctic char spawning in lakes and Dolly Varden in rivers (DeLacy and Morton 1943; Dennert et al. 2016), though additional explanations are possible; if spawning habitats do

overlap, hybridization could be limited by differences in spawning times or in the sections of rivers used, or by mate preference. Reproductive isolation and limited hybridization among sympatric or spatially proximate populations may additionally be facilitated by different selective pressures on juvenile life histories (i.e., isolation-by-adaptation; Bond et al. 2015). While this requires more research, it is possible as well that hybrids are produced but, as sympatric salmonids often occupy distinct feeding niches, hybrids may be morphologically intermediate and inadequately adapted to available environmental niches (Hagen and Taylor 2001; Dennert et al. 2016).

1.3.2.1 Arctic char

Anadromous Arctic char have been well-studied in many systems across the circumpolar Arctic. Research in the high Arctic has shown that young-of-the-year Arctic char are able to migrate into coastal and estuarine habitats (Loewen 2015), though authors of a recent review reported that anadromous Arctic char generally make their first seaward migration between ages 2 and 11, with age of first migration varying among systems (see Power and Reist 2018). Arctic char in some populations may make annual seaward migrations, while in other populations, individuals may skip migration and remain in freshwater in certain years (e.g., Gyselman and Broughton 1991; Gilbert et al. 2016).

Anadromous Arctic char typically exhibit three distinct migrations each year that they migrate: a spring feeding migration to the marine environment, a fall spawning migration to freshwater spawning sites, and a fall overwintering migration to freshwater overwintering sites (Moore et al. 2017). Migration timing is variable across systems, with the downstream migration to marine environments generally occurring from late spring to mid-summer as the ice breaks

along the rivers, and the upstream spawning migration taking place from late summer through early fall (Dempson and Green 1985; Quinn et al. 2016). Fidelity by juveniles and non-reproductive adults to overwintering systems is variable and can be related to migratory harshness (the distance and difficulty of the migratory route), meaning that populations regularly mix during overwintering (Gilbert et al. 2016; Moore et al. 2016; Moore et al. 2017). Because fidelity to spawning sites appears to be higher than fidelity to overwintering sites, mixing of overwintering populations does not necessarily translate to gene flow and genetic mixing between populations (Moore et al. 2013; Moore et al. 2017).

Anadromous fishes of the genus *Salvelinus*, including Arctic char, have relatively low saltwater tolerance and are generally unable to survive freezing winter ocean temperatures, meaning that fish must return annually to fresh water to overwinter (Klemetsen et al. 2003; Moore et al. 2013; Moore et al. 2017); accordingly, anadromous chars are thought to lose and redevelop their ability to tolerate saltwater ("reverse smoltification") with each subsequent migration and overwintering period (Aas-Hansen et al. 2005; Bystriansky et al. 2007). As Arctic char (and Dolly Varden) must spawn and overwinter in places that do not freeze completely through in the winter (Gallagher et al. 2018), the habitat must be sufficiently deep, fed by groundwater or, in the case of most rivers that support spawning and overwintering, sufficiently far south (Power 2002). In the high Arctic, where lotic systems are more likely to freeze to bottom, Arctic char were long thought to spawn and overwinter only in lakes (Johnson 1980; Richardson et al. 2001). However, riverine-overwintering anadromous populations have been identified in the Beiarelva River in Norway (Jensen 1994) and in three rivers in the Canadian Arctic: the Kellet River, Nunavut and the Hornaday River, Northwest Territories (Harwood and Babaluk 2014), and the Coppermine River, Nunavut (Smith et al. 2022). There are, additionally,

three reported instances of Arctic char occupying at least brackish habitats during winter. Two populations of Arctic char in Nunavut have been found to tolerate freezing ocean temperatures (below 0ºC; Bystriansky et al. 2007; Smith et al. 2022), and anadromous Arctic char in northern Norway from riverine systems that are not connected to lakes use estuarine and marine habitats throughout winter, presumably because the estuarine and marine habitats are warmer than the rivers (Jensen and Rikardsen 2012). It thus appears that seasonal fluctuations in osmoregulatory capacity may be dynamic across populations, and that the physiological cost of winter saltwater tolerance may be preferable over cold, volatile riverine conditions (Jensen and Rikardsen 2012).

When overwintering in freshwater systems, anadromous Arctic char generally remain at overwintering sites until ice breakup in the spring, although they can move downstream and into the marine environment before or during ice breakup (Scott and Crossman 1973; Hammer et al. 2022; Smith et al. 2022). A longer duration of residency in salt water, as facilitated by an early marine migration, likely maximizes resource use in the more productive marine ecosystem (Hammer et al. 2022). During the marine feeding period, Arctic char appear to often remain in estuaries and nearshore habitats, where both water salinity and risk of predation are relatively low, though migration distance and habitat use may be sex-dependent (Moore et al. 2016), and long-distance migration has recently been detected (Hollins et al. 2022). Notably, Gulseth et al. (2001) found that estuary use by first-time migrants does not reflect osmoregulatory capacity, as those individuals were able to tolerate exposure to salt water.

Arctic char spawn in lakes, rivers, and streams depending on the life history of the individual or population and on the characteristics of the system (e.g., substrate characteristics, water depth, and flow; Power and Reist 2018; Bilous and Dunmall 2020). Fecundity tends to increase with fork length and decrease with latitude, though the strength of those relationships

vary depending on life history (Power et al. 2005a). Spawning may occur annually (in the southern portion of the range) or in alternate or intermittent years (in northern populations; Scott and Crossman 1973; Johnson 1980; Moore et al. 2013; Power and Reist 2018; Alekseyev et al. 2021). In partially migratory populations (i.e., those where a portion of the population migrates and a portion remains resident), anadromous individuals, which can be produced by either anadromous or non-anadromous parents, reach a larger maximum size and reach sexual maturity at an older age than non-anadromous individuals (Nordeng 1983). Arctic char often exhibit fidelity to their natal systems or to the site of first spawning (Johnson 1980), though the rate of straying in Arctic char (which may be for overwintering rather than spawning purposes) has been estimated to be as high as 53% (Gyselman 1994). Arctic char populations often display hierarchical population structure across geographic scales (e.g., Harris et al. 2014; Dallaire et al. 2021), and straying in spawning years more commonly occurs between nearby systems; genetic differentiation between nearby systems may be eroded by even a small number of individuals straying in a spawning year, especially if population sizes are small (Bond et al. 2015).

Arctic char most commonly spawn in the fall and early winter, with northern populations spawning earlier (Madsen et al. 2020). Non-anadromous individuals can also spawn in the spring and summer (Johnson 1980; Klemetsen 2010), though in the southern portion of the species' range, warmer water temperatures likely make conditions unfavorable for egg incubation, thereby preventing spring spawning (Johnson 1980). Spring- and summer-spawning char have been identified in Iceland (Sandlund et al. 1992), Norway (Hesthagen et al. 1995), the UK (Johnson 1980; Corrigan et al. 2011), and in several lakes in Russia (Alekseyev et al. 2021), and always in sympatry with more typical fall-spawning char (Alekseyev et al. 2021). Researchers studying char in Windermere, a cold, deep, glacial lake in England, found that spring spawners

produced more and smaller eggs than did fall spawners (Johnson 1980). Fall spawners also spawned in shallower water, on average, than did spring spawners, and consequently may experience increased rates of predation (Frost 1965; Corrigan et al. 2011).

1.3.2.2 Dolly Varden

Anadromous Dolly Varden generally reach sexual maturity at age 4-9, and similar to Arctic char, they return to freshwater to spawn (Armstrong and Morrow 1980; Gallagher et al. 2018). Dolly Varden populations can be summer- or fall-spawning (DeCicco 1997) and spawning can occur annually, in alternate years, or every few years, though anadromous individuals generally spawn every other year (Armstrong and Morrow 1980; Sawatzky and Reist 2021).

In populations supporting anadromous *S. m. malma*, individuals generally remain in fresh water until age 2-5, when they smolt and migrate to the marine ecosystem (Armstrong and Morrow 1980; Gallagher et al. 2018). Similar to Arctic char, anadromous Dolly Varden make spring feeding migrations to sea before generally returning to fresh water to overwinter (Armstrong and Morrow 1980). The exact timing of both the seaward and return migrations depends on the age and size of the individual. In several rivers in Kamchatka, large spawners and juveniles move downstream earliest in the season, and large fish then return to fresh water before smaller and younger individuals (Tiller 2013); similar patterns have been observed in Arctic char (e.g., Johnson 1980; Svenning and Gullestad 2002; Smith 2022), though in Svalbard only with the upstream migration (Gulseth and Nilssen 2000).

Properties of anadromous migrations are affected by factors such as ocean productivity, fish size, and fish age, and can vary among populations (Underwood et al. 1996). Both northern

and southern form anadromous Dolly Varden (*S. m. malma* and *S. m. lordi*) may migrate annually (Bond et al. 2015; Hart et al. 2015), or may skip migration and remain in fresh water during the summer feeding period before perhaps migrating again the following year (Gallagher et al. 2018). While younger Dolly Varden that skip migration resume anadromy after one season in fresh water, older Dolly Varden that do not incur as much benefit from the marine environment may cease migration entirely and adopt a resident life history for the remainder of their lives, particularly if the food and energy sources in the fresh water system are sufficient (Bond et al. 2015).

Skipped migration is affected by migratory harshness and individual condition, and represents a trade-off between growth and reproduction (Gallagher et al. 2018). In the Canning River, Brown et al. (2019) confirmed that Dolly Varden can skip migration in the season before they spawn, which may be a bet-hedging strategy to protect against increased mortality rates at sea; however, some individuals that will spawn in the fall will go to sea in that same year. In the Rat River in Canada's Northwest Territories, where the migration from the ocean to spawning and overwintering sites is approximately 800 kilometers, Gallagher et al. (2018) found that fish that skipped migration always migrated the following year. Dolly Varden in the Rat River regularly skip migration, and spawning generally occurs in the year in which the fish skipped migration, with few individuals spawning in the preceding or succeeding years, likely because the fish were restoring their energy supplies (Gallagher et al. 2018). Skipped spawning has also been observed among Dolly Varden in certain rivers in Kamchatka, which researchers have also speculated is due to insufficient energy stores due to a relatively short marine feeding periods of approximately two months (Tiller 2013).

While anadromous Dolly Varden have long been thought to undertake primarily coastal

migrations (see Courtney et al. 2018) individuals can and frequently do undertake long-distance ocean migrations of up to hundreds – or occasionally thousands – of kilometers (DeCicco 1992; Morita et al. 2009; Courtney et al. 2015; Courtney et al. 2018; Gallagher et al. 2021). Utilization of offshore habitats during the summer migratory period has also been documented (Morita et al. 2009) and may maximize foraging opportunities (Courtney et al. 2018, Gallagher et al. 2021). Individuals use nearshore brackish habitats during the early part of the growing season especially, suggesting that habitat use and reliance changes over time (Underwood et al. 1996) and that conservation and management practices must be focused on all critical habitats. Habitat use may vary with fish size and age, with younger fish primarily using less-saline nearshore and estuarine areas, and older and/or larger fish making longer-distance movements and using offshore habitats (Sawatzky and Reist 2021). From a climate change perspective, shorter-distance migrations may be more beneficial, as individuals would only have to adapt to changing conditions on a small geographic scale (Bond and Quinn 2013).

Anadromous southern form Dolly Varden, *S. m. lordi*, often exhibit a complex migration pattern, depending on whether individuals originated in a system with or without a lake (Armstrong 1974; Armstrong and Morrow 1980; Armstrong 1984). Whereas spawning occurs in rivers and streams with flowing water, which provides needed oxygen to developing eggs, overwintering frequently occurs in lakes (COSEWIC 2010; Kowalchuk et al. 2010). Similar to Arctic char, anadromous Dolly Varden that originate in lake systems leave lakes in the spring to make a seaward feeding migration before returning to lakes in the late summer or fall to overwinter. Migratory runs of fish include smolts and non-spawners, which may enter and leave multiple freshwater systems during the migratory period, and fall spawners, which travel directly from the ocean to the spawning site (Armstrong 1984).

As southern form Dolly Varden typically overwinter in lake systems, fish that originate in non-lake systems must find a suitable lake in which to overwinter. Anadromous southern form fish leave their natal streams in the spring and migrate to the ocean, where they feed and move into and out of freshwater systems until finding one connected to a lake suitable for overwintering. After overwintering in a lake, non-spawners migrate again to the ocean, where they feed and may enter and leave other freshwater stream and river systems before migrating back to the lake to overwinter (Armstrong and Morrow 1980). Current-year spawners also make a spring seaward migration, but move directly to their natal systems without entering any other freshwater systems. After spawning, surviving fish move directly to lakes to overwinter (Armstrong 1974; Armstrong and Morrow 1980; Armstrong 1984). This pattern of migration tactics is much more common in anadromous southern than in northern Dolly Varden, which tend to exhibit more 'traditional' anadromous behavior (Kowalchuk et al. 2010). While it has not been confirmed, researchers have hypothesized that southern form Dolly Varden might on occasion overwinter at sea, a behavior which could reflect the timing of attempted entry into freshwater – individuals entering streams late in the season may find sea water warmer than fresh water, and thus may derive a physiological benefit from remaining in nearshore marine or brackish waters (Bernard et al. 1995), perhaps at an osmoregulatory cost.

Migrations and seasonal movements are observed not only in anadromous Dolly Varden, but can be undertaken by freshwater-resident (adfluvial and stream-resident) fish as well (e.g., Bryant et al. 2009). For example, stream-resident Dolly Varden in Japan's Shiisorapuchi River make annual migrations between the main stem and river tributaries for spawning, feeding, and overwintering (Koizumi and Maekawa 2003; Koizumi et al. 2006). Tributaries represent particularly important spawning grounds for several Dolly Varden populations. In the

Shiisorapuchi River, spawning appears to occur exclusively in tributaries, while Bramblett et al. (2002) found that in river systems southeastern Alaska, Dolly Varden rely on tributaries year-round, including during spawning, and that tributaries are used by both resident and anadromous individuals.

1.3.3 Common morphotypes: origins and patterns of divergence

1.3.3.1 Arctic char

Periods of glacial and post-glacial isolation and secondary contact, combined with the ability to adapt to a range of systems and environments, have resulted in the evolution of a diversity of Arctic char morphs within life history types, and both within and among populations. Morphs may be affected by distinct selective pressures, depending on factors such as habitat and diet preferences and time since divergence (Knudsen et al. 2011; Simonsen et al. 2017). Arctic char are phenotypically plastic and readily make use of, and adapt to, available niches within systems (Amundsen et al. 2008; Reist et al. 2013; Elmer 2016). Lake-resident Arctic char populations, which may be isolated or found sympatrically with anadromous Arctic char, often contain two or three sympatric morphs that separate along a benthic-pelagic or benthivorous-planktivorous-piscivorous resource axis (Table 3; Johnson 1980; Jonsson and Jonsson 2001; Klemetsen 2010). Populations may also diverge into pelagic-profundal morphs (Hooker et al. 2016), though this appears to happen less frequently, and morphs in those systems appear to have higher levels of genetic differentiation than do morphs that have diverged along other axes (Kess et al. 2021). Differences in preferences of water depth and intraspecific partitioning of food sources have led to well-described variation among morphs in head and body shape, size, color, fin and mouth placement, and/or spawning time and location, and this variation appears to be

driven by a combination of genetics and the environment (e.g., O'Connell and Dempson 2002; Power et al. 2005b; Klemetsen 2010; Corrigan et al. 2011).

Some lakes, including Thingvallavatn in Iceland (Figure 1.1), support more than three sympatric morphs of Arctic char (Skúlason et al. 1999; Snorrason and Skúlason 2004; Klemetsen 2010). In those systems, morph divergence occurs along both water depth and prey resource axes and may have been facilitated and/or maintained by both habitat segregation and spatial and temporal differences in spawning (Skúlason et al. 1999; Noakes 2008; Skoglund et al. 2015). Sympatric morphs are often genetically distinct (e.g., Guðbrandsson et al. 2019), though across populations, genetic divergence of char morphs and life histories generally does not seem to be driven by parallel evolution (Salisbury and Ruzzante 2022; Salisbury et al. 2022), suggesting that phenotypically identical morphs can evolve via different pathways in different systems (Salisbury and Ruzzante 2022).

Researchers have repeatedly questioned whether morphs evolved independently within systems following one colonization event from a single glacial refugium, or whether morphs evolved separately in multiple glacial refugia and dispersed during multiple colonization events (Behnke 1972; Kapralova et al. 2011; Skúlason et al. 2019). There is evidence from proximate systems supporting both sympatric and allopatric morph divergence (e.g., Garduño-Paz et al. 2012). Populations that have been isolated since initial post-glacial colonization events have experienced minimal gene flow between systems and it is likely that in these systems morphs evolved repeatedly and independently (Kapralova et al. 2011). This is supported by the fact that there is higher genetic differentiation between similar morphs in different systems than between different morphs within systems (Gíslason et al. 1999); these systems may have been colonized by fish from a single glacial refugia.

While patterns of greater among- than within-population genetic variation are common, there are instances where different morphs within systems are more genetically distinct from each other than from the same morph in different systems. In Lake Fjellfrøsvatn, Norway, the reproductively isolated fall-spawning littoral and winter-spawning profundal Arctic char morphs display significant genetic and ontogenetic variation even though they are thought to have evolved sympatrically (Klemetsen et al. 1997; Westgaard et al. 2004; Knudsen et al. 2006; Amundsen et al. 2008; Præbel et al. 2016). Several non-landlocked lakes in Greenland also support sympatric and genetically distinct morphs (Doenz et al. 2019), including lakes Tasersuaq and Saqqaata Tasia in southern Greenland, which support five morphs each (Doenz et al. 2019). The same morphs in different lakes are more genetically similar than are different morphs in the same lake, and this may reflect patterns of post-glacial colonization within these systems, as these lakes are immediately adjacent to each other and were likely connected hydrologically until very recently (Doenz et al. 2019).

Phenotypic variation within morphs and populations can be (but is not always) adaptive, and impacted by the ecology of distinct niches (Kapralova et al. 2011). In Lake Rannoch, Scotland, morphs differ in head morphology, diet, and coloration. The lake supports a brightly-colored planktivorous morph and two cryptically-colored morphs with distinct head morphologies and spawning locations, of which one morph is piscivorous and the other benthivorous (Adams et al. 1998). In the same lake, researchers studying whether time since morph divergence was correlated with divergence in anatomical traits concluded that divergence was in fact facilitated by the need to adapt to new and diverse environments (Bryce et al. 2016).

While niche separation can occur rapidly, differentiation and sympatric isolation can be reversed with changing environmental gradients if the morphs are not genetically distinct

(Savvaitova 1980), or if environmental effects are responsible for more variation in the trait (i.e., body size or craniofacial morphology) than are genetic effects. A three-year hatchery study showed that when raised under identical conditions, dwarf Arctic char can reach sizes comparable to large piscivorous Arctic char (Janhunen et al. 2010), which supports the assertion that morph segregation in some systems has evolved to maximize resource use. In studying the offspring of benthivorous and planktivorous char from Loch Rannoch that were raised in a controlled environment, Adams and Huntingford (2004) found that phenotypic variation in head shape was more strongly impacted by the environment than by genetics, though a prior study of fish from the same system did show a degree of genetic variation between morphs (Adams and Huntingford 2002). These studies support the importance of phenotypic plasticity and gene-by-environment interactions in morph divergence, while also highlighting the occurrence of different drivers and controls of morph divergence among populations.

Morph divergence may also be influenced by factors including epigenetics, which could facilitate more rapid divergence (Skúlason et al. 1999; Adams et al. 2003; Skúlason et al. 2019), as well as the presence of few other species in lakes occupied by Arctic char. The presence and frequency of multiple char morphs in lake systems deepens lingering questions of how to define a species, and at what point morphs, forms, ecotypes, or populations should be managed separately.

1.3.3.2 Dolly Varden

The Pacific origins of Dolly Varden (Yamamoto et al. 2014) may explain why this species is more often found in riverine than lacustrine habitats, as much of the Pacific distribution is located in mountainous terrain and Dolly Varden likely evolved to occupy streams

(Melnik et al. 2020). As rivers support a lower diversity of available niches than lakes, sympatric Dolly Varden morphs are less common than are sympatric Arctic char morphs (Melnik et al. 2020). More commonly, Dolly Varden populations minimize intraspecific competition by adopting distinct life histories (Pichugin 2015; Markevich et al. 2018). For example, there are anadromous and adfluvial Dolly Varden (*S. m. malma*) and adfluvial stone char (*S. m. kuznetzovi*) in the Kamchatka River Basin, where the two subspecies occupy partitioned habitats and have distinct life histories and feeding and migratory behaviors (Melnik et al. 2020; Tables B.1-B.2). There is, however, at least one lake in Kamchatka that supports benthivorous and piscivorous Dolly Varden, and populations in isolated volcanic lakes regularly consist of 'normal' and cannibalistic morphs of Dolly Varden (Markevich et al. 2018). Volcanic activity in the Pacific region produced lakes with high habitat diversity and low species diversity (Markevich et al. 2018), presumably facilitating morph divergence not seen in lakes in North America, though further research is necessary.

Perhaps the most interesting case of sympatric Dolly Varden morphs is in Lake Kronotskoye, Kamchatka, where eight morphs have been identified that differentiate along both a water depth gradient and a resource-use gradient (Markevich et al. 2018, Esin et al. 2020). Morph divergence, which appears to have resulted from a combination of sympatric and allopatric divergence (Ostberg et al. 2009), was likely facilitated by disruptive selection on multiple scales and timeframes in the lake, which supports only Dolly Varden and kokanee (*Oncorhynchus nerka*) and formed 12-14,000 years ago as a result of volcanic activity (Markevich et al. 2018). Across the entire distribution of Dolly Varden, this is, to date, the only system where such diversity has been documented. In studying five morphs within the system, Ostberg et al. (2009) found that colonization occurred from two separate systems or refugia, and

that further morphological diversification occurred within the lake following the colonization events. Consequently, Esin et al. (2020) identified five of eight morphs in the lake as genetically distinct. After divergence, these Dolly Varden morphs, as well as the Arctic char morphs discussed previously, may maintain segregation through spatial and temporal differences in spawning that lead to reproductive isolation, the accumulation of genetic differences, and the establishment of hybrid incompatibility (Ostberg et al. 2009; Küttner et al. 2014; Markevich et al. 2018). It is important to acknowledge that Dolly Varden remain understudied relative to Arctic char, and given that few lake systems supporting Dolly Varden have been rigorously studied, it is likely that there is a bias in our understanding of intra-specific diversity and that we substantially underestimate Dolly Varden diversity.

1.3.4 Projected effects of climate change

1.3.4.1 Arctic char

Morphs, life histories, and populations of Arctic char are likely to be differentially affected by and vulnerable to climate-induced changes. Migratory (i.e., anadromous and potadromous) chars that are exposed to multiple environments and that rely on distinct habitats at different life stages are especially vulnerable to climate-induced changes (e.g., Reist et al. 2006), habitat alteration, and other human-induced threats (Strayer and Dudgeon 2010; Muhlfeld et al. 2018; Dauwalter et al. 2020). The vulnerability of Arctic char to climate change in a given system is affected by the latitude, altitude, and depth of the system (Winfield et al. 2010), with significant population declines expected for shallower, lower altitude, and more southerly populations. For example, population declines have been noted in systems in the UK, near the southern portion of the species' range in Europe (Winfield et al. 2010). In the Canadian Arctic,

researchers noted that individual growth was impacted in a shallow lake that experienced more rapid warming than did nearby deeper lakes (Murdoch and Power 2013). In Arctic char, anadromy is more prevalent toward the middle, latitudinally, of the range, and becomes more limited at the northern and southern edges of the range (e.g., Loewen 2015). Genomic research and environmental modelling on Canadian Arctic char populations suggests that more southerly anadromous populations may have reduced adaptive capacity and be especially vulnerable to climate-induced changes, and that anadromy may become a nonviable life history strategy for Arctic char at the southern edge of their range (Layton et al. 2021).

As waters warm and southern species extend their ranges farther north, increased interspecific competition may affect Arctic char. Though often the first species to colonize newly available post-glacial habitats (Hammar 1987), Arctic char are sensitive to competition and environmental changes, and are often outcompeted in more southerly systems by species such as brown trout, Dolly Varden, lake trout, and brook trout (Johnson 1980; Behnke 1984; Hammar 1987). Many of these anadromous salmonids are expected to invade and/or become more prevalent in northern systems as water temperatures increase and the ice-free period becomes longer, displacing anadromous and resident (i.e., non-landlocked) Arctic char or limiting them to the extreme northern extent of their range (Reist et al. 2006; Svenning et al. 2021). Many Pacific salmon species, including but not limited to pink salmon (*Oncorhynchus gorbuscha*), sockeye salmon (*O. nerka*), chinook salmon (*O. tshawytscha*), and coho salmon (*O. kisutch*), as well as Atlantic salmon (*Salmo salar*), have already been found in northern systems that were historically too cold for those species to tolerate (Dunmall et al. 2016; Bilous and Dunmall 2020). Although Arctic char are able to adjust their foraging patterns and habitat use in response to changing environmental conditions and prey abundance (Cote et al. 2021), Atlantic salmon are

stronger competitors in warmer environments and have greater absolute metabolic scope and a higher critical thermal maximum than do Arctic char, allowing for increased growth, reproduction, and survival in warmer water temperatures (Penney et al. 2014). In some populations, a shift in species composition has already been documented (e.g., Svenning et al. 2016). Importantly, it is not just overall water temperatures that facilitate range extensions of more southerly species; rather, water temperatures must be suitably warm in specific habitats that support critical life history strategies, such as spawning, overwintering, and egg incubation (Dunmall et al. 2016). Implications of shifts in species' compositions will not be limited to ecology and biodiversity, but will also likely include food security, as at least in the shorter term, subsistence fishers may be hesitant to consume novel species (e.g., Chila et al. 2022).

Warming water is likely to affect every part of the Arctic char life cycle, including food availability, the amount of energy an individual can spend on foraging, and movement to spawning and overwintering habitats. During the annual migratory cycle of anadromous Arctic char, individuals can experience temperatures that range from ~ 0ºC to 21ºC (Gilbert et al. 2020); at the upper end of this range, fish may experience adverse physiological effects (Gilbert et al. 2020). While at sea in the Canadian Arctic, Arctic char repeatedly dive into deeper waters, likely in search of prey, but spend the majority of their time in the uppermost portion of the water column where water temperatures generally range from 4-8ºC (Harris et al. 2020). If marine waters during the summer feeding period warm beyond the temperature at which Arctic char can efficiently convert food into energy (~9.4ºC), then it has been hypothesized that Arctic char may experience higher mortality while overwintering due to insufficient energy stores (Spares et al. 2012), as feeding during the winter may be limited (e.g., Grainger 1953). Should ocean temperatures continue to warm, Arctic char may be forced into deeper, cooler waters, altering

habitat and resource use and potentially affecting subsistence and commercial fishing endeavors (Harris et al. 2020). Anadromy may also decrease in prevalence as freshwater systems become more productive and the benefits of migration are reduced (Reist et al. 2006), which would have ecological and socioeconomic impacts. Increasing temperatures can change water turbidity via thawing permafrost, as well as the structure of migration corridors and spawning habitat. Other temperature-related changes that are occurring and/or expected to occur in northern aquatic ecosystems, including changes the timing of ice break-up and freeze-up, changes in precipitation (i.e., the nature and distribution of precipitation events), and phenological shifts (Reist et al. 2006) may also affect populations of Arctic char.

Individual fish can respond to climate change through phenotypic plasticity or via microevolutionary response, and in addition to indirect effects resulting from habitat changes, warmer water temperatures may lead to shifts in phenotypic traits. Some traits, such as head, mouth, and body shape, are highly plastic and strongly correlated with an individual's feeding preferences (Garduño-Paz and Adams 2010). Increased temperatures have been shown to cause both an overall shift in the expression of those traits and, in a controlled setting, decreased phenotypic variation within a population (Hooker et al. 2022). Additionally, Campbell et al. (2021) found differences in bone ossification, number of vertebrae, escape response performance, and morphology between Arctic char raised at 5°C and 9°C. Shifts at the individual level may impact population-level adaptive capacity and ecosystem functioning. As Arctic char have a relatively long generation time, phenotypic plasticity may be a critical component of individual shorter-term responses to contemporary environmental conditions (Christensen et al. 2018). To further elucidate evolution and genomic adaptation on an environmentally-relevant scales, researchers must study not just commonly researched SNPs (single nucleotide

polymorphisms), but also genetic variants with different mutation rates and roles in adaptation, including structural variants (i.e., inversions, insertions, deletions, duplications, and copy number variants) and epigenetics (Layton and Bradbury 2022).

1.3.4.2 Dolly Varden

Like Arctic char, Dolly Varden is a cold water-adapted species that faces range-wide threats from climate change, notably with regard to shifting relationships with other salmonid species. Semelparous Pacific salmon species (*Oncorhynchus* spp.) provide an influx of marine-derived nutrients into freshwater systems during and following their fall upstream migration, and Pacific salmon eggs and juveniles represent a critical food source for both resident and anadromous Dolly Varden (Denton et al. 2009). However, in systems where both are anadromous, climate change may cause a mismatch in upstream and/or downstream migration timing between Dolly Varden and Pacific salmon species, leading to trophic mismatches and potential system-level impacts (Bell et al. 2017). As Pacific salmon move along the Alaska and Yukon North Slope and through the western and central Canadian Arctic into systems currently occupied by Dolly Varden that have not evolved with salmon, the influx of resources into freshwater systems may increase the proportion of resident fish in partially migratory populations (Dunmall et al. 2016; Bell et al. 2017; Gallagher et al. 2019).

Climate change will also affect growth rates of Dolly Varden. Courtney et al. (2019) found that northern form Dolly Varden across the Alaskan and Canadian Arctic increased in length between 1969 and 2015, likely due to higher water temperatures, an increase in prey abundance as prey species shift northward, and changes in the timing of ice breakup and freeze-up facilitating a longer marine feeding season for anadromous individuals. A similar trend of

increased growth has been observed in Arctic char, which could affect life history decisions in partially migratory populations (Grenier and Tallman 2021). However, benefits of warmer water decrease as water temperatures near a species' critical thermal maximum. A laboratory study showed that Dolly Varden experience a suppressed appetite at 16°C and mortality at 20°C and above (Takami et al. 1997). Sympatric white-spotted char appear to be less sensitive to warmer water temperatures, outcompeting Dolly Varden and not experiencing negative consequences to appetite or mortality until water temperatures hit 24°C and 26°C, respectively (Takami et al. 1997; Taniguchi and Nakano 2000).

Dolly Varden form a critical component of subsistence fisheries throughout parts of Alaska and northern Canada (Moerlein and Carothers 2012; Gallagher et al. 2021), and subsistence fishing in Arctic North America is being challenged by declines in the numbers of fish present in local rivers, and by shifts in Dolly Varden migration timing – this is especially challenging for fishers who have traditionally fished heavily during specific weeks of the year, and must now adjust their efforts (COSEWIC 2010; Moerlein and Carothers 2012). The climate-induced challenges that Dolly Varden face may also be exacerbated by anthropogenic activities, including shipping and oil exploration, that are becoming more common as the duration of the ice-free period increases (Gallagher et al. 2021). Warming water temperatures and changing sea ice may force Dolly Varden into deeper waters, which will impact coastal subsistence fisheries and effectiveness of current conservation and management efforts (Gallagher et al. 2021).

1.3.5 Current knowledge gaps and research priorities

To advance conservation and management of Arctic char and Dolly Varden in the face of continuing environmental changes and other threats, there are several pressing questions that

need to be addressed on varying geographic scales, including but not limited to:

1. What levels of taxonomic diversity exist within both species' groups? What are the best ways to identify the various taxa, and what are their geographical distributions?
2. What types of ecophenotypic diversity exist within both species' groups and within particular populations and/or complex ecosystems?
3. Can char taxonomy be resolved at the intra- and inter-specific levels? At what level should conservation efforts be focused? When should subspecies, ecomorphs, or forms be treated and managed as distinct units or species?
4. What are the effects of climate variability and change (and their follow-on effects) on freshwater and marine habitat availability and use, and with regard to population productivity and sustainability? How does this affect fishers and fisheries in terms of fish abundance and fishing timing or effort?
5. What are the environmental drivers affecting population productivity, and how will climate change affect this at various life stages and for different life histories (i.e., in various habitats)?
6. In systems where Arctic char and Dolly Varden coexist, how are habitats and resources partitioned? In these systems, do individuals have mtDNA haplotypes and nuclear DNA markers that align from a species identification perspective? If a mismatch exists, how does that affect habitat and resource use? Similarly, better understanding is required for habitat usage and importance for allopatric populations.
7. What is the true distribution of both Dolly Varden and Arctic char in the North American Arctic? Have Dolly Varden expanded their range in recent years, or have scientists, for example, overlooked a longstanding presence of Dolly Varden in systems east of the

Mackenzie River (e.g., Armstrong and Morrow 1980; Behnke 1980)?

8. In complex systems and systems where Arctic char and Dolly Varden coexist, where do adults spawn and overwinter? What drives the limited observed hybridization between Arctic char and Dolly Varden? Is introgression a potential problem?

There are many tools, both innovative and traditional, that researchers can employ to answer these questions. Here, we present a non-exhaustive selection of options.

The field of genomics has advanced rapidly, and high-throughput genotyping technologies are now available for many salmonid species, including *Salvelinus* fishes (Nugent et al. 2019), though such methods can be time- and cost-intensive. Genomic tools generate large amounts of data, which can be used to differentiate between closely related species, and linking genetic and genomic diversity with physical aspects of taxa and forms is necessary to accurately resolve questions about char diversity. The fine-scale data obtained from genomic methods can also be used to understand, in combination with other tools, inter- and intra-specific population-level dynamics and local, regional, and large-scale intraspecific variation, which can in turn provide insight into habitat and resource use and potential effects of climate change. Telemetry, otolith microchemistry, stomach content analyses, and biotracers including isotopes, fatty acids, and highly branched isoprenoids are additional tools that can be used to understand intraspecific habitat use and resource partitioning, and are perhaps even more powerful when used in concert with genomics than when implemented independently. Such practices are also important when thinking about the conservation of a single species, and the level at which conservation units should be managed. Using morphometrics and microsatellites, for example, Adams et al. (2007) determined that 22 Scottish Arctic char populations were genetically and phenotypically distinct and should be managed independently. Environmental DNA should also be explored for its

feasibility and potential for widespread determination of char diversity in remote systems. We highlight the benefits of using multiple methods in tandem (e.g., as done by Moore et al. 2017) to understand more comprehensively the systems in question and to better understand and adapt to continued environmental change.

Across the circumpolar North, research on Arctic char and Dolly Varden is invariably linked with the cultures, traditions, and livelihoods of Indigenous peoples (e.g., Nuttall et al. 2005; Prno et al. 2011; Lavrillier 2013). A goal for research that involves and affects communities and traditional ways of life should be to build capacity for local peoples to take the lead on conducting research that is important to them and their communities (e.g., Bell and Harwood 2012; Hovel et al. 2020). To do this, reciprocal knowledge sharing and engagement by scientists and local and traditional knowledge holders in mutually respectful research methods are key; establishing the association between different ways of knowing will only strengthen ongoing partnerships and conservation efforts. Community-partnered research and monitoring ensures that data collection is being conducted respectfully and in a way that addresses community concerns and priorities, and also provides a crucial opportunity to pair multiple ways of knowing (e.g., Reid et al. 2021). These approaches allow researchers and community partners to co-develop system-level management and conservation plans that will remain viable in the face of climate-induced changes (DFO et al. 2019). To understand the effects that climate-induced changes to char populations have on fishers and fisheries in terms of fish abundance (e.g., Smart 2021), fishing timing, and fishing effort, scientists must work with Indigenous partners to annually document all sources char harvesting (e.g., subsistence, recreational, and commercial), collaboratively documenting information for co-management purposes.

For ongoing research in remote locations, tools that require few resources and that

produce valuable data are especially powerful. Morphometry, for example, is inexpensive and requires, at its simplest, just two tools: a camera (phone cameras are viable options) and a ruler or some other object that can be used for scale. Community partners can easily be trained on best practices for picture taking, and the data generated can be used to inform several of the aforementioned research questions (e.g., Gutzmann et al. 2022). Pictures can also be taken on fish that are being harvested for subsistence; this is especially important when working with vulnerable or declining fisheries.

1.4 Conclusions

When investigating a question about *Salvelinus* ecology, biology, or life history within and among individuals and populations, the most likely answer is, "It varies." Arctic char and Dolly Varden exhibit high levels of among- and within-population variability and are able to adapt to available niches in myriad ecosystems across their ranges. It is shortsighted to speak of the characteristics of the chars in absolutes, and we caution against generalizing about the species across their spatial ranges. Rather, conclusions must be drawn only for the populations that have been directly studied, which will provide a credible foundation for targeted management and conservation initiatives. Behnke (1984) asked whether analyzing population-level morphological and ecological divergence matters more than determining phylogenetic relationships. In the face of a changing climate, we argue that the answer is yes. As cold water-adapted species, Arctic char and Dolly Varden are at risk of losing substantial portions of their ranges as waters warm. Climate-induced changes will impact the food web structure of the ecosystem and virtually every life stage of these fishes, as well as the culture, economy, and food security of Indigenous communities that depend on subsistence char harvesting. Similar issues

are also relevant to other species and classifications of chars (*Salvelinus* spp.), including bull trout, lake trout, and brook trout. To work towards effective conservation and management of Arctic char and Dolly Varden, researchers must work with communities, and knowledge of the ecology and biology of *Salvelinus* fishes must translate to culturally relevant, local, evidence-based management plans.

1.5 Research objectives

In my PhD research, I aimed to address several of the pressing research questions detailed above. My research is detailed in three data chapters.

In my first data chapter, Chapter 2, I collated meristic data – specifically pyloric caeca counts and the total number of gill rakers along the first gill arch – from peer-reviewed papers, books, government reports, and previously unanalyzed data collections. In total, data from 374 populations were included in this chapter. The objective of this chapter was to investigate differences in meristic characters over the distributional ranges of Arctic char and Dolly Varden. By compiling population mean data from across the distributional ranges of Arctic char and Dolly Varden, I showed that the two species form largely distinct clusters when jointly analyzing the total number of gill rakers along the first gill arch and the number of pyloric caeca. Five years of data from the Coppermine River in the central Canadian Arctic (spanning from 1961 to 2020) showed a probable shift in the species composition of chars in the system over time, though further research is necessary.

Building on the results presented in Chapter 2, in Chapter 3 I investigated the contemporary composition of chars in the Coppermine River and surrounding Coronation Gulf, using individual meristics, morphometrics, and the recently developed 87K *Salvelinus* SNP chip.

The objectives of this chapter were to:

1. Assess the species-level diversity of *Salvelinus* fishes in the Coppermine River and Coronation Gulf, an area known to be taxonomically complex, as well as in additional systems east of the Mackenzie River, using the recently developed *Salvelinus* SNP array;
2. Examine the extent of hybridization between sympatric Arctic char and Dolly Varden, should both species be identified in any system; and,
3. Investigate, based on the results from Objective 1, variability in morphology and meristics between char that are genetically Arctic char and those that are genetically Dolly Varden, to identify potential community-accessible methods for species identification and monitoring.

I confirmed the presence of sympatric anadromous Arctic char and Dolly Varden in two systems east of the Mackenzie River, including the Coppermine River, and I identified a third system that supports only Dolly Varden. Arctic char and Dolly Varden are morphologically and meristically distinct, and there is limited observed hybridization between the two species.

The Coppermine River has for generations supported a subsistence char fishery for Inuit in the nearby community of Kugluktuk, Nunavut. Fishers are concerned about changes to the river and the char, and in Chapter 4, I interviewed 17 elders and fishers from Kugluktuk about char fishing and how fishing and fish in the Coppermine River have changed over time. The objective of this chapter was to document general aspects of the subsistence char fishery, how fish and/or the fishery may be changing, and the types of fish captured, including whether both Dolly Varden and Arctic char are captured by Inuit fishers in the Coppermine River. Many fishers have noticed changes to the fish and the fishery over the past ten years, and they believe

that the changes have been caused by environmental change, including climate change. Fishers confirmed that they have caught both Arctic char and Dolly Varden in the Coppermine River, which supports the results presented in Chapter 3.

Chapter 5 synthesizes the results presented in chapters 2-4, and I also highlight continued and ongoing research efforts that will allow a more fulsome understanding of char species dynamics in the central Canadian Arctic.

Chapter 2

Gill raker and pyloric caeca counts differ between Arctic char (*Salvelinus alpinus*) and Dolly Varden (*S. malma*) populations across their ranges

2.1 Introduction

For over a century, scientists have used meristics – countable characteristics – to differentiate between different forms and species of fishes (Jordan and Gilbert 1882; Fowler 1970). Meristic characters can be affected by genetics and/or the environment, and commonly analyzed characters include fin [branchiostegal] rays, vertebrae, scales along the lateral line, gill rakers, and pyloric caeca (Fowler 1970). Even after the advent and widespread application of genetic techniques to study inter- and intra-specific differences between and among closely related species, analyses of meristic characters remain an effective and efficient– in terms of both time and cost – method to investigate differences among species, morphs, forms, and life history types of highly diverse fishes, such as chars (*Salvelinus* spp.).

Within the genus *Salvelinus*, meristic characters have long been used in attempts to differentiate Dolly Varden (*Salvelinus malma*) from bull trout (*S. confluentus*) in British Columbia, and to differentiate Arctic char (*S. alpinus*) from Dolly Varden in Alaska and Russia (DeLacy and Morton 1943; McPhail 1961; Behnke 1980; Morrow 1980; Behnke 1984; Reist and Sawatzky 2010). Given the complicated taxonomy of *Salvelinus* fishes and because individual meristic counts can overlap between Arctic char and Dolly Varden, researchers long debated: i) the validity of considering Dolly Varden a distinct species; and ii) whether and which meristic characters could be used to effectively and consistently differentiate between the two species

(e.g., Barsukov 1960; Behnke 1980; Savvaitova 1980). Reist et al. (1997) showed that, when analyzed together, total gill raker counts (i.e., the number of gill rakers on the first gill arch) and pyloric caeca counts could effectively and consistently distinguish Arctic char from Dolly Varden in the western and central North American Arctic; Dolly Varden tended to have lower gill raker and pyloric caeca counts than Arctic char in the studied region. As gill rakers and pyloric caeca are involved in feeding and digestion, this variation could point to interspecific differences in prey preference. In addition to differentiating between closely related *Salvelinus* species, researchers have also used meristics in efforts to differentiate among sympatric forms, morphs, and life history types of both Arctic char and Dolly Varden within systems and populations across their ranges (e.g., Hesthagen et al. 1995; Alekseyev et al. 2013; Alekseyev et al. 2014; Alekseyev et al. 2019).

There has been longstanding and widespread interest in the use of meristics to investigate phylogenetic and ecological relationships and char diversity within the Arctic char species complex, and in studies of the broader 'char problem' (i.e., the intraspecific diversity char populations display over limited geographic areas; Skreslet 1973; Klemetsen 2010). Most individual studies, however, have analyzed meristic characters in char species over a geographic range that is limited relative to the overall species' distributions (see Table C.1). Consequently, our objective was to investigate differences in meristic characters over the distributional ranges of Arctic char and Dolly Varden. This represents the first range-wide assessment of meristic differences between the two species. As the distributions of, and interactions between, Arctic char and Dolly Varden are changing in response to climate change, the need to accurately and consistently identify and differentiate the species using accessible, effective, and inexpensive techniques is, and will continue to be, highly relevant for conservation and management of

critically important char fisheries.

2.2 Methods and Approach

We searched Web of Science, Google Scholar, and Canada's Federal Science Libraries Network for papers that reported both total gill raker and pyloric caeca counts for one or more populations of Arctic char and/or Dolly Varden. We used the search strings '("Arctic char*" OR "Dolly Varden") AND ("gill raker*" AND caeca)'; '"Arctic char*" AND meristics"'; and, '"Dolly Varden" AND meristics"'. We also searched the references of resulting papers for any literature that may have been missed in initial searches. Additionally, we collated data from published books, such as *Charrs: Salmonid fishes of the genus* Salvelinus (Balon 1980). Only papers published in English or translated into English were included. Papers were excluded if mean counts of both total gill rakers and pyloric caeca were not provided or could not be calculated, and/or if total gill raker data were not presented or could not be calculated (i.e., if only upper or lower counts were presented). After screening, 38 papers published between 1943 and 2021 were included. We also included previously unanalyzed data collected by Fisheries and Oceans Canada and by the authors between 1987 and 2020 (CPG: 2002, 2004, 2017, 2018, and 2019; HKS: 2006; SYW and community research assistants: 2019 and 2020). For the data collected by the authors, pyloric caeca were counted by separating and removing each from the cecal mass, and all gill rakers, including rudimentary rakers, along the first left gill arch were counted. Data included in this analysis represent average (at the level of the population) gill raker and pyloric caeca counts that were collated and/or calculated (from raw data) for 374 populations (Table C.1). Study systems and waterbodies are represented more than once if multiple papers were published on the system, or if average values were provided for multiple years.

Char included in the analysis were coded as either Arctic char or Dolly Varden according to designations used in the original papers, with some important exceptions. Prior to 1980, char populations located as far south as the lower Kuskokwim River, Alaska, and extending north and east to the lower Mackenzie River basin, Canada, were classified as western Arctic-Bering Sea Arctic char. These char, however, overlapped morphologically and ecologically with northern form Dolly Varden (McPhail 1961; Morrow 1980). Species classifications presented in papers published before 1980 were thus examined and, where appropriate, species were reclassified (Table C.1) based on currently accepted criteria, as per Morrow (1980). Some researchers through the mid-20th century also believed that Dolly Varden were synonymous with and/or a subspecies of Arctic char (e.g., Barsukov 1960), meaning that species designations in the original papers were often convoluted; in those cases, subsequently published literature on char from the same systems was assessed to classify the species designation of the population in question. We also removed populations identified as Dolly Varden that may actually be bull trout (e.g., populations included in McPhail (1961) that should be reclassified based on Cavender (1978)). Additionally, in areas supporting multiple forms of char, or with taxonomically unresolved populations, researchers often used meristic characters to identify individuals to the species level (e.g., McPhail 1961; Behnke 1972); this would result in circularity in our analyses. We thus cross-checked the species designations of those populations with more recently published literature that included non-meristic information to ensure that to the best of our knowledge, classifications align with currently accepted designations.

Using the R package 'MASS', we performed a linear discriminant function analysis (LDA) using the two meristic characters of interest – total gill raker counts and pyloric caeca counts – as independent variables, and species classification as the dependent variable. To

evaluate the efficacy of using the meristic characters to differentiate between the two species, we also calculated the misclassification rate. To investigate whether the ability to discriminate between Arctic char and Dolly Varden using counts of pyloric caeca and total gill rakers varies among regions, LDA analyses were performed on the full dataset (Figures 2.1A and 2.1B) and on data subsets for the following regions: i) Central Canadian Arctic (Mackenzie River, NT, east to Cambridge Bay, NU); ii) Eastern North America (east of Cambridge Bay, NU); iii) North Pacific; iv) Norway; v) Russia; vi) Western North America (north of the Alaska Peninsula and east to the Mackenzie River); and, vii) North American Pacific Coast (Alaska Peninsula and south).

2.3 Results and Discussion

Consistent with Reist et al. (1997), we found distinct clustering between populations of Arctic char and Dolly Varden when using counts (arithmetic means for each population/system) of both total gill rakers and pyloric caeca (Figure 2.1B). In North America, northern form Dolly Varden (*S. m. malma*; "Western North America" and "Central Canadian Arctic") and southern form Dolly Varden (*S. m. lordi*; "North American Pacific Coast") also appear to be meristically distinct, with southern form Dolly Varden displaying fewer gill rakers along the first left gill arch (Figure 2.1B; Table C.1). The two Asian forms of Dolly Varden (*S. m. kraschenninnikovi*/*S. m. curilus* and *S. malma*; Table C.1) also appear to be distinct from each other, with *S. m. kraschenninnikovi/S. m. curilus*, the southern Asian Dolly Varden, displaying fewer pyloric caeca than *S. malma* individuals (Pichugin et al. 2008; Esin 2015).

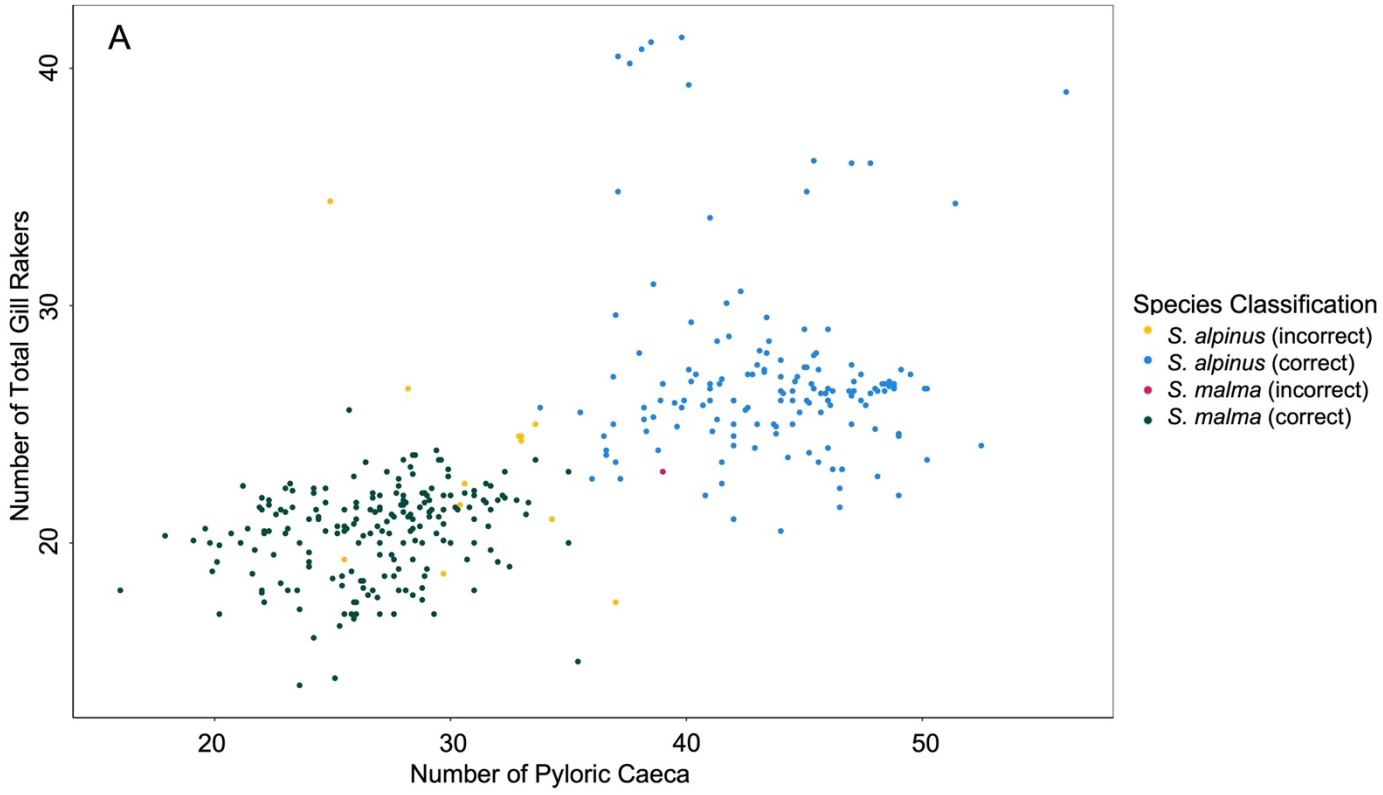
The majority of populations represented in this analysis are from Arctic and sub-Arctic North America and Russia; the searches we employed yielded data from only one western

European population of Arctic char in Lake Sirdalsvatn, Norway (Hesthagen et al 1995). The two morphs of Arctic char in this lake have high gill raker counts typical of Arctic char, but pyloric caeca counts that overlap with those generally attributed to Dolly Varden. While additional studies conducted on European Arctic char populations have presented meristic data, no others captured by our search included both gill raker and pyloric caeca data, instead including alternative characteristics, such as the number of branchiostegal rays (e.g., Doherty and McCarthy 2004).

Perhaps the most interesting system for which we have meristic data is the Coppermine River in Nunavut, Canada. For this river, we were able to collate meristic data gathered in 1961 ("Bloody Falls"; McPhail 1961), 1994, 2003, 2019, and 2020 (Figure 2.1C; Table C.1). In 1961, the mean meristic counts for *Salvelinus* captured from this river were situated within the Arctic char cluster (Figure 2.1C). With each successive time point, however, the mean counts shift toward the cluster of fish that is meristically Dolly Varden (Figure 2.1C; Table C.1). This aligns with observations of elders in the community of Kugluktuk (a hamlet located at the mouth of the Coppermine River) who have reported that they catch more Dolly Varden-like chars now than they did in previous decades (Chapter 4).

Results of the linear discriminant function analysis revealed that the combination of pyloric caeca and total gill raker counts correctly classified 96.3% of fish (360/374; LDA Axis 1 Wilks' $\lambda = 0.205$, $df = 2$, $p < 0.001$) relative to the classifications (sometimes updated to reflect current understanding; see Methods) reported in original publications. One Dolly Varden population and 13 Arctic char populations were misclassified using pyloric caeca and gill raker counts (Figures 2.1A and 2.1B). Though we sought to confirm the species identification of samples collected prior to 1980 (see Methods), this was difficult to achieve for populations that

were not the focus of subsequent research. As such, it is possible that error in the original species classification of one char population each in Russia and Western North America (Table 2.1) explain two of the misclassifications. Accuracy of classification also qualitatively varied among regions (Table 2.1). Both Norwegian populations were misclassified, as were eight populations from the central Canadian Arctic. The relatively high misclassification among char populations from the central Canadian Arctic is consistent with the observation that char diversity in the region is complex (Reist and Sawatzky 2010). Continued work in areas supporting sympatric Arctic char and Dolly Varden (i.e., systems in the central Canadian Arctic; Chapter 3) will be able to assess whether species identification using nuclear DNA, mitochondrial DNA, and meristics are aligned, or if there is evidence for introgression that has led to inconsistent results among methods.



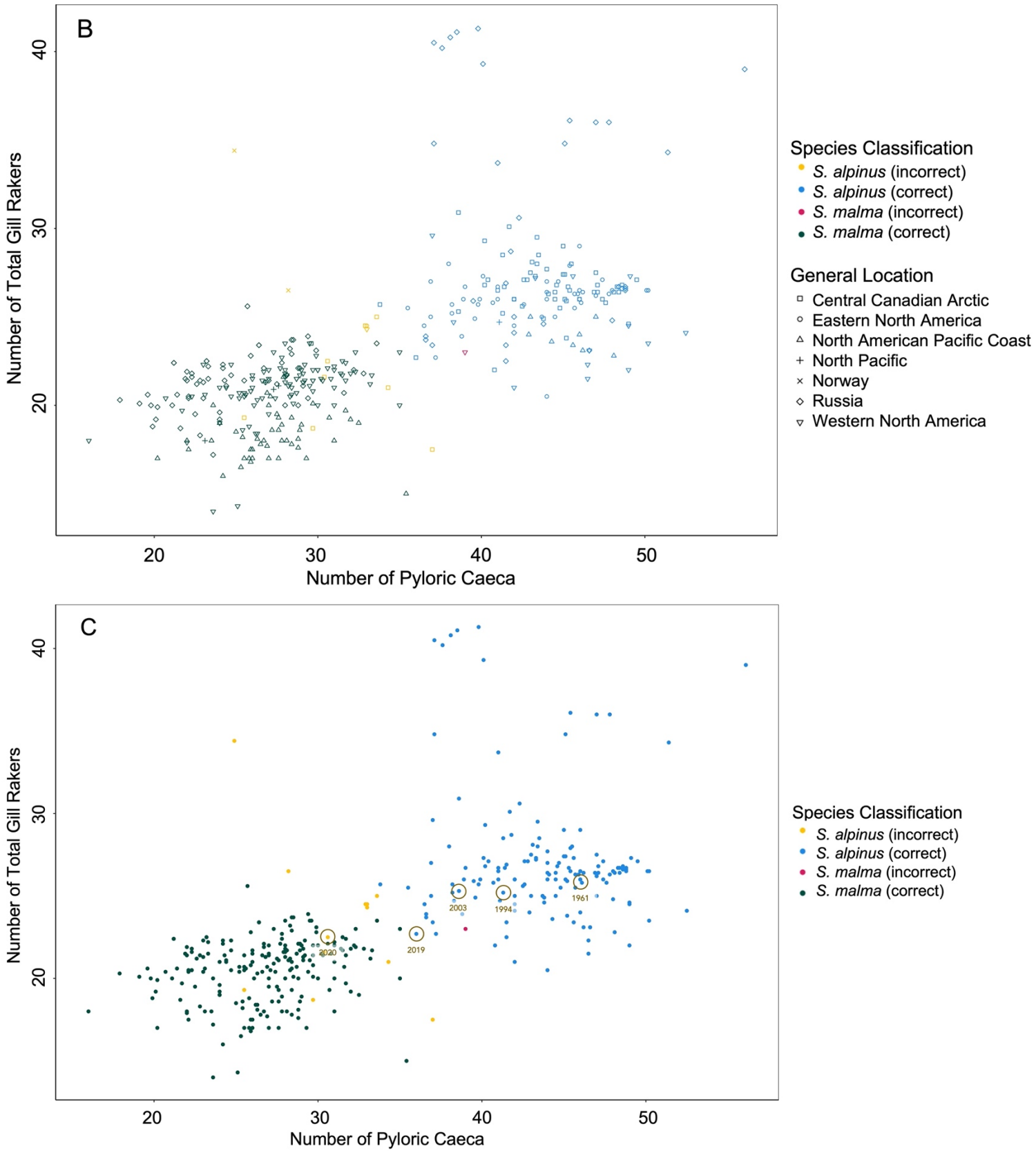


Figure 2.1: *Average gill raker and pyloric caeca counts for 374 Arctic char and Dolly Varden populations (A), for each of several regions (B). Symbol colors represent correct or incorrect classification by a linear discriminant function analysis. Five years of data for the Coppermine*

River are highlighted in panel C, and suggest a shift in Salvelinus *species composition in the system over time.*

Table 2.1: *Region-specific species classification accuracy using a linear discriminant function analysis applied to total gill raker and pyloric caeca counts that were averaged for populations.*

Region	Number of Populations	Number Correctly Classified	Percent Correctly Classified
Central Canadian Arctic	61	53	86.9
Eastern North America	44	43	77.7
North Pacific	5	5	100
Norway	2	0	0
Russia	99	98	99
North American Pacific Coast	56	56	100
Western North America	107	105	98.1

In this analysis, we used meristic data that were averaged at the level of populations, and we acknowledge that this approach has limitations. Individuals within populations exhibit variability in gill raker and pyloric caeca counts, and this will be exacerbated and affect analyses and interpretations when both species are present in a system. In the Coppermine River in the central Canadian Arctic, for example, previously published mitochondrial DNA data indicate that there are sympatric Arctic char and Dolly Varden in the system (Reist and Sawatzky 2010). The presence of both species would not be captured with the population-level meristic data presented here, and may well have contributed to some of the misclassifications. Distribution and relative abundance of Dolly Varden in river systems in the central Canadian Arctic, including the Coppermine River, have previously been the subject of scientific discussion (Reist and Sawatzky 2010), and our presentation of both historic and contemporary meristic population mean counts suggest that additional research using more advanced methods on *Salvelinus* fishes in the region, including in the Coppermine River, is warranted. Given the information loss that comes with analyzing population means, we caution against using the population mean data presented in this

contribution to draw inferences about the species composition of a given population; to do that, individual-level meristic data or data collected from other analytical techniques must be used.

2.4 Conclusions

This range-wide analysis of both Arctic char and Dolly Varden conclusively shows that the two species are largely distinct in their meristic characters across their distributional ranges, though there is variation among regions that may be driven by complex *Salvelinus* distributional patterns. While both species display substantial intraspecific variation in population-level mean counts for these two meristic characters (Figure 2.1; Table 2.1), Dolly Varden generally have fewer pyloric caeca and gill rakers than do Arctic char. Discussions around the diversity, phylogenetic history, and distribution of these two species are complex and can be contentious. We show that meristics provide a labor- and cost-efficient starting point for studying differences within contemporary populations and, if multiple years of data are available, as a foundation for possible investigations of shifts and changes over time.

Chapter 3

Identification of sympatric anadromous Arctic char (*Salvelinus alpinus*) and Dolly Varden (*S. malma*) in the central Canadian Arctic

3.1 Introduction

The genus *Salvelinus* has long been recognized as taxonomically and phylogenetically complex, with the number of accepted species within the genus fluctuating over time and among methods used for identification and differentiation. In western North America, for example, there was long uncertainty over the species status of bull trout (*S. confluentus*), until Cavender (1978) demonstrated their distinctiveness from Dolly Varden (*S. malma*) using morphometrics and meristics. Aware of the difficulties involved in distinguishing and differentiating species, Savvaitova (1980) did not believe that Dolly Varden warranted species status, instead thinking them to be a form of Arctic char (*S. alpinus*); Behnke (1980) on the other hand, advocated for the recognition of Arctic char and Dolly Varden as distinct species belonging to a broader Arctic char species complex. Around the same time, researchers working with phenotypically divergent char populations in the United Kingdom and Ireland, among other locations, classified each population as a distinct species, designations which have since been largely disregarded (see Igoe and Hammar 2004; Maitland et al. 2007). Finally, in the western North American Arctic, char that had previously been classified as western Arctic-Bering Sea Arctic char (McPhail 1961) were found to be indistinguishable from northern form Dolly Varden (*S. m. malma*; Morrow 1980). It is understandable, then, that the genus *Salvelinus* has been described as "a taxonomic nightmare" (Klemetsen 2010), as well as "involved," "confusing," and "difficult" by many

researchers (e.g., McPhail 1961; Cavender 1978; Behnke 1984; Brunner 2001).

Complicating our understanding of char diversity and taxonomy is the fact that chars display substantial phenotypic, ecological, and biological variation within and among populations across their ranges; such variation led Klemetsen to ask if (2010) and then suggest that (2013) Arctic char is "the most variable vertebrate on Earth." Both Arctic char and Dolly Varden display substantial intraspecific diversity that has likely contributed to confusion over their distributional limits, with both species diverging along depth and resource axes to make use of available niches (Johnson 1980; Jonsson and Jonsson 2001; Klemetsen 2010; Reist et al. 2013; Markevich et al. 2018; Esin et al. 2020).

Diversity in *Salvelinus* fishes is likely driven by a combination of sympatric speciation and repeated colonizations of systems by fish from multiple glacial refugia (Klemetsen 2010; Klemetsen 2013; Muir et al. 2016; Reist et al. 2016). Species, morphs, forms, and life history types within a system may be adapted to specific niches and partition resources either spatially (e.g., by utilizing distinct habitats) or temporally (e.g., by spawning at different times; Klemetsen 2010; Dennert et al. 2016; Muir et al. 2016; Perreault-Payette et al. 2017). As inter- and intra-specific char diversity is facilitated by both phenotypic plasticity and genetics (Skulasson et al. 1999; Kapralova et al. 2011; Skulasson et al. 2019), and chars are considered to be generalists at the population level (Amundsen 1995; Elmer 2016), investigations of *Salvelinus* species occurring in sympatry should likely include multiple genetic and non-genetic (e.g., morphology) methods that are applied to fish captured from a wide range of habitats within the system or systems of interest.

Despite the recognized global complexity of *Salvelinus* fishes, the distribution of chars – specifically Arctic char and Dolly Varden – in the central Canadian Arctic was long thought by

researchers to be relatively simple: the Mackenzie River has long been formally reported to represent the geographic boundary between Dolly Varden and anadromous Arctic char (e.g., Armstrong and Morrow 1980; Behnke 1980; Reist et al. 1997; Figure D.1). All char east of the Mackenzie River, as well as char in lacustrine systems west of the Mackenzie River, have been thought to be Arctic char, whereas char in riverine and marine systems west of the Mackenzie River have conventionally been thought to be Dolly Varden (Figure D.2; see Reist et al. 1997; Reist and Sawatzky 2010). Recently, however, the validity of the Mackenzie River as a species boundary for Dolly Varden has come into question, with Dolly Varden identified or reported in at least three systems east of the Mackenzie River (Sawatzky et al. 2007; Reist and Sawatzky 2010; McNicholl et al. 2020). In one of those systems, the Coppermine River, limited mitochondrial DNA (mtDNA) data (Reist and Sawatzky 2010) as well as locally observed differences in morphology among chars caught by subsistence fishers, suggest the presence of two types of char – Arctic char and northern form Dolly Varden – but more research is necessary.

Chars are critically important to food security in remote northern communities (Hammar 1987; Power et al. 2008; Klemetsen 2010; Reist et al. 2013; Elmer 2016), including in the hamlet of Kugluktuk, Nunavut (population ~1500), which sits at the mouth of the Coppermine River (Figure 3.1). Since approximately 2015, fishers from Kugluktuk have reported catching fewer char in the Coppermine River during the summer and fall ice-free period (though some fishers noticed an increase in char abundance in summer 2022; Chapter 4), and also through the ice in winter (Prno et al. 2011; Prno 2019). In addition to changes in abundance, fishers in Kugluktuk have reported physical variation in fish appearance (e.g., Prno et al. 2011); fishers are catching "normal" char that have fatter bodies and more pointed heads, as well as char that are more

elongate and that have a different head shape (Figure D.2). These differences may correspond with differences between species, but have not been thoroughly investigated.

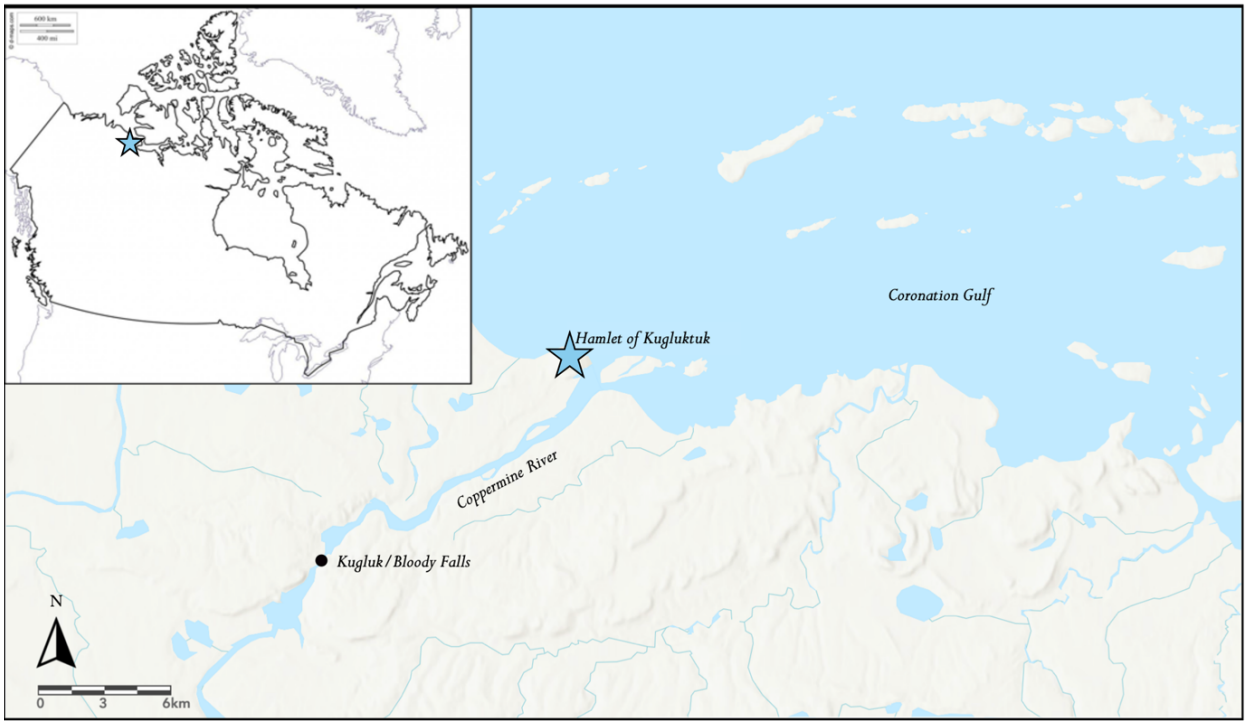


Figure 3.1: *Map highlighting the area of interest for this study, the Coppermine River and Coronation Gulf, which are located in the west Kitikmeot region of Nunavut, Canada.*

Located approximately 750 kilometers east of the Mackenzie River, the Coppermine River is well outside the purported range of Dolly Varden as reported by Armstrong and Morrow (1980) and Behnke (1980), as well as by subsequent researchers. Additionally, northern form Dolly Varden is a Species of Special Concern in Canada due to limited available spawning and overwintering habitats (COSEWIC 2010) in their confirmed range west of the Mackenzie River; the presence of Dolly Varden in more easterly systems would indicate more suitable habitats and a wider range than previously thought.

Given the uncertainties and apparent complexities regarding char diversity in the Coppermine River, the critical importance of the subsistence char fishery, the impacts of climate change on anadromous fishes (Reist et al. 2006), and the conservation status of Dolly Varden

(COSEWIC 2010), further information on the species composition of char fishes within the Coppermine River is urgently needed. So, too, are accessible methods and techniques that can be reliably applied by community fishers to identify and distinguish between the two species, if both are present. As such, the objectives of this study were to:

1) Assess the species-level diversity of *Salvelinus* fishes in the Coppermine River and Coronation Gulf, an area known to be taxonomically complex, as well as in additional systems east of the Mackenzie River, using the recently developed *Salvelinus* SNP array (Nugent et al. 2019);
2) Examine the extent of hybridization between sympatric Arctic char and Dolly Varden, should both species be identified in any system; and,
3) Investigate, based on the results from Objective 1, variability in morphology and meristics between char that are genetically Arctic char and those that are genetically Dolly Varden to identify potential community-accessible methods for species identification and monitoring.

3.2 Methods and Approach

3.2.1 Field collection

Char from the Coppermine River and Coronation Gulf were collected in 2018-2021 using 5-inch mesh monofilament gill nets and rod and reel; a total of 771 char were collected by harvesters. To prevent additional fishing pressure, all char sampled around Kugluktuk came from the nets (or rods) of subsistence fishers, who allowed for adipose fin clips and photographs to be taken. Adipose fin clips were collected with clean scissors, stored in paper, and air-dried.

Samples from reference populations of Dolly Varden and Arctic char were required for

this study (Figure 3.2), and we used archived fin clips or skin samples from fish collected by coauthors to meet this need. Fin clips or skin samples collected for several previous studies had been frozen at -20°C and archived such that they could be used in future projects (including this one). Reference Arctic char samples used in this study were collected in: 2017 from Darnley Bay, Northwest Territories (CPG); 2006, 2007, and 2011 from systems around Hope Bay, Nunavut (HKS); and 2018 and 2019 from the Sylvia Grinnell River, Nunavut (ZAM, RFT). Reference northern form Dolly Varden (*S. m. malma*) samples – both resident and anadromous individuals – were obtained in 2018 and 2019 from Babbage River, Yukon (CPG) (Figure 3.2). Numbers of samples available from the reference populations are shown in Table D.1.

To support analyses of morphometric variation, fish from the Coppermine River, Hope Bay, Sylvia Grinnell River, Darnley Bay, and Babbage River were photographed in the field or in the lab with their left lateral side visible. Paired fins (e.g., the pectoral and pelvic fins) were folded against the body of the fish, while the dorsal and anal fins were extended (Muir et al. 2012). The mouth and opercle were closed, held with pins when necessary, and each fish was oriented along the axis from the mouth to the center of the caudal fin (Figure D.3). Given differing access to gear across years and sampling locations, fish were photographed using either a DSLR camera, a point and shoot camera, or a phone camera. We also collected pyloric caeca and the first left gill arch from 113 fish from the Coppermine River in 2019 and 2020; samples were labeled, frozen at -20°C, and transported back to the lab for analysis.

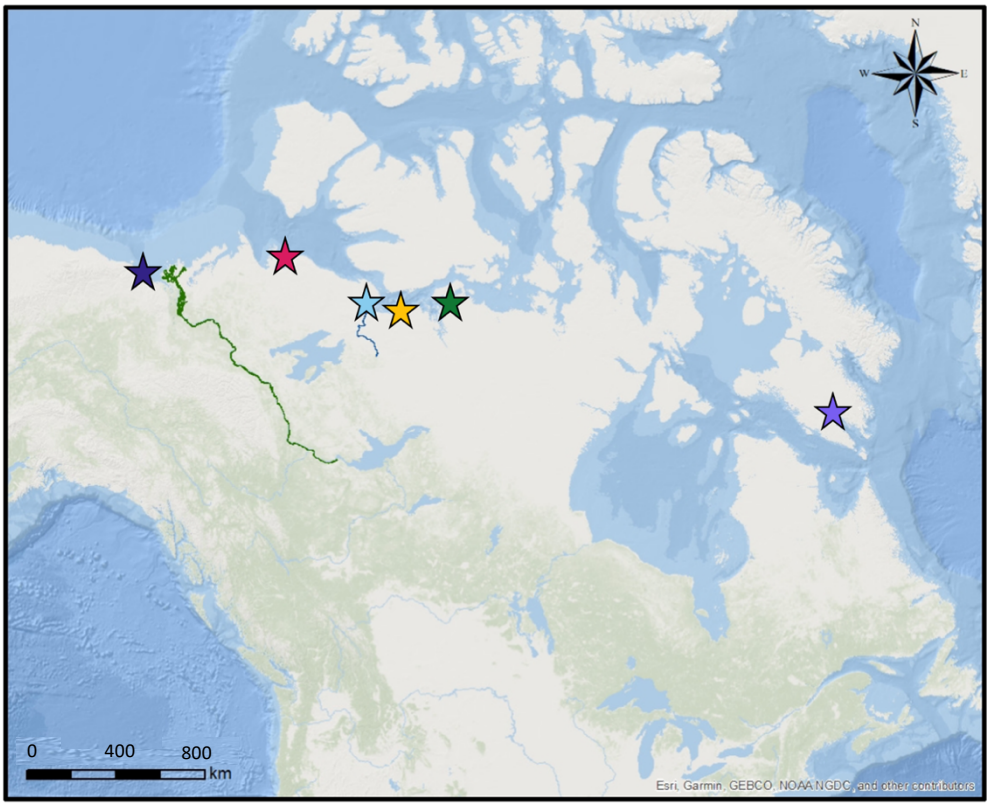


Figure 3.2: *Map of sampling locations. From W to E: Babbage River (purple; reference Dolly Varden); Darnley Bay (pink; recent evidence suggests Dolly Varden are present in the system (McNicholl et al. 2020) as well as Arctic char); Coppermine River (light blue; system of interest); Tree River (yellow; likely Dolly Varden - see Somorjai 2001; Reist and Sawatzky 2010; Byers et al. 2019); Hope Bay (green; reference Arctic char); and Sylvia Grinnell River (purple; reference Arctic char). The Mackenzie River is shown in green.*

3.2.2 Lab and data analyses

To address objectives 1 and 2, DNA was extracted from fin clips and skin tissue following either the Qiagen DNeasy Blood and Tissue DNA extraction protocol, a standard salt precipitation protocol, or a phenol-chloroform extraction protocol (Table D.2), depending on a combination of sample quality, type, and preservation method. Nucleic acid concentrations of all samples were then quantified using a Qubit machine, and DNA quality was assessed by running 2-4 µL of DNA mixed with Gel Red on a 1.5% agarose gel viewed under UV light. DNA from a

subset of samples (n = 338; Table 3.1) was sent to the Clinical Genomics Centre at Mount Sinai Hospital, Toronto to be genotyped using the 87K *Salvelinus* SNP chip (Nugent et al. 2019). Full-plate QC was performed at Mount Sinai, and all samples were normalized to a standard concentration of 10.0 ng/µL.

Table 3.1: *Numbers of fish from each location that were genotyped and photographed. The Tree River fish were subsampled from archived DFO samples, and no full fish were available to be photographed.*

Location	Species	Number of fish genotyped	Number of individuals remaining after filtering	Number of fish photographed
Babbage River	*Salvelinus malma malma*	24	22	48
Darnley Bay	*Salvelinus alpinus*	10	10	34
Coppermine River	*Salvelinus malma* and/or *Salvelinus alpinus*	231	221	334
Tree River	Purported *Salvelinus malma*	44	42	0
Hope Bay	*Salvelinus alpinus*	16	16	78
Sylvia Grinnell River	*Salvelinus alpinus*	13	13	311

Following SNP genotyping, data were extracted from the resulting .CEL files using the Axiom Analysis Suite software. We used the '*Salvelinus alpinus*' library file and altered the Axiom Analysis Suite parameters set to retain all data for downstream analyses (Table D.3). Since SNP genotyping relies on relative fluorescence, we extracted all data as a batch once the final group of samples had been genotyped.

We used Plink to filter out individuals and SNPs with >10% missing genotype data, and SNPs with minor allele frequencies (MAF) <5%, and to perform a PCA on the filtered data. Following filtering for missing data and MAF, we retained 324 individuals and 67,014 SNPs. We visualized the data using the R package 'ggplot2'. To investigate genetic structuring within

and among sampling sites (i.e., unknown Coppermine River samples and samples from known Dolly Varden and Arctic char populations), we ran command-line STRUCTURE (Pritchard et al. 2000) for values of K (number of distinct genetic groups) that varied from 1 (i.e., the null hypothesis of one taxon present) to 8. To account for the potential of slight variation in population assignments, we ran three iterations of each K value, all with a burn-in period of 5,000 followed by 10,000 repetitions, and then used Structure Harvester (Earl and vonHoldt 2012) to calculate ΔK values (Evanno et al. 2005), which allowed us to choose the most appropriate K value for our data (Figure D.4). We also re-ran three cycles of STRUCTURE for one value of K, K = 5, using a burn-in period of 30,000 steps followed by 50,000 MCMC sample repetitions; this allowed us to assess whether increasing the number of iterations affected our interpretations. We recognize that the burn-in period and number of repetitions used here is lower than most of what has been published in the literature. However, as our goal was to investigate species diversity and not to discern fine-scale population structure, and because our species classifications remained consistent across runs and iterations (Figure D.5), we believe that the analyses performed here accurately represent the biological variation present among the sampled populations.

Morphometric analyses aimed to investigate whether Arctic char and Dolly Varden differed consistently along phenotypic axes. For the morphometric analyses, 805 photos were of high enough quality for analysis. Following Perreault-Payette et al. (2017), photos were imported into Autodesk Revit and aligned within a rectangular grid that was anchored at the tip of the snout and the mid-point of the hypural plate. Once anchored, 20%, 30%, 40%, and 50% body length were demarcated with the grid. To enable downstream analyses, a TPS file of the images was created with tpsUtil, which was imported into tpsDig2 (Rohlf 2015). We placed 16

landmarks and four semi-landmarks (the body length percentages) on each fish (Figure 3.3), following Muir et al. (2012). We then slid the semi-landmarks in tpsUtil, input the data into tpsRelw, and exported the scaled and aligned coordinates for use in downstream analyses.

To test the predictive power of morphometric data in species classification (i.e., whether an individual's species classification using morphometrics matched the classification using genomics), we conducted a linear discriminant function analysis (LDA) in the R package 'MASS'. We used the scaled and aligned body shape information (40 Procrustes coordinates, representing the 20 (x, y) coordinates landmarked on each fish) as independent variables and genomic species classification as the dependent variable. Of the 805 photographs that remained following filtering, we either had genomics data or could infer species for 586 samples ("known" samples); where the genomics data indicated that the population was 100% Arctic char or Dolly Varden (i.e., Sylvia Grinnell River, Hope Bay, and Babbage River), we inferred that the species composition was true for the whole population and classified samples that were not genotyped accordingly. To assess the efficacy of morphometrics in determining and distinguishing species identified using genomics, we calculated misclassification rates, again using the R package 'MASS', using only the "known" samples. The remaining 219 photos were of char from the Coppermine River and Darnley Bay for which we did not have genomic data. As the available data from those two systems indicated the presence of both Arctic char and Dolly Varden, those fish were classified as "unknown." After assessing the reliability of morphometrics in predicting species identification using the "known" samples, we then used the full set of samples and separated the data into a training set (known samples) and predicted set (unknown samples); this allowed us to predict the species identification of the samples for which we lacked or could not infer corresponding genetic information.

Given the results of the LDA, which indicated that morphometrics reliably differentiated between species (see Results), and to assess the drivers of body shape variation between species, we generated partial warp scores using tpsRelw and imported them into MorphoJ, along with associated species data when available. As we were interested in differences between species, we restricted our analyses to the samples for which we had or could infer species information (n = 586). Using known samples, we then ran a principal component analysis (PCA) and created a wireframe graph to visualize differences in body shape along principal components.

Meristic characters were assessed by counting the pyloric caeca and gill rakers from each sampled individual that had also been sent to be genotyped using the SNP chip (n = 34; 10 Arctic char and 24 Dolly Varden, as identified via genomics). Samples for which we did not have corresponding genomic data were excluded from analyses. Pyloric caeca were counted by separating and removing each from the cecal mass. All gill rakers along the first left gill arch, including the rudimentary rakers, were counted. We visualized differences in gill raker and pyloric caeca counts between Arctic char and Dolly Varden using 'ggplot2' in R. To assess whether meristics characters differentiated between individual fish known to be genetically Arctic char or Dolly Varden, we performed another LDA and calculated the misclassification rate following the methods detailed above in order. Statistics were calculated using the 'Discriminant' function in SPSS.



Figure 3.3: *Example of a gridded and landmarked fish. Green dots represent fixed landmarks, and pink dots represent semi-landmarks. All landmarks were retained for analyses.*

3.3 Results and Discussion

3.3.1 What is the species composition of chars in the Coppermine River?

Genomic data indicated that both Arctic char and northern form Dolly Varden are present in rivers east of the Mackenzie River, including in the Coppermine River (Figure 3.4; Figure 3.5). Results of STRUCTURE analyses that were performed on the full data set (i.e., using the data from all six sampling locations) indicated that the data could best be partitioned into two genetic groups (i.e., K = 2; Figure D.4). Assessment of the reference samples reveals that these groups reflect the presence of Arctic char and Dolly Varden, which are genetically distinct both within and among systems (Figure 3.4; Figure 3.5). PC1, which explained 81% of the variance in genomic data, differentiated between the two species. PC2 explained an additional 5% of the variance, and may differentiate between glacial refugia and/or provide insight into the patterns

and timing of postglacial recolonization. Following the last glacial maximum, char are believed to have recolonized Arctic North America from two glacial refugia (Moore et al. 2015); colonization may have occurred in multiple waves and/or from proximate systems, which could lead to the variation observed on PC2, but further research is necessary.

In assessing samples specifically from the Coppermine River, 165 (74.7%) of the 221 fish that remained after filtering were Dolly Varden, 55 (24.9%) were Arctic char, and one (0.5%) appeared to be an Arctic char–Dolly Varden hybrid (Figure 3.4). While the species composition of chars in the Coppermine River and broader Coronation Gulf area has been known to be complex (see Sawatzky et al. 2007; Reist and Sawatzky 2010), this is the first published use of next-generation genomics techniques to confirm long-held speculations and assertions that contemporary Dolly Varden populations are present in the central Canadian Arctic east of the Mackenzie River. The data indicate that riverine habitats east of the Mackenzie River are suitable for Dolly Varden, and that the distribution and composition of *Salvelinus* species in the central Canadian Arctic is more complicated than previously thought.

In addition to the Dolly Varden identified in the Coppermine River, we identified Dolly Varden in two other systems east of the Mackenzie River (Figure 3.4; Figure 3.5): Darnley Bay (n = 3; 30% of fish genotyped) and Tree River (n = 42; 100% of fish genotyped). We also determined that the Dolly Varden in the central Canadian Arctic are northern form Dolly Varden (*S. m. malma*), not the southern form Dolly Varden (*S. m. lordi*) found in southern Alaska, coastal British Columbia, and Yukon. In preliminary genetic analyses performed for this chapter, we included samples from three systems that support southern form Dolly Varden: Stella Lake and Unnamed Creek, Yukon (landlocked populations), and Sashin Creek, Alaska (anadromous or partially anadromous population). Figure D.6 shows genomic differences between the *S. m. lordi*

populations, which form a distinct cluster on the PCA, and Dolly Varden from the Coppermine and Tree rivers.

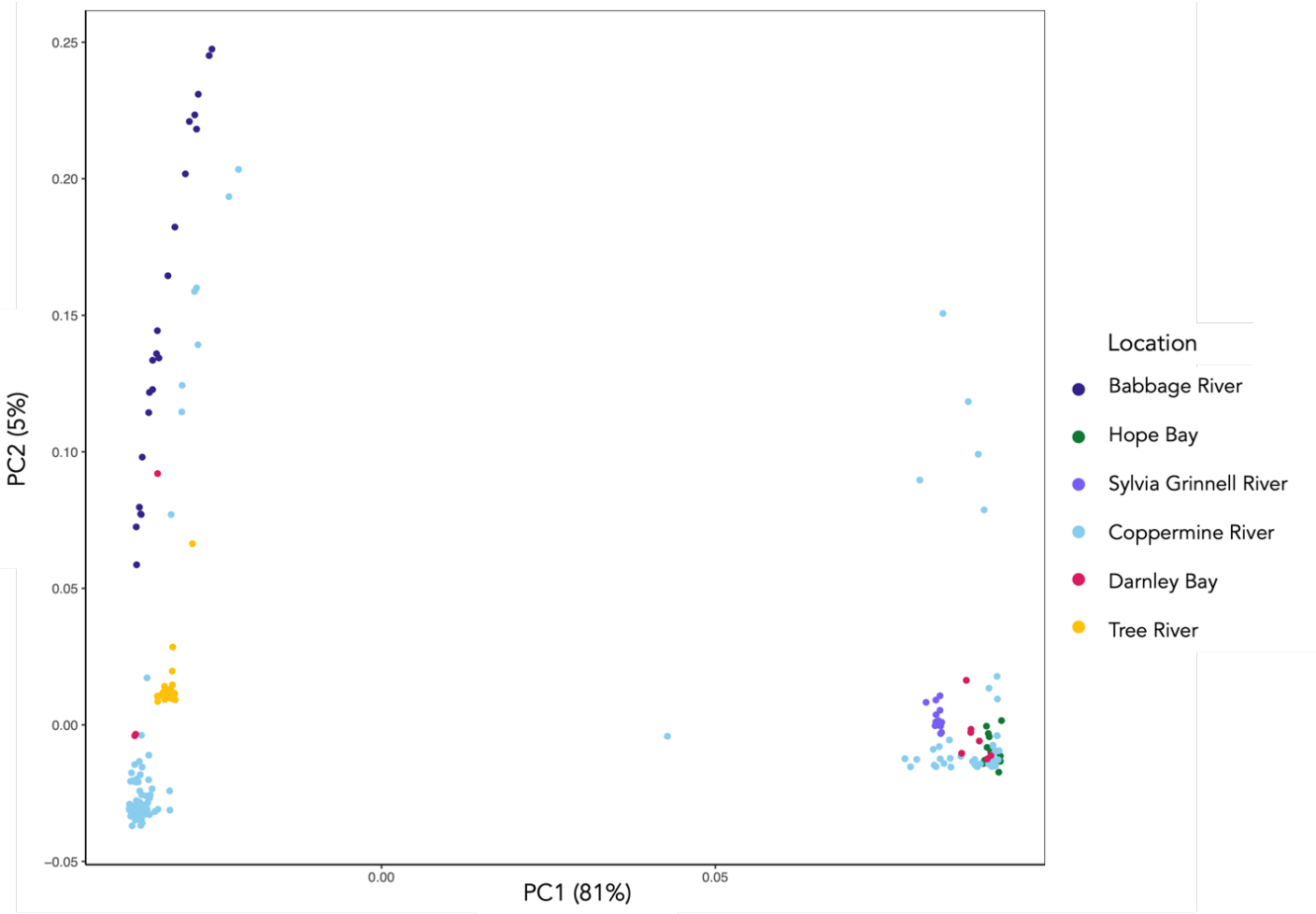


Figure 3.4: *Principal component analysis of filtered SNP data. Dolly Varden (left) separate from Arctic char (right) along PC1. Variability along PC2 may indicate glacial refugia, but more research is necessary to confirm. Populations included are: Babbage River (purple; reference Dolly Varden); Darnley Bay (pink; recent evidence suggests Dolly Varden are present in the system (McNicholl et al. 2020) as well as Arctic char); Coppermine River (light blue; focal system of interest); Tree River (yellow; likely Dolly Varden - see Somorjai 2001; Reist and Sawatzky 2010; Byers et al. 2019); Hope Bay (green; reference Arctic char); and Sylvia Grinnell River (purple; reference Arctic char).*

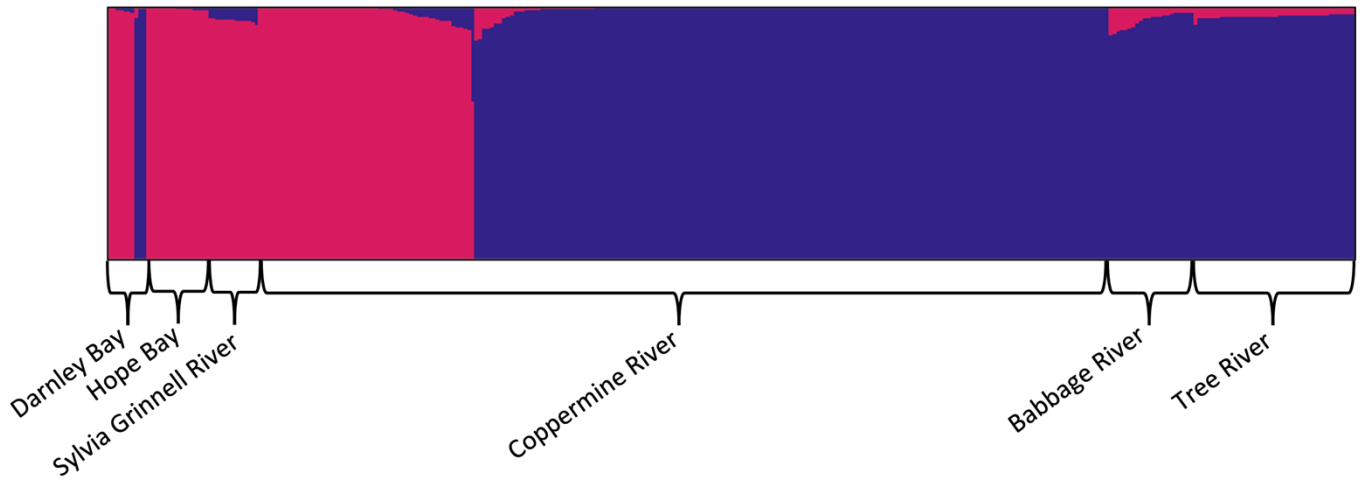


Figure 3.5: *STRUCTURE results for K = 2, for fish from all sampling locations. Each column represents an individual. Using the ΔK statistic (Evanno et al. 2005), we determined that the data could be best partitioned into two genetic clusters, corresponding to genetic differentiation between Arctic char (Darnley Bay (pink), Hope Bay, Sylvia Grinnell River, Coppermine River) and Dolly Varden (Darnley Bay (purple), Coppermine River, Babbage River, Tree River).*

The frequency of Dolly Varden identified in the Coppermine River (~75% of chars analyzed) was surprising based on the limited previous mtDNA analyses performed on char from the system. Reist and Sawatzky (2010) identified Dolly Varden mtDNA haplotypes in 19% of char analyzed from the Coppermine River, and we predicted that if nuclear DNA analyses also indicated the presence of Dolly Varden in the Coppermine River, the proportion of Dolly Varden identified would roughly align with the previously observed mtDNA haplotype frequency. A similar mismatch in the frequency of Dolly Varden identified using nuclear and mitochondrial DNA was observed for the Tree River samples. Though limited data has been published to support or refute the claim, the Tree River has long been speculated to support Dolly Varden (see Somorjai 2001; Reist and Sawatzky 2010; Byers et al. 2019). While Reist and Sawatzky (2010) identified Dolly Varden haplotypes in 74% of Tree River char, here, 100% of char genotyped (n = 42) were Dolly Varden (Figure 3.4; Figure 3.5).

There are multiple possible explanations for the observed mismatches in frequency (~19% v. ~75%; ~74% v. 100%). First, while nuclear DNA is an indication of contemporary

population dynamics, mtDNA indicates historical population dynamics (McPhail 1961; Redenbach and Taylor 2002; Taylor et al. 2008). It is possible that mtDNA gene flow occurred from either Arctic char or Dolly Varden into the other species following postglacial recolonization into the system (i.e., historical introgression), and that mtDNA haplotypes have been maintained in the Coppermine River and Tree River that do not align with the contemporary species diversity observed; continued research investigating the mtDNA haplotypes of samples genotyped herein will lend insight into this possibility.

The second possible explanation for the difference in inferred frequency of Dolly Varden is that the species compositions of chars in the Coppermine and Tree rivers have changed over time. Though genetic material from historical samples has yet to be analyzed, meristics data (see Chapter 2) indicate that there has been a shift in species composition in the Coppermine River between 1961 and 2020, which represents the date range of both contemporary and accessible archived samples/data. Average gill raker and pyloric caeca counts for the Coppermine River char population have decreased over time, from a population that was meristically Arctic char in 1961 toward a population that was meristically Dolly Varden in 2020 (see Chapter 2). This shift may have been driven by changing environmental conditions in the Coppermine River that favored Dolly Varden and allowed them to increase in abundance (e.g., if shallow water levels and warming water temperatures prevented Arctic char from reaching lacustrine spawning and/or overwintering grounds), though additional research must be performed to assess whether the observed shift in meristics correlates with a change in the genetic makeup of the population. While reports from local fishers, limited mtDNA data, and mentions in previous literature suggest that Dolly Varden have long been present in the Coronation Gulf area, it is possible as well that Dolly Varden are expanding their range eastward in the Canadian Arctic, with their

dispersal facilitated by climate change, and that their presence in the Coppermine River and broader central Canadian Arctic is a recent phenomenon. At warmer temperatures, Arctic char are often outcompeted in freshwater by other salmonids (e.g., lake trout (*S. namaycush*) and brook trout (*S. fontinalis*); Hammar 1987); Dolly Varden may be more adaptable competitors than Arctic char and be more effective at taking advantage of changing environmental conditions.

The complexity of *Salvelinus* distribution in the central Canadian Arctic and the need for fine-scale species composition data is illustrated by the recent revelation that the *Salvelinus* SNP chip (Nugent et al. 2019) was inadvertently developed using genomics data from both Arctic char and Dolly Varden individuals, rather than Arctic char only. The array was thus not specific to Arctic char, as was intended; in fact, the sequenced fish that were later determined to be Dolly Varden (i.e., those included in developing both the SNP array and the *Salvelinus* genome) were from a hatchery line that originated from the Tree River (Christensen et al. 2018; Nugent et al. 2019; Shedko 2019). While the SNP chip was used in the work presented herein and remained useful to us (we began this work before the problem was realized) regardless of what species it was based on, the discovery of the problem and the data presented here on wild populations indicate that the Mackenzie River is not the eastward distributional range boundary for Dolly Varden as had previously been believed (Armstrong and Morrow 1980; Behnke 1980), and that we cannot assume all chars in the central Canadian Arctic are Arctic char.

In addition to allowing identification of both Dolly Varden and Arctic char in the Coronation Gulf, our genomics data also indicate differences in the intraspecific diversity of both Arctic char and Dolly Varden across the populations included. While subsequent in-depth hierarchical population structure will be investigated and evaluated, the STRUCTURE results for

K = 5 indicate that Arctic char from the Coppermine River, Sylvia Grinnell River, Darnley Bay, and Hope Bay are relatively genetically homogenous, whereas the Dolly Varden from the Coppermine River, Babbage River, and Tree River have some shared genetic material but are largely genetically distinct (Figure D.5). These data suggest that Dolly Varden colonized the central Arctic in multiple waves and/or from multiple glacial refugia, with some degree of isolation between populations. The Dolly Varden populations do, however, appear to have experienced some degree of secondary contact between populations, either contemporarily (i.e., via migration) or historically (i.e., via colonization of multiple systems by individuals in a single wave from the same glacial refugium, even if that was not the sole colonization of the system). Of the three Dolly Varden identified in Darnley Bay, two appear to have shared ancestry with Tree River and/or Coppermine River Dolly Varden, while the third appears to have shared ancestry with Babbage River Dolly Varden (Figure 3.5); there are also two individuals from the Tree River and ten individuals from the Coppermine River that appear to have shared ancestry with Babbage River Dolly Varden (Figure D.5). The complex situation observed across Dolly Varden populations and the relative homogeny observed across Arctic char populations likely indicates different patterns of postglacial recolonization and occurrences of secondary contact, though we acknowledge the need for corresponding mtDNA to make appropriate inferences regarding historical movement patterns.

3.3.2 Is there evidence of hybridization in the Coppermine River?

Of the 221 Coppermine River char genotyped, only one hybrid individual was detected (Figure 3.4); no Arctic char–Dolly Varden hybrids were detected in any other system sampled. The hybrid individual appears to be a cross between an Arctic char and a Tree River Dolly

Varden (Figure D.5), which is surprising since contact between Coppermine River and Tree River chars is thought to be uncommon (17 knowledge holders (harvesters and fishers) identified by Kugluktuk Hunters and Trappers Organization, Kugluktuk, NU, oral interviews, May 2022 and January 2023). The limited hybridization observed here suggests that Arctic char and Dolly Varden spawn at different times and/or in different locations, or that the two species either cannot or do not interbreed due to other mechanisms or processes. These data are consistent with the low levels of hybridization documented between Arctic char and Dolly Varden in other systems, including in Alaska and Yukon, where the two species are sympatric (Taylor and May-McNally 2015). While the lack of hybridization appears to be a commonality, we note that there are life history differences between the Coppermine River and previously studied systems: both Arctic char and Dolly Varden in the Coppermine River are anadromous, whereas in Alaska and Yukon, Arctic char are freshwater-resident. We might therefore expect hybridization to be more common in the Coronation Gulf systems (including the Coppermine River) than in Alaska and Yukon as a result of the species having a shared life history.

In the Coppermine River, habitat partitioning between Arctic char and Dolly Varden remains unknown. Differences in head and body morphology between the two species, however, suggests that Arctic char and Dolly Varden likely use distinct habitats and food sources. In systems north of the Alaska Peninsula and west of the Mackenzie River, where sympatric Arctic char and northern form Dolly Varden have previously been documented (e.g., Taylor et al. 2008), the two species largely occupy distinct habitats; Arctic char generally occupy lacustrine habitats whereas Dolly Varden, which are commonly anadromous, favor riverine habitats during freshwater life stages (Taylor et al. 2008; Hart et al. 2015; May-McNally et al. 2015; Arostegui and Quinn 2019). Unlike most other fishes within Salmonidae, which hybridize when in

sympatry (see Verspoor and Hammar 1991), there are to date no previously confirmed F_1 Arctic char – northern form Dolly Varden hybrids (Taylor et al. 2008; May-McNally et al. 2015), though mitochondrial DNA analyses have suggested that there may have been historical gene flow between the species (Reist and Sawatzky 2010; Taylor et al. 2008). The lack of contemporary hybridization may be facilitated by differences in habitat use and spawning locations; although habitat partitioning is likely not absolute (Johnson 1980; Harwood and Babaluk 2014; Power and Reist 2018), Arctic char are commonly thought to spawn in lakes and Dolly Varden in rivers (DeLacy and Morton 1943; Dennert et al. 2016). In all previously studied systems, however, Arctic char and Dolly Varden have displayed variability in life history strategy and tactics. In the Coppermine River, local knowledge, as well as catch locations of morphologically distinct chars suggest that both species are anadromous; use of distinct habitats during the spawning period would minimize competition and possibly limit the potential for hybridization between the two species, but further research is necessary.

While the exact spawning times and locations of Coppermine River char remain unknown, fishers have reported that the char migrate upriver in the fall in two main pulses ~2-4 weeks apart (17 knowledge holders (harvesters and fishers) identified by Kugluktuk Hunters and Trappers Organization, Kugluktuk, NU, oral interviews, May 2022 and January 2023). There is evidence in the Coppermine River that larger char move upriver earlier than smaller char (Smith 2020), and it is possible that variation in size and migration timing correlates with differences in species. Results of a Welch's two-sample t-test suggest significant differences in average fork lengths of Arctic char and Dolly Varden (Figure D.7; Welch's two-sample t-test, $df = 42.36$, $p < 0.001$), specifically for fish we were able to identify to the species level using SNP data. It appears that Dolly Varden in the Coppermine River are on average larger than the Arctic char in

the system (Figure D.7). We note, however, that differences in group sizes may contribute to the variation observed (i.e., if we failed to capture the size range of Arctic char present in the system; $n_{\text{Arctic char}} = 34$, $n_{\text{Dolly Varden}} = 140$), and species-specific differences in migration timing is an important avenue for future research.

3.3.3 Can Arctic char and Dolly Varden be reliably distinguished using morphometric and meristic data?

Community-partnered and community-driven research (e.g., Bell and Harwood 2012; Hovel et al. 2020) is a current priority in the Arctic, and accessible and cost-effective monitoring tools, including morphometrics and meristics, could be useful in distinguishing Arctic char and Dolly Varden alongside powerful genomic tools such as SNP chips. Recognizing that advanced molecular analyses are not accessible to most northern communities, and the need for data sovereignty and reconciliation in the Canadian Arctic (see Wong et al. 2020), we investigated whether Arctic char and Dolly Varden in the Coppermine River could be differentiated morphologically and meristically, such that community-based management of the subsistence fishery could be enhanced at relatively low cost.

As indicated through analyses performed on morphological data, Arctic char and Dolly Varden have significantly different body shapes, and the two species can be distinguished using morphometric and meristic analyses (Figure 3.6; Figure 3.7; LDA Axis 1 Wilks' $\lambda = 0.165$, $df = 36$, $p < 0.001$). We unfortunately did not have a usable photograph or meristic counts of the hybrid fish, and so we were unable to assess whether the individual was morphologically and/or meristically intermediate, as compared to the analyzed Arctic char and Dolly Varden. An LDA performed on the morphology data from the samples for which we either had genomics data or

could confidently infer species correctly classified 99.15% of fish (581/586) as either Arctic char or Dolly Varden. Two Arctic char and three Dolly Varden were misclassified (Table 3.2). Splitting the full dataset into a training set of the known samples and a predicted set of unknown samples allowed us to predict the species of samples that did not have corresponding genomic information. Of the 219 samples for which we sought to predict species, 66 were classified as Arctic char (43 from the Coppermine River and 23 from Darnley Bay) and 153 were classified as Dolly Varden (152 from the Coppermine River and 1 from Darnley Bay; Figure 3.6B). The PCA, run to visualize the body shape variation driving differences between species, again indicated clustering of Arctic char and Dolly Varden (Figure 3.7), though there was some overlap between groups. Variation along PC1, which explained 38% of the variance, was driven by differences in body curvature and depth and variation in head shape. PC2, which separated Arctic char and Dolly Varden, explained 18% of the variance and was driven by differences in body length and the origin of the insertion of the pelvic fin (Figure 3.7). In short, Dolly Varden had more streamlined bodies and elongated heads as compared to Arctic char. There do not appear to be sex-specific differences in body shape (Figure D.8), at least when classifying individuals as male or female using a set of SNPs that has been reported to differentiate chars of either sex (Nugent et al. 2019), though we note that a comparison of genomic sex identifications and identifications of sex through inspection of gonads revealed some mismatches between the methods.

Table 3.2: *Number of samples known to be either Arctic char or Dolly Varden that were misclassified in an LDA based on morphology data. A total of 586 samples were included in the LDA analysis; 5/586 were misclassified.*

Genomic Species	Location	Number of Misclassified Samples
Arctic char	Hope Bay	1
Arctic char	Coppermine River	1
Dolly Varden	Coppermine River	2
Dolly Varden	Darnley Bay	1

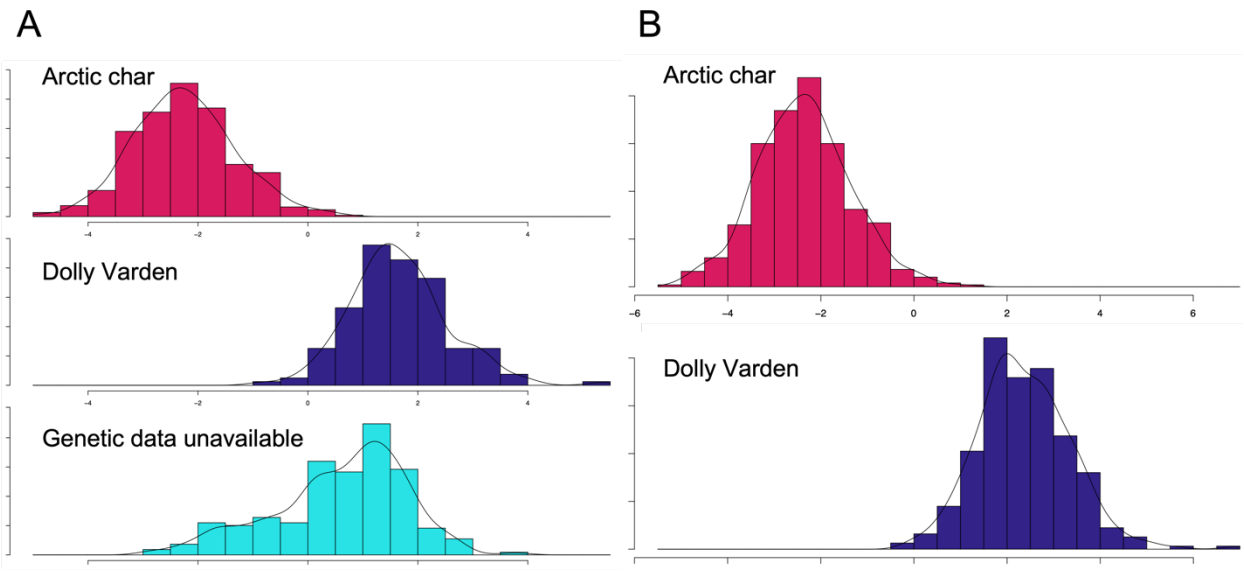


Figure 3.6: *Linear discriminant analysis on body shape coordinates of 805 Arctic char and Dolly Varden. (A) Visualization of known and inferred Arctic char and Dolly Varden, with samples from complex systems (i.e., where both Arctic char and Dolly Varden were identified via genomics) classified as unknown. (B) Species identification of unknown samples was predicted by splitting the data into a test set (known samples) and a predicted set (unknown samples).*

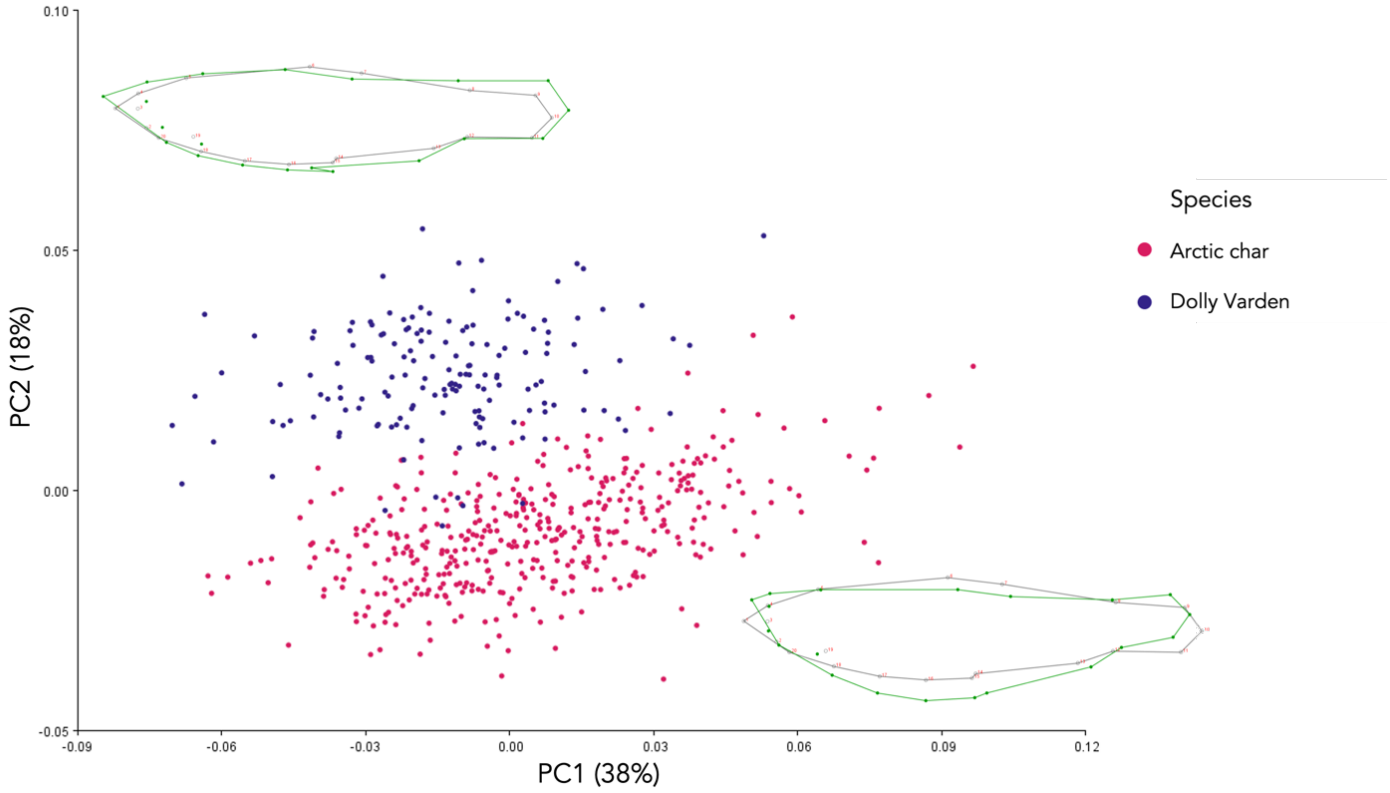


Figure 3.7: *Principal component analysis on partial warp scores of 586 Arctic char and Dolly Varden. Variation on principal component 1 is driven by differences in body depth and head shape. Principal component 2 differentiates Arctic char from Dolly Varden, and variation is driven by differences in body length and the origin of the insertion of the pelvic fin. Wireframe graphs show the deviation (green) from the consensus shape (gray) for each displayed principal component.*

In addition to morphological and genomic analyses, we investigated variability in meristic characters between Arctic char and Dolly Varden in the Coppermine River (as classified using the *Salvelinus* SNP chip). Meristic characters (i.e., branchiostegal rays, vertebrae, scales along the lateral line, gill rakers, and pyloric caeca; Fowler 1970) have commonly been used in attempts to differentiate *Salvelinus* species. Researchers once debated whether Arctic char and Dolly Varden could be distinguished via meristic characters (e.g., Barsukov 1960; Behnke 1980; Savvaitova 1980), though Reist et al. (1997) showed that Arctic char and Dolly Varden could be reliably differentiated by jointly analyzing pyloric caeca counts and the number of gill rakers on the first gill arch. Meristic characters may be of particular use to communities in monitoring fisheries that include both Arctic char and Dolly Varden, as training on extractions of gill rakers

and pyloric caeca is highly feasible and counting of these characters is more straightforward than genomic analyses or the image analyses required for morphometrics.

We found that Arctic char and Dolly Varden, as identified through genomic analyses, had significantly different numbers of gill rakers and pyloric caeca (MANOVA, $F = 16.51$, df = 2, 31, $P < 0.001$; Figure 3.8). Consistent with the collated arithmetic mean data presented in Chapter 2, Arctic char generally had higher gill raker and pyloric caeca counts than Dolly Varden. Results of an LDA did cluster one Dolly Varden individual within the Arctic char group, and five Arctic char individuals within the Dolly Varden group (Figure D.9), though the group means are significantly different (LDA Axis 1 Wilks' $\lambda = 0.484$, df = 2, $p < 0.001$). With larger sample sizes, particularly of Arctic char, it is possible that the misclassification rate would decrease. While meristic differentiation is not absolute, meristics do largely differentiate the two species, and could be a promising and accessible method for community-based monitoring of subsistence fisheries.

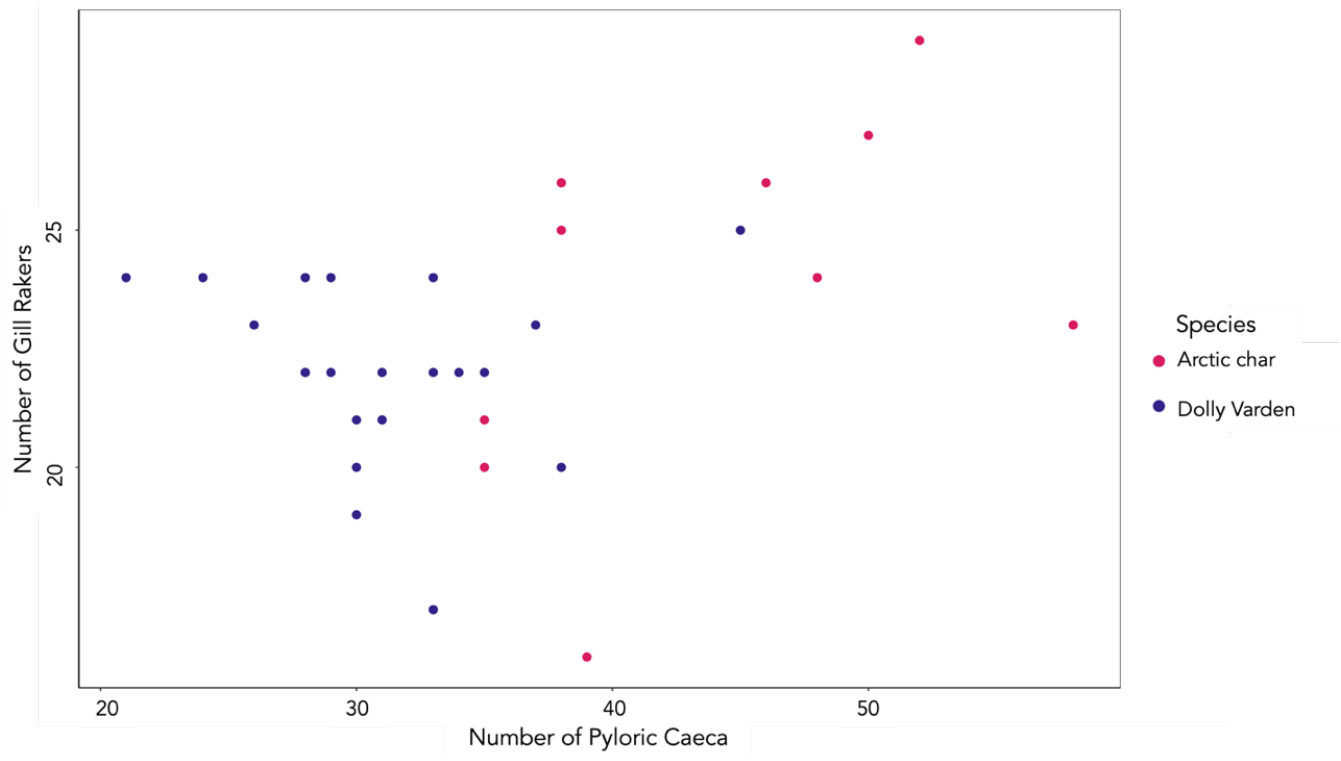


Figure 3.8: *Counts of meristic characters for individual Arctic char (n = 10) and Dolly Varden (n = 24) from the Coppermine River, sampled in 2019 and 2020, as classified via genomic analyses. Meristic data were more limited than genomic or morphology data because of limitations associated with sampling fish that were being used for subsistence.*

3.4 Conclusions

Our combined genomic and morphometric data confirm that Dolly Varden are present in the central Canadian Arctic, east of the Mackenzie River. We identified three systems – Darnley Bay, Coppermine River, and Tree River – that support Dolly Varden. Two of these three systems, Darnley Bay and Coppermine River, also support Arctic char, and both Arctic char and Dolly Varden are anadromous in both systems. Accordingly, the Mackenzie River is not the firm range boundary for Dolly Varden that scientists long presumed it to be.

Though sympatric Arctic char and Dolly Varden can be found in numerous systems west of the Mackenzie River, in those systems the two species display disparate life history strategies (i.e., Dolly Varden are anadromous or riverine, and Arctic char are lacustrine), which likely results in reduced competition (DeLacy and Morton 1943; Behnke 1980; Morrow 1980; May-McNally et al. 2015; Taylor 2016). The presence of sympatric anadromous Arctic char and Dolly Varden in the systems analyzed here suggests that in large systems such as the Coppermine River (Coronation Gulf) and the Hornaday River (Darnley Bay), Arctic char and Dolly Varden can partition habitat and resources so as to minimize direct competition. Even in systems where the species have a shared life history, hybridization is exceedingly rare; here, we identified just one hybrid individual. The two species likely maintain distinct spawning times and habitats, though the exact mechanisms that drive the observed lack of hybridization remain unknown and deserve further study.

Not only are Dolly Varden present in the central Canadian Arctic, as confirmed using

next-generation sequencing techniques, but Dolly Varden and Arctic char in the region are also morphologically and meristically distinct; this has important implications for community-based fisheries management, as using morphometry and/or meristics to identify the species present at a location or in a population is much more cost- and time-effective than relying on genetics and genomics. The use of morphometric or meristic analyses in complex systems like the Coppermine River and Darnley Bay may facilitate our understanding of differences in habitat use or prey preference between Arctic char and Dolly Varden, thereby allowing for more effective and targeted species-level conservation initiatives.

Chapter 4

Local knowledge documentation of Arctic char (*Salvelinus alpinus*) and Dolly Varden (*S. malma*) in the Coppermine River

4.1 Contributions of local fishers and attribution

This study relied entirely on the deep knowledge and generous participation of seventeen elders and/or fishers from the community of Kugluktuk. We are grateful for the stories and knowledge they shared, and for their willingness to be interviewed. Fifteen of seventeen participants agreed to be identified in reporting products that are prepared for the community (two will remain anonymous). In accordance with our ethics clearance and consent forms, all interviewees are being kept anonymous in academic outputs, including this thesis. Quotes are thus not attributed to a specific interviewee, either by name or initials. Some authors anonymize contributors or interviewees by using numbers, but we have chosen not to do this out of acknowledgement for past wrongs and respect for interviewees; for decades in the 20th century, Inuit were tracked and settled by the government using numbered "Eskimo ID tags."

4.2 Introduction

In remote northern communities where resources are limited and imported store-bought food is often prohibitively expensive, chars (*Salvelinus* spp.) harvested from subsistence fisheries form a critical component of food security (Hammar 1987; Power et al. 2008; Klemetsen 2010; Reist et al. 2013; Elmer 2016). Char, the favored food fish in many coastal Inuit communities (e.g., Prno 2019), can be fished for under the ice and in open water, using rod and reel, gill nets,

traditional kakivaks (fishing spears), and jigs, and many communities retain traditions of sharing, where fishers share their catches with others in the community who are unable to harvest char themselves (Prno et al. 2011; Prno 2019). In addition to subsistence fishing, in which families harvest for personal (or shared personal) use, there are three other types of char fisheries in northern Canada: recreational, commercial (including export and local scale), and food security (i.e., fishers are paid to fish for the community; Castañeda et al. 2020). The existence of these diverse types of char fisheries highlights the broad importance of char to people's lives and livelihoods in Inuit Nunangat.

One community that has long relied on subsistence char fishing is Kugluktuk, Nunavut (refer to Figure 3.1). Kugluktuk, a hamlet located on the Coronation Gulf in Nunavut's western Kitikmeot region, sits immediately west of the mouth of the Coppermine River; the lower Coppermine River, which extends ~12 kms upstream from the mouth to Kugluk [Bloody] Falls, has for generations been a very important area for community members to catch char. Over the past several years, however, fishers in Kugluktuk have reported changes to the char in the Coppermine River, both in terms of abundance and physical appearance. Changes have been noted during the summer and fall ice-free fishing periods, and also during the winter under-ice fishing period (Prno et al. 2011; Prno 2019).

In 2017, a partnership was formed between the Kugluktuk Hunters and Trappers Organization (HTO), the University of Waterloo, and Fisheries and Oceans Canada to identify migratory patterns and overwintering habitats of char in the Coppermine River, and to assess the diversity of chars present in the system. As part of the project, HTO board members discussed incorporating local and traditional knowledge to fill in any gaps from previously collated reports, and to document recent changes in the area. Local and traditional knowledge can complement

western science, providing a more complete understanding of culturally significant systems and the threats and changes they face (e.g., Alessa et al. 2016; Dubos et al. 2023). Including local, traditional, and/or Indigenous knowledge is also an important part of reconciliation in science in Canada (Wong et al. 2020).



Figure 4.1: *The community of Kugluktuk and the Coppermine River, looking south.*

Traditional and local knowledge have been previously documented in Kugluktuk, most recently in 2018 (Prno 2019). While several themes are similar between earlier interviews and those conducted here and seven participants were interviewed both times, what sets this knowledge documentation apart is a focus on the composition and diversity of chars in the Coppermine River, which has not previously been discussed in depth with Inuit knowledge holders, as well as the links to associated environmental change and ongoing genomics and morphometrics research that is being conducted in close collaboration with the community. The objective of this study was thus to document: 1) general aspects of the subsistence char fishery; 2) how fish and/or the fishery may be changing; and, 3) the types of fish captured, including

whether both Dolly Varden (*Salvelinus malma*) and Arctic char (*S. alpinus*) are captured by Inuit fishers in the Coppermine River.

4.3 Methods and Approach

Interviews with elders and fishers were conducted in Kugluktuk by SYW in May 2022, July 2022, and January 2023. Participants were all active fishers in the community and were recommended by the Kugluktuk Hunters and Trappers Organization (HTO). In total, 17 fishers – 16 men and one woman, ranging in age from 33 to 76 – were interviewed. Validation interviews, which were conducted to confirm that information shared in the initial interviews was accurately represented, were conducted for eight of the 17 participants. Due to an associated char sampling component of the project that has been ongoing in Kugluktuk since 2017, many participants were already familiar with lead author SYW, who has worked in Kugluktuk since 2019. Interviews took place in the HTO building, and each participant was interviewed individually. While an Inuinnaqtun interpreter was available upon request, all participants expressed that they were comfortable being interviewed in English, and thus all interviews were conducted in English.

Interviews were semi-structured; all participants were asked several key questions, many of them open-ended, and participants were welcome to share as much or as little about char, on-the-land activities, and concerns regarding environmental changes as they felt comfortable with. The interview guide was drafted by SYW and reviewed by HKS and AD prior to the start of the interviews (see Appendix E). Before each interview, the interviewee was provided with information about the project and an overview of the confidentiality and information release guidelines governing the work, which, together with the interview guide, recruitment strategies, honorarium practices, and data storage guidelines, were reviewed by the University of Waterloo

Research Ethics Board (Human Research Authorization #41574). All participants participated voluntarily, and were informed of their ability to withdraw their agreement to participate at any point up to two weeks after being interviewed; no participant chose to withdraw. Participants were also asked: 1) if they would prefer to remain confidential or if they were comfortable having their names used in outputs returned or presented to the community; 2) if their interviews could be recorded; and, 3) if they were comfortable being photographed. Two participants wished to remain anonymous, one was not comfortable with their validation interview being recorded, and three declined to be photographed. In recognition of their time and contribution to the work, participants were provided with honoraria. Interviews were digitally transcribed using Otter.ai. As local and traditional knowledge is often place-based, access to appropriate maps was very important in the success of the interviews. Guided by knowledgeable coauthor AD, we chose to use 1:250,000 maps in a paper format during interviews. These maps covered western Nunavut, as many fishers in the community travel extensively by boat and snow machine.

Current ongoing research on char in Kugluktuk by us and other groups reflects community priorities and questions, and has sought to assess general aspects of the fishery as well as specific questions regarding the composition of chars in the Coppermine River. One focal question is whether both Arctic char and Dolly Varden are present in the system. Our research team, which includes both Inuit and non-Inuit members, were committed to addressing this question using both western science (Chapter 3) and local/traditional knowledge. This was done to facilitate the most holistic understanding possible, and to ensure that temporal changes – which are often better understood with traditional/local knowledge because historical western science data are lacking – were captured. The authors acknowledge that the terms local knowledge, traditional knowledge, ancestral knowledge, Indigenous knowledge, and Inuit

Quajimajatuqangit are used in different contexts for this type of work, and that there can be scholarly, political, cultural, regional, national, and other debates regarding which term is most appropriate. The community of Kugluktuk prefers the terms traditional knowledge and local knowledge, so those are the terms we use in this work.

As part of interviews conducted in May and July 2022 and to specifically address research objectives around the species composition of char in the Coppermine River, we asked participants if they had ever caught Dolly Varden in the Coppermine River or other nearby areas, such as the Tree River. We quickly realized that the majority of participants were unfamiliar with the term "Dolly Varden," and that our question was thus ineffective. After many discussions, we revised the question for the January 2023 interviews, and instead asked interviewees (new participants and those participating in validations) to draw the different types of char that they catch. The first few participants asked to draw were uncomfortable doing so. We then pivoted again and showed participants two photos of char that had been caught in the Coppermine River: one that had been genetically confirmed to be an Arctic char, and one that had been genetically confirmed to be a Dolly Varden. Participants were then asked if they caught char that looked "like this" (while being shown the Arctic char photo), or "like this" (while being shown the Dolly Varden photo). By revising the question, we were able to determine that fishers were, in fact, catching both species. All participants who were shown the photos (9/17) reported that they had caught both types of fish, and different people refer to the longer, skinnier Dolly Varden using a variety of different descriptors and names (see below).

4.4 Results and Discussion

4.4.1 Fishing traditions and timing

Participants, most of whom were born in or around Kugluktuk, ranged in age from 33 to 76. When asked for how long they had been fishing in the area, participants largely responded with statements such as, "my whole life," "as long as I can remember," or "since I moved to Kugluktuk." Some participants recalled their early experiences:

> *"I remember as a little kid fishing and because I was the oldest grandchild, everybody was willing to help me and teach me and I remember even cutting fish at a really young age."*

> *"I've been fishing since I was able to hold up a fishing rod. So probably four or five years old. I can remember my first time ever, doing my first ever cast. I asked my grandfather if he could cast it out for me. And I had a little tiny Mickey Mouse fishing rod. I still remember that Mickey Mouse fishing rod."*

> *"All my life. All my life. Since I was three. A little boy. Got my first char up the river. A little one. I asked my dad, 'I got a fish, dad, what do I do now?!' He says, 'Run up the hill! Pull your line, the hook.' That was fun."*

Though fishers do target other species of fish in the area, including trout (Ihok, *Salvelinus namaycush*) grayling (Innagayok, *Thymallus arcticus*), cod (Uugak, including *Gadus ogac*), whitefish (Kapihilik, including *Coregonus clupeaformis*), flounder (Natangnak, including *Pleuronectes glacialis* and *Platichythys stellatus)*, and Pacific herring (Innuinaqtun name unknown, *Clupea pallasii*), most fishers predominantly fish for Arctic char (Ikalukpik,

Salvelinus alpinus). Char are deeply important to culture, community, and tradition in Kugluktuk, and several participants reflected on the importance of char:

> *"Char is my main diet ever since I was brought up. It's passed on from generation to generation. It's been our staple diet from day one I guess. It's good for our heart. It's good for our body."*

> *"If you have a few fish in the container, you're doing pretty good. Fish is really not the only source of food. But fish is everybody's food, because you can eat it frozen, you can eat it raw, you can cook it."*

> *"Oh, I love to have the char. They're good for your health and your food. That's what I like to provide."*

Fishers catch char throughout most of the year in Kugluktuk, and the fishing gear used varies among seasons. Following ice break-up in the early summer, when the water is murky, and during freeze-up in the late fall, fishing occurs primarily via gill net; when the water clears up in the summer, people will fish using rods, traditional kakivaks, and jigs. There is also personal preference involved, with one participant remarking that he's "got no patience" for using a rod. Another participant noted that nets and rods serve different purposes:

> *"Sometimes I use fishing rod. When I'm looking for food, I use fishnets.*"

Minimal char fishing occurs in late winter, because thick ice can stick to nets and cause them to get tangled and stuck; "winter" and "late fall" (which we acknowledge are western terms) were largely used synonymously by fishers who reported fishing under the ice, with the time period generally referring to periods of fishing during and proximate to freeze-up. However,

fishing for other species does occur during winter (Prno 2019), and one participant interviewed shared that he will try to fish for lake trout during winter, to have something different to eat.

In different seasons, fishers need to catch different numbers of fish. In summer, one participant shared that fishers can put their nets in for a day to catch what they need for supper the following evening; fishers can easily remove their nets when they've caught what they need, and put them back in when they need more fish. In the fall, however, many fishers try to catch enough char to last them through the winter; the need for more fish can cause any decrease in char abundance to appear more pronounced during this season. Though it has since changed, in the past fishers would catch up to 100 char in the summer season, which was enough to provide for their families.

> *"Oh, anywhere from, when the fishing was good, especially here, we would catch about 75 to 80 or maybe more. We'd make dry fish and all that, and bring them back to town for us to put in the freezer or share them with our relatives in town. But lately, it's been poor."*

Fishers were asked where they usually fish for char, and why those are good places for char fishing. Some participants noted that their fishing spots are traditional locations where their parents and grandparents fished before them, and where they grew up fishing:

> *"I guess it's just more traditional, like my grandparents were fishing there. So my parents were fishing there and I guess just brought up using those areas traditionally."* -

> *"Well, it's just from traditional knowledge, where people go."*

Others noted that their choices were affected by logistics, including the geomorphology of the Coppermine River (i.e., the presence of Kugluk Falls ~12 kilometers upriver) and the ease of

fishing where their families have cabins; for example, the Coppermine River represents an accessible fishing location to community members who are unable to travel long distances, either because they do not have a boat or for personal reasons. Several participants noted that char prefer cold water, and that in July and August, char are often found around the islands near town where water temperatures in known ocean currents are cool.

Fishers keep their catch for their family and share char with family, friends, and elders who are unable to fish themselves; there is a strong tradition of sharing in the community that has been instilled from previous generations. Though not an official interview question, several participants were asked if they generally try to catch a certain number of fish in a year. The majority of those asked shared that they try to catch just what they need for subsistence. Preferred char preparation methods include drying fillets to make biffi (dried fish; Figure 4.2), cutting char up and freezing them for later use, smoking the fish, making soup or stew, and preparing for immediate use. More than the other preparation methods, making biffi is seasonal; fishers rarely prepare biffi in the mid-summer heat, and instead do so in the cooler weather of early summer and fall. A healthy looking char was described by interviewees as having no wounds or scars and no aberrations in the flesh, and brightly colored meat.

Several fishers said that the fishing is generally good in the early summer when the river breaks and there are chunks of ice floating around. Fishers know that they have many char in their nets when the floats on the net disappear under the water surface, and fishers can tell whether char are moving upstream or downstream based on the direction the fish are facing in the nets.

> *"For example, July, August, either they're close by the rivers, so they're just heading out into the ocean. But like August, September, we fish in the islands and along the coast.*

Like August, September. And September, October, November it's fall time, they're coming back up the river."



Figure 4.2: *Char fillets drying to make biffi.*

4.4.2 Spawning and overwintering habitats

Little is known about char spawning and overwintering habitats in the Coppermine River. Fishers stated that char in the area overwinter in the lower Coppermine River (i.e., below Kugluk Falls), above the falls, and in the ocean. Although a winter return to freshwater is thought to be a necessity for char due to an inability to tolerate freezing ocean temperatures, char from three populations, including the Coppermine River (Smith et al. 2022), have previously been found to occupy brackish, estuarine, and/or marine habitats during or throughout the winter (Bystriansky et al. 2007; Jensen and Rikardsen 2012; Smith et al. 2022).

With minimal exceptions, participants have not observed char spawning. However, the majority believe that spawning occurs between late-August/September and November above the falls, possibly in lakes and creeks that are connected to the Coppermine River, where fishers do not travel. Interviewees also speculated that spawning may occur in other coastal rivers, and most stated that spawning char prefer shallow, wider portions of the river with more rocks and slower-moving water, though one interviewee stated that spawning may occur in areas with strong currents. Another noted that in his experience, char ignore hooks when they are moving to the spawning grounds, stating that *"if the hook were beside them they'd just swim right by."* One fisher recalled that in the late 1990s and early 2000s, he and his late brother-in-law observed char spawning in a lake about 40 miles from the Coppermine River:

> *"My late brother-in-law, he was tagging fish here, in the Coppermine River…And down here in the lake, we went fishing there in the lake in the fall time for char. We were getting the fish that he was tagging in the summer. He was tagging them in August, and mid-October the same year, we were getting them in the lake. And they lay eggs. They went up that river and go in that lake and they lay eggs…We could see where they lay eggs. They turn red, too…Where they lay eggs, we could see them on the bottom…And they swim around it, the female and the male. And the male putting white stuff on it."*

4.4.3 Char species present in the Coppermine River

> *"Dolly Varden is a real hard species to recognize unless you're fishing with a fishing rod. Dolly Varden is a funny fish. It's almost identical to char."*

When asked if they had ever caught Dolly Varden in or around the Coppermine River, seven participants responded that they had caught or believed they had caught Dolly Varden, one

participant had heard about Dolly Varden in the area but not caught any himself, and five participants had either never heard of Dolly Varden or had never caught any. Fishers reported distinguishing Arctic char and Dolly Varden using spot patterns and abundance, tail shape (deep V or straighter), and/or flesh coloration. Three fishers said that they noticed a difference in taste between the fish they called Arctic char and those they called Dolly Varden, while the majority of fishers had not noticed any difference in taste or fish health between the two species. Through speaking further with participants who reported catching Dolly Varden, and by showing those participants an assortment of photographs and asking whether they would classify the fish pictured as "Arctic char", "Dolly Varden", "hybrid", or "other", we quickly realized that there was not consensus in the classification methods or characteristics among participants or with the western science definitions of the two different species. As it became apparent that fishers were not all talking about the same thing when they referenced "Dolly Varden," we decided to change and clarify our question for the validation interviews. The results of the original classification activity are not included in this chapter.

After reframing the question about the char species present in the Coppermine River and showing participants a picture of an Arctic char and another picture of a Dolly Varden, everyone interviewed stated that they had caught both species in and around the Coppermine River. One fisher, confused by SYW's original mention of Dolly Varden (without being shown a photo), stated upon seeing the picture that he referred to Dolly Varden as "bullet char" because of their thin, elongated bodies. While some fishers couldn't speak to whether they caught more of one species or the other, one fisher noted that he has been catching more Dolly Varden in recent years. No fisher recalled catching Arctic char and Dolly Varden at different times or in different locations. Fishers have also reported catching some char that are long and skinny, which are not

as appetizing to fishers. Those who have caught such fish suggested that those individuals may have spent an additional summer in freshwater where food resources are poorer (i.e., possibly skipping migration), but it is possible that the differences in body size and shape observed by fishers correspond to differences between species.

The presence of Dolly Varden in the Coppermine River as reported by interview participants responding to pictures aligns with genomics, morphometrics, and meristics data also analyzed as part of the larger Kugluktuk Arctic char project. Genomic and morphometric data indicate that approximately 75% of char in the area are Dolly Varden (see Chapter 3), while analyses of meristic characters suggest a change in the composition of chars in the Coppermine River over time (see Chapter 2), which was also suggested by interview participants.



Figure 4.3: *An example of the photos of Arctic char (top) and Dolly Varden (bottom), as identified using genomics, that were shown to interview participants.*

4.4.4 Changes in fish abundance

While multiple fishers interviewed in January 2023 reported a rebound in the Coppermine River char population during summer 2022, the majority of fishers interviewed also stated that over the past five to ten years or so, the char population in the Coppermine River has been declining. However, some fishers expressed uncertainty about whether the char population has been decreasing in numbers (i.e., char are dying and/or spawning is decreased), or if the char have instead been moving elsewhere, leading to a decrease in the number of char captured in the Coppermine River without impacting the species overall. Many fishers also drew comparisons to observed changes in the caribou population of the area.

> *"Twenty years ago you used to catch lots of char in the nets, fall time. But these days, today it's like, you're lucky to get 15, 20 even."*

> *"During the fall, I've noticed a lot of other fishermen talk about how they're not catching as much fish as previous years…I guess it's been within the last ten years that everyone's noticed that decline in the fish stocks…Just from my social media I've noticed that some communities in the east noticed like an increase in fish numbers."*

> *"Almost like maybe seven years or more [that changes have been observed]. Even our caribou today are doing the same thing because – we believe it's from the climate change where the ocean is not freezing sooner."*

> *"It seems there's fewer but, like same with caribou, maybe they've just moved away or, I know char like colder water, or need it, and our river's been shallow and warmer."*

"So, that's how I noticed that there's a decline in the char in the Coppermine [by not catching fish in nets]. Or the fish are just saying that this is not a good area to go in. Because of all the decline. So I'm hoping they're moving somewhere else instead of declining...We might have a healthy population but maybe they're going somewhere else. Because everywhere you fish, it seems like everywhere you fish is declining. I'm thinking, well I'm hoping, that the fish aren't declining, they're just moving somewhere else. It could be from climate change to the water temperature."

"The char is disappearing. For the last ten years. The char, it's getting hard to get a char in the river. Very hard to get, very hard. And lots of people, when they go check the fish nets, they're coming home with nothing."

"In the past I used to go Honda, it must be 40 miles south along the river. Used to see some large chars going up the river. You can't see, it's not like in the past, now. There's too little water. Climate change. I think the water is too warm. I think they're staying out in the ocean more than the rivers now. In the past it used to be really good fishing here."

"It's pretty much in the fall when we set nets behind town. That way as the river freezes we get quite a few char. But last few years, there's been hardly any. I don't know what's going on with the fish."

"We used to get a lot of char here. But weather was colder."

Asked if they caught enough char to meet their needs and the needs of their families, participants gave mixed responses. A few fishers stated that they are able to sustain their families with the amount of char they are currently catching, while the majority reported that as of late, they have been unable to catch enough char. This appeared to vary based on whether fishers fished solely or primarily within the Coppermine River (these participants reported not catching enough char) or if they had the means and resources to fish in systems farther from town.

"Where my camp is, I get enough…Twenty-six miles down, where my camp is, it's good, the fish looks good there."

"This year I bought more char from the stores than I caught on my nets."

"My dad smokes fish too but this past couple years he hasn't smoked enough. Just because we haven't caught enough."

"The last few years? Not really. It's been really slow. Even out there where at most times it's a better fishing area."

"For the winter? Nope. Not anymore. Used to. Used to get a lot of char in the freezer for winter. But nowadays it's difficult. You have to buy it now at the store in the winter."

"Not really for a few years now, been pretty slow."

While some participants only fish in the spring and summer, others continue to fish in the fall by setting nets under the ice following river freeze-up. One fisher, who has long set nets

under the ice, remarked that catching char has become hardest during the fall time; last year, in three nets, he caught seven char total in three months.

> *"Usually on the ice they'd form up and it's thick enough to go put fish nets out. I always follow my late father-in-law's traditional fishing spot, cause he was always the first one to put fish nets out here…I have three nets out trying to catch char and whitefish and all that. But this year it was poor. We never got neither whitefish or char that much like we used to in the past. I think what's happening is the river's freezing too late now to catch the fish going upstream, and downstream. Whichever it is, we're always missing it."*

Another shared about an increase in fishing effort from his parents' generation to today:

> *"My mum and dad only had one or two nets. And today a person like myself would have maybe four, five, just to try to get that amount of fish in before the ice gets too thick."*

A couple of older participants spoke of their perspectives shifting with age. One participant shared that he hadn't fished for a couple of years because of how slow the fishing has been. When asked if he would start setting nets and fishing again if the char population rebounded, he responded:

> *"I would, but I think everybody got to know that you'd only… just get what you need. Get what you need and take your nets out so we can – now that you're older you start thinking of saving the animals, the caribou, the fish, the seals, whatever…Yeah, if they came back, I might get some fish for the family and that's it."*

4.4.5 Salmon in the Coppermine River, and effects on char

In the Canadian Arctic, fishers have been documenting an increase in Pacific salmon species as the climate has changed, likely due to an increase in habitat availability as waters have

warmed (Dunmall et al. 2013; Dunmall et al. 2018); fishers in western Arctic communities have caught a variety of Pacific salmon species, including pink (*Oncorhynchus gorbuscha*), chum (*O. keta*), sockeye (*O. nerka*), and Chinook (*O. tshawytscha*) salmon, in varying quantities (Dunmall et al. 2013). Six participants interviewed here reported that they have noticed or heard about salmon in the area in recent years, and that the presence of Pacific salmon species is a change; similar increases in Pacific salmon abundance have been documented in other Arctic communities (e.g., Dunmall et al. 2018; Chila et al. 2022). While one fisher interviewed here noted that he had heard rumors that salmon could negatively impact the char population, fishers have not observed a direct link between the presence of salmon and a decline in char abundance; at present, fishers have reported more concern about the effects of ongoing environmental and climatic changes on char in and around the Coppermine River.

4.4.6 Environmental concerns

The majority of fishers interviewed are concerned about the decline of char in the Coppermine River. Fishers are concerned about several factors, including: decreasing snowfall, low water levels in the river, increasing water temperature in the river, shifting currents, coastal erosion, changes in the timing of ice freeze-up and break-up, an increase in the seal population, possible overfishing, overall climate change itself, and potential pollution from the Diavik and Ekati mines, which sit by Lac de Gras, the headwaters of the Coppermine River (Table 4.1). One fisher observed that ice break-up has gotten approximately one month earlier over the past 20 years; he used to be able to snowmobile on the ocean as late as July 1st.

> *"Many, many years ago we had a lot of fish cause we had colder weather. But the weather today – changing. It's getting too warm. Getting too hot."*

Some fishers speculated that char may be moving to colder areas, including farther out into the ocean. One fisher, who spoke of the natural cycles that animals and nature go through, shared that his concern is not that the fish are declining, but the impact of rapid environmental changes:

> *"There is always caribou in those [exploratory mining] camps, you know, it just – their pattern of migration slowly changes, as the climate is changing. Depending on the feeding, too, on the ground, they can't migrate on the same ground all the time. Because it takes a while for whatever they eat to grow back cause its cold summer sometimes and their feed is not available there. So they always look for a better feeding ground before they can go in that direction…So maybe that's what's happening with the fish, too. The fish gotta eat too, eh? The warmer the weather, the banks they erode and they go into the river and it takes away some of the – maybe cover up all the food. And stuff like that that they used to eat along the shores. But it takes a while for animals to come back once their food is replenished again, when they'll come back, for sure, cause it's a big river…The elders call that the cycle of life. It's like every 75 years or something. That's what my grandfather was saying. Some summers, it's hard to see caribous, and then after they start coming around again, they start getting to see lots again. But every 75 years, the population grows so much. And that's when the wolves, they start getting better prey for themselves. And they start getting more pups again, so their population grows. But, it's a way maybe, maybe that's the way the fish are here too, like that, in the rivers…I never worry about it that much, cause I know nature always balances itself out…But the fish in the Coppermine River, I worry about because of climate change…I have worries about the climate change and the way the river is changing…Climate change has really affected our fishing."*

Table 4.1: *Environmental changes and concerns of local fishers.*

Concern	Example Quotes
Decreased snowfall	*"This year, I know it's gonna be low levels cause there's hardly any snow…there's just not much snow this year. So I think this year the river level is going to be really low."*
Low water levels	*"People do complain about water levels being too low. Because there's a lot of places where the [carvers] used to go to go get soapstone carving…they can't even go by there anymore. The water levels are too low."* *"There's some low parts now that used to be deep. You hit the bottom, when you go boating up the river."*
Increasing water temperature	*"Now it's getting pretty hard to get Arctic char in the rivers…Cause of the water is getting so warm, I think…Nowadays it's too warm. It used to be really good…I think they're moving out into the ocean where it's cold or whatever."*
Shifting currents	*"Out here in the Coronation Gulf, I notice some currents shifting, almost. Currents out here. Like my uncle, he's passed on now, but that's what he noticed, one part he noticed was like, current was this way years ago and then shifted northeast almost."*
	"I think too much of soil erosion is going into the river. And then you could notice along our sandbars.

	There's some sandbars forming now, in some areas down here that were never there before."
Coastal erosion	*"And when the river is low you could see the permafrost. At the bottom of it, you see the permafrost there. And then below the permafrost it's eroding too. Lots of sand coming down, lots of sand and soil. And you notice more and more branches of trees coming down too, during breakup. You see some trees floating along the river there. But they stop once the ice is all gone. That river's changing."*
Changes in timing of ice formation	*"Climate change has really affected our fishing. Cause we're having late ice buildup, eh. Freezing, ice freezing. And earlier, early breakups. And when the river starts getting, the opening of the river starts getting further and further out, a lot of people used to troll along the edge of the ice there. Good fishing, used to be. But the last couple of years, you're lucky if you get one or two in a couple of days."* *"Thinner ice during the winter, late freeze-up also in early winter. Hotter summers too, actually."* *"Melting faster, every year. Right now it's pretty funny, the ice right now, compared to a couple years back. We used to be able to skidoo June 21st. But not anymore."*
Increase in seal population	*"Could be the year, it could also be the seal population. Cause some years you don't see very many seals around town, but some of the years, some sort of like see a spike in the seal population and I guess that would impact the amount of char we get."*

	"Lots of seals come, always eating fish. Your fish on your net, alright. So I don't know why, it's probably because of so much seals that we get. That would be one of the reason why our fishing is not very good, because so much seal, eh."
Possible overfishing	*"I noticed that decline quite a few years back because people weren't getting very much fish. And I think the reason was there was too many nets during the fall. They got nets from down here all the way up to, almost to the rapids and there's no way the fish could've survived…I think the only way to get the fish back is, control the fishing. Everybody knows they're declining, right?"* *"I'm not too sure why's that. I just figured maybe getting fished out or I don't know. Community's getting too big and everybody's doing nets."*
Climate change	*"Like I said, the climate changed and I think it's affecting the char."* *"Yeah, just heat, that's it. Climate change, I guess. Getting all these weird bugs too and everything."*
Potential pollution from diamond mines	*"I'm pretty sure that the Coppermine River had influence from those mines because this comes pretty much from Lac de Gras."* *"Sometimes we think that the water could be polluted from the mines, maybe. It could be because the diamond mine in Lac de Gras and Ekati; the waters there flow into the Coppermine River…And sometimes we might have thought the water could be polluted from the mines and that fish could notice*

the water is polluted and that they're not here anymore…Before there were mines all around the area used to be good fishing all summer long, all winter, all fall, spring"

4.4.7 Protecting the char fishery for future generations

We asked participants if they thought there was anything more that could be done to protect the fishery, or if there was any additional research that they would like to see done. Participants were overall pleased with the ongoing research. Some expressed the need for additional and continued research, including to determine where fish are overwintering, and where they are going and what habitats they are using at different times of the year. Many participants also expressed concern about snagging occurring around Kugluk Falls, sharing that snagging causes physical injuries to the fish; fishers will not eat or otherwise use ill or injured fish. To combat snagging, one participant suggested better protection around the falls, while others suggested encouraging the use of kakivaks (traditional fish spears) among young people in the community.

Several years ago, the HTO facilitated a net exchange program in Kugluktuk, in which fishers exchanged nets of smaller mesh sizes for new five and a half inch mesh nets; the goal of the program was to protect smaller char (Prno 2019). Three participants interviewed here spoke about the benefits of the mesh size regulations. One participant explained:

"The mesh size I think should remain the same, the way it is…Four and a half is good enough to get a good sized whitefish. But they're too small for the char, cause you get small char that are the same size as whitefish. So the young ones are not getting a chance to go up to spawn up at the river."

4.5 Conclusions

Seventeen fishers were interviewed about their experiences fishing for char in the Coppermine River, and the changes they have witnessed in fish and the fishery over their lifetimes. Over the past decade or so, fishers have observed changes in the abundance of char in the Coppermine River. Participants pointed to several environmental factors and changes that concern them, and many of the factors can be grouped broadly as "effects of climate change." Fishers are also catching two species (as defined by western science) of char in the Coppermine River – Arctic char and Dolly Varden – but do not refer to or discriminate between the two species of fish in the same way that western scientists do. Although the Coppermine River has long been thought by western scientists to be outside the range of Dolly Varden, the reports of the species' presence by fishers interviewed here align with contemporaneous genomic and morphometric data (see Chapter 3). By incorporating local knowledge and linking fishers' observations with western scientific data, we are able to gain a more comprehensive understanding of the changes occurring in the Coppermine River, their possible effects on the char population, and priorities for future co-produced research and monitoring that will further the conservation and management of the subsistence char fishery.

Chapter 5

General Discussion

5.1 Research synthesis

In this thesis, I investigated the diversity of chars (*Salvelinus* spp.) in the Canadian Arctic, with specific focus on assessing the presence of northern form Dolly Varden (*Salvelinus malma malma*) in river systems east of the Mackenzie River, which has been generally scientifically accepted as the species' distributional boundary in North America (e.g., Armstrong and Morrow 1980; Behnke 1980; Reist et al. 1997). The uncertainty regarding the composition of chars in river systems in the central Canadian Arctic is likely due to a variety of factors, including: 1) historically limited sampling throughout the area; 2) a belief that suitable Dolly Varden habitat was limited; and 3) the substantial inter- and intra-specific diversity that both Arctic char and Dolly Varden display over limited geographic areas, making it hard to resolve taxonomic relationships; this latter point contributed to the coning of the term 'the charr problem' (e.g., Klemetsen 2010) and highlights complexity displayed by chars not just in the Canadian Arctic but across the species' ranges.

While I analyzed fish from three systems east of the Mackenzie River where previous researchers have speculated or reported the presence of Dolly Varden (Reist and Sawatzky 2010; McNicholl et al. 2020) and identified Dolly Varden in all three, my focal system was the Coppermine River in the central Canadian Arctic. The Coppermine River supports a critically important subsistence char fishery for Inuit in the community of Kugluktuk, Nunavut, and fishers and representatives from the Kugluktuk Hunters and Trappers Organization had requested

scientific study of the population because numbers of char in the system had appeared to decline in recent years, and because some fishers had reported changes and variation in the appearance of chars they were catching in the river. Furthering the understanding char diversity in this region was also of interest because Dolly Varden are classified as a Species of Special Concern in Canada.

The importance of and interest in chars to and by western scientists, fisheries practitioners, community members, and subsistence fishers was the impetus for my research, and in data chapters 2-4, I began to address several of the pressing research questions first presented in Chapter 1. Inferences in this thesis were based on novel (e.g., genomics) and conventional (e.g., meristics) western science techniques and Inuit knowledge; incorporating multiple ways of knowing and co-producing knowledge with Indigenous knowledge holders (e.g., Smart 2021; Dubos et al. 2023) allowed us to develop a stronger understanding of char population dynamics while also working towards reconciliation in Arctic research (e.g., Wong et al. 2020).

5.1.1 What is the distribution of Dolly Varden and Arctic char in the North American Arctic? Have Dolly Varden expanded their range in recent years, or have scientists overlooked a longstanding presence of Dolly Varden in systems east of the Mackenzie River?

In the central Canadian Arctic, Dolly Varden are present in at least three systems east of the Mackenzie River (Chapter 3): Darnley Bay, Coppermine River, and Tree River. Of those three systems, two, Darnley Bay and Coppermine River, support sympatric anadromous Arctic char and anadromous Dolly Varden, while the Tree River supports only Dolly Varden (as inferred from nuclear DNA; Figure 3.4). Arctic char and Dolly Varden are genetically distinct (Figure 3.4; Figure 3.5), and Dolly Varden display genetic variation across populations (Figure

3.5; Figure D.5), which suggests that Dolly Varden colonized the central Arctic in multiple waves and/or from multiple glacial refugia. These data challenge the validity of the Mackenzie River as the eastern extent of Dolly Varden in the North American Arctic.

Reports from fishers interviewed in Chapter 4, limited mtDNA data (Reist and Sawatzky 2010), and mentions in the literature (e.g., Somorjai 2001; Byers et al. 2019) suggest that Dolly Varden have long been present in the Tree River. In the Coppermine River, I believe, based on reports from fishers in Kugluktuk (Chapter 4), the meristics data presented in Chapter 2, and limited mtDNA data, that Dolly Varden have also been present in the Coppermine River for at least several decades (and possibly longer, though at present I lack the data necessary to make such an inference), and that Dolly Varden may have increased in abundance and frequency in the system over the past several decades. Nuclear DNA data from the Coppermine River indicates that approximately 75% of char in the contemporary system are northern form Dolly Varden, and that the remaining 25% of individuals are Arctic char (Chapter 3). Reist and Sawatzky (2010) identified Dolly Varden mitochondrial haplotypes in only ~19% of Coppermine River char, which suggests either that nuclear and mitochondrial DNA do not align, or that there has been an increase in the abundance of Dolly Varden in the Coppermine River in recent years. Such an increase in Dolly Varden abundance appears to be supported by analyses of mean meristic characters (Chapter 2); from 1961 to 2020, there was a decrease in the mean meristic counts of Coppermine River char, with the population (average) becoming more meristically Dolly Varden-like. Upon being shown photographs of fish that had been genetically classified as Arctic char or Dolly Varden (Chapter 4), fishers confirmed that they have been catching both Arctic char and Dolly Varden in the Coppermine River, and some participants remarked that over the past few years, they had been catching more fish that looked like Dolly Varden and fewer of the

Arctic char that had been abundant in the past.

Without access to archived genetic material from char caught in the Coppermine River, I cannot be certain exactly if or when Dolly Varden began to increase in abundance in the system. If there has been a shift in species composition, it is possible that warming water temperatures and decreasing water levels in the Coppermine River and tributaries are making it difficult for Arctic char, a species widely thought to spawn in lacustrine habitats (DeLacy and Morton 1943), from reaching their spawning grounds (see Reist et al. 2006 for predicted effects of climate change on Arctic anadromous fishes), which then opened or widened a niche for riverine-spawning Dolly Varden. Additional research must be done in the Coppermine River to determine the spawning locations of Arctic char and Dolly Varden, as this information remains unknown even to lifelong fishers (Chapter 4), due to minimal fishing upstream of Kugluk Falls where char spawning is believed to occur.

5.1.1.1 Will the confirmed presence of Dolly Varden in the Coppermine River affect subsistence fishing?

Northern form Dolly Varden are currently listed as a Species of Special Concern under Canada's Species at Risk Act, having been designated as such because of the species' limited available spawning and overwintering habitats in the western Canadian Arctic (COSEWIC 2010). Given the COSEWIC status of Dolly Varden, one concern I had upon starting this project was whether the potential confirmation of Dolly Varden in the Coppermine River would have an impact on subsistence fishers' ability to harvest char from the system. At present, it would not. As a Species of Special Concern (as compared to a Threatened, Endangered, or Extirpated species, which are the other Species at Risk Act designations; Species at Risk Act 2002), Dolly

Varden are still permitted to be harvested by fishers. The confirmation of northern form Dolly Varden in the Coppermine River could prompt Fisheries and Oceans Canada (DFO), the Nunavut Wildlife Management Board (NWMB), and the Kugluktuk Hunters and Trappers Organization (HTO) to develop an Integrated Fisheries Management Plan to encourage the protection and sustainable harvesting of Dolly Varden and, likely, Arctic char as well, as the ecology, biology, and life histories of the two species in the Coppermine River often overlap.

Given that the COSEWIC status of Dolly Varden was based on assumptions around available habitat that we now know need to be revisited, it is also possible that the status of the species may change, if and when it is reviewed. I believe a review may be necessary; conservation and management decisions and initiatives in Canada must be based on accurate knowledge of the species' range and distribution, and data-based management and recovery plans are crucial to ensuring the persistence of Dolly Varden populations in the Canadian Arctic, as well as the viability of important subsistence fisheries in the region. Climate change makes such knowledge even more pertinent and pressing. Dolly Varden and associated fisheries will likely be affected, both positively and negatively, by climate-induced environmental changes (e.g., Moerlein and Carothers 2012; Bell et al. 2017; Gallagher et al. 2019; Courtney et al. 2019). Without an accurate understanding now of the species' distribution, it will be impossible, in the near- or long-term future, to know how the distribution is changing, and which areas and habitats should be targeted for conservation and/or restoration efforts.

5.1.2 What are possible direct and indirect effects of climate variability and change on freshwater and marine habitat availability and use by chars? How are changes affecting fishers and fisheries, and how can we advance stewardship of the fishery?

The Canadian Arctic is warming at approximately three times the global rate (IPCC 2013), and climate change represents a significant threat to Inuit who continue to depend on the land (Helgason et al. 2006). In Kugluktuk, chars form a critical component of food security, and fishers often share their catch with family and others in the community who are unable to fish for themselves (Chapter 4; Prno et al. 2011; Prno 2019). Since approximately 2015, many fishers in Kugluktuk have noticed a decline in the number of char in the Coppermine River, and uncertainty remains about whether char are dying and/or failing to spawn, or if they are moving elsewhere. The fishers I interviewed described many environmental changes that they have noticed over the years, and which they find concerning; these changes include increasing water temperatures, changes in the timing of ice formation and break-up, coastal erosion, shifting water currents, decreased snowfall and low water levels in the river, an increase in the seal population (seals are infrequently hunted in Kugluktuk), possible overfishing by a growing community, and potential pollution from upstream diamond mines (Table 4.1). Char abundance is also linked to prevalence and abundance of capelin (*Mallotus villosus*), an important prey source which can vary among years. Many changes in environment and prey abundance are related to the consequences of a changing climate. One fisher reflected that he had been taught by his father and grandfather that "nature always balances itself out" – animal populations undergo naturally oscillating cycles, and this fisher's concern was not that the char population is declining, because it could reflect a natural fluctuation, but that rapid environmental changes are exacerbating the decline in ways that nature may not be able to balance out (Chapter 4).

While additional research must be done to understand char habitat use and habitat partitioning between Arctic char and Dolly Varden, many fishers have found that fishing in the Coppermine River has gotten especially difficult over the past few years (though the char

population did experience a rebound in summer 2022), and that char seem to be moving into deeper, cooler waters during their marine migration. Several fishers are no longer able to catch enough char to meet their needs, and many now supplement with char purchased and flown in from other communities. At least one fisher has stopped setting nets over the past couple of years, in part to do what he can to help the char population recover (Chapter 4). When asked if he would resume setting nets if the char population rebounded, he commented that he would set nets to catch only as many fish as his family needs, and then he would remove his nets so as to not put unnecessary strain on the population. Taken together, the observations from Inuit fishers highlight a need to more fully understand the drivers of, and mechanisms behind, declines and/or changes in the Coppermine River char population, in order to steward the fishery for subsequent generations.

As shown in Chapter 3, there are several tools that can be used to evaluate the diversity of chars in a given system, data that can then be used to identify critical habitats and understand how habitat use is changing with a changing climate. As Arctic char and Dolly Varden appear to differ in their head and body shapes, by using a reference set of photographs of char that have been identified to the species-level using genomics, and corresponding coordinates representing designated body shape parameters, char of uncertain species identity can be classified as either Arctic char or Dolly Varden. In systems where the two species occur sympatrically and cannot be distinguished on the basis of life history variation, the ability to classify fish using only a photograph again has important implications for community-based fisheries monitoring and conservation if future work determines that morphologically distinct chars utilize different habitats. Identifying critical habitats would also be very useful for regulatory agencies and Indigenous governments and organizations (e.g., Kitikmeot Inuit Association) that are

developing inventories of habitats to be restored and/or upgraded by proponents subject to offsetting requirements under the *Fisheries Act*.

5.2 Future and continued research

The work presented in this thesis has highlighted the importance of addressing many additional avenues of research and research questions that were presented in Chapter 1. Several of the questions that I find especially intriguing are expanded upon below.

5.2.1 In systems where Arctic char and Dolly Varden coexist, how are habitats and resources partitioned? What drives the limited hybridization between Arctic char and Dolly Varden?

Of the 221 Coppermine River char included in the genomic analyses presented in this thesis (Chapter 3), there was only one hybrid individual identified (Figure 3.4). Though Dolly Varden and Arctic char display low levels of hybridization in other systems where they are sympatric (Taylor and May-McNally 2015), in those systems the two species exhibit distinct life histories – Dolly Varden are anadromous and more commonly occupy riverine habitats while in freshwater, whereas Arctic char are freshwater residents and more commonly occupy lacustrine habitats (Taylor et al. 2008; Hart et al. 2015; May-McNally et al. 2015; Arostegui and Quinn 2019). In the Coppermine River, both Arctic char and Dolly Varden were caught in nets set in the marine environment (i.e., the two species do not appear to partition between salt and fresh water during the main summer feeding period), and fishers can also tell when fish are moving into the river from the ocean by the direction that the fish are facing in the nets (Chapter 4). This indicates that the Coppermine River supports anadromous Arctic char and anadromous Dolly Varden. Though the two species appear to have a shared life history, this does not appear to

facilitate an increased rate of hybridization.

Researchers have suggested that behavioral, physiological, and/or morphological differences between Arctic char and Dolly Varden may impact the production and/or viability of hybrid individuals (e.g., May-McNally et al. 2015; Dennert et al. 2016). To better understand how Arctic char and Dolly Varden will react to changing environmental conditions both independently and as members of a species complex, continued research should investigate drivers behind the lack of hybridization between the two species in systems where individuals of the same life history occur sympatrically. While it is possible that limited hybridization is driven by differences in spawning times and/or habitat or mate preference or behavioral differences, it is also possible that non-viable hybrid offspring are in fact produced; the latter possibility could indicate that hybrid offspring of parents adapted to distinct food sources are morphologically intermediate and poorly adapted to available environmental niches (e.g., Hagen and Taylor 2001; Dennert et al. 2016). Variation in body and head morphology (Chapter 3) suggests that in systems where the two species are sympatric, Arctic char and Dolly Varden likely make use of distinct habitats and resources, including prey sources; additional research in the Coppermine River and other rivers east of the Mackenzie should investigate the prey preferences of both Arctic char and Dolly Varden, whether prey consumption varies by char species (as confirmed using genomics, morphometrics, and/or meristics), and if and how variation in resource use corresponds to differences in habitat use. Field research on questions related to spawning behavior, as well as lab experiments focused on hybrid production, could provide insight into resource use and partitioning between the evolutionarily closely related Arctic char and Dolly Varden. Understanding habitat and resource use and partitioning by Arctic char and Dolly Varden at all life stages is critical to long-term data-driven conservation and management efforts

of char fisheries.

5.2.2 In systems supporting sympatric anadromous Arctic char and Dolly Varden, do individuals have mtDNA haplotypes and nuclear DNA markers that align from a species identification perspective? What are the biological and ecological implications of a mismatch, if one exists?

Given the complexity of chars and the difficulty in elucidating inter- and intra-specific relationships, both nuclear and mitochondrial DNA are useful in attempts to understand contemporary and historical population dynamics, including the evolutionary relationships between Arctic char and Dolly Varden. MtDNA haplotypes provide insight into patterns of postglacial recolonization, secondary contact between fish from different glacial lineages, and population bottlenecks and subsequent periods of expansion (e.g., Moore et al. 2015). A question of interest is whether chars in the central Canadian Arctic have nuclear and mitochondrial DNA that align geographically and from a species perspective (e.g., whether both indicate that an individual is an Arctic char) or if there is a mismatch (i.e., mito-nuclear discordance; Toews and Brelsford 2012; Després 2019) between the two (e.g., the individual has nuclear DNA consistent with Arctic char and a Dolly Varden mtDNA haplotype). Mito-nuclear discordance can be driven by several factors, including differences in inheritance patterns of, and selection pressures on, the two genomes, hybridization and introgression between previously isolated groups or taxa (i.e., biogeographic discordance), differences in habitat preference by individuals of different mtDNA lineages, and sex-biased dispersal (Toews and Brelsford 2012). If mito-nuclear discordance is prevalent among central Canadian Arctic chars, understanding the drivers of such discordance can help us understand population dynamics and how natural selection has acted on both Arctic char and Dolly Varden in the region, which can then help us to infer how genotypes and

phenotypes may be impacted by climate change. Additionally, this line of research could strengthen our understanding of interspecific relationships and secondary contact in the Canadian Arctic between fish of different glacial lineages (e.g., Yamamoto et al. 2023), and may aid in our understanding of the processes and factors limiting Arctic char-Dolly Varden hybridization.

In the Coppermine River, it may be possible to analyze both contemporary (i.e., those presented in Chapter 3) and historical (i.e., genetic samples and morphometric data corresponding to some of the data presented in Chapter 2) samples. This would allow us to examine whether and how the population has changed genetically over time, including whether the observed shift in meristic characters over the past several decades (Figure 2.1C) corresponds to a shift in the genetic species composition of chars in the system. Linking genetic and phenotypic data can provide insight into the natural selection that has occurred within the population, and may allow us to better understand the drivers of the observed shift in meristic characters, which could in turn provide insight for current and future management initiatives.

5.2.3 Can char taxonomy be resolved? At what level should conservation and management efforts be focused?

As reviewed in Chapter 1, Arctic char and Dolly Varden display substantial intraspecific diversity across their ranges, often even within populations or over a small geographic scale. Previous research in the central Canadian Arctic has indicated that there are stocks and units below the species level that should be managed independently (Harris et al. 2016). Given the phenotypic, genetic, and ecological variation present within and among Arctic char and Dolly Varden populations, different systems and populations may require tailored, system-specific management approaches. In the Coppermine River, additional research on resource and habitat

use, including determining whether Arctic char and Dolly Varden consume different prey sources and make use of different spawning and overwintering habitats, will help focus stewardship and management efforts from as informed a perspective as possible.

Results from STRUCTURE analyses (Figure 3.5; Figure D.5) indicate that in the Canadian Arctic, Arctic char and Dolly Varden should likely be managed separately and differently (though we acknowledge the complexity of such a task in systems where the species are sympatric, especially given persistent data gaps). SNP data (Chapter 3) reveal relative genetic heterogeneity across the sampled Arctic char populations, whereas the Dolly Varden populations may support distinct genetic clusters. An important avenue for future research is to assess whether any SNPs with fixed differences between Arctic char and Dolly Varden (i.e., markers where every individual of one species has the 'AA' genotype, and every individual of the other species has the 'BB' genotype) are associated with genes known to be involved in physiological processes; these processes could include osmoregulation, saltwater tolerance, or temperature regulation. While both Arctic char and Dolly Varden appear to be anadromous in systems east of the Mackenzie River in which they occur sympatrically, Dolly Varden are generally thought to be comparatively 'more anadromous' due to differences in life history when the two species occur sympatrically west of the Mackenzie River (e.g., Taylor et al. 2008), and as indicated in part by the more streamlined body shape that Dolly Varden tend to have (e.g., Figure 4.3). Additionally, in the Coppermine River, western scientific data (Smith 2020) and reports from fishers indicate that larger char move downriver earlier in the summer and upriver earlier in the fall. The Arctic char and Dolly Varden included in these analyses had significantly different fork lengths (Figure D.7) – Dolly Varden had a longer average fork length than did Arctic char. There may be differences in the timing and duration of marine migrations, and movement patterns,

between the species that reflect differences in physiology, and which would require species-specific fisheries management plans. Future researchers could also look at differences in gene expression between Arctic char and Dolly Varden at a specific time during migration (i.e., during the downstream or upstream migration periods), to evaluate variability in molecular pathways and mechanisms. For example, cortisol production, lipid metabolism, or phototransduction are known to be associated with migration in other salmonids (i.e., Hale et al. 2016), and may differ between the species. Taken together, physiological analyses and assessments of gene expression could provide insight into the behavioral and resource use differences by Arctic char and Dolly Varden and contribute to data-based management of the species.

5.2.4 Do western science concepts of species align with or apply to the observations and perceptions of Inuit subsistence fishers?

As western-trained scientists, we are often focused on classifying and categorizing things – how can we partition the natural world into discrete segments, with everything neatly in its own box and connected in clear, quantifiable ways? The sheer number of species concepts that have been proposed by biologists and taxonomists – upwards of 20 have been proposed (Mayden 1997) – highlights our ongoing subscription to the idea that one day we will discover the "true" relationships among organisms; in a 2011 paper, science philosopher John Wilkins remarked that "there are n + 1 definitions of 'species' in a room of *n* biologists." Depending on what species concept is applied (see De Queiroz (2007) for a list of several species concepts), Arctic char and Dolly Varden may or may not meet the required criteria to be classified as distinct species. In the Coppermine River specifically, is such a designation, in and of itself, truly of significance?

From a western science perspective, this research contributes to our understanding of the

Arctic char "species complex" (Behnke 1980; Taylor 2016). Over the decades, *Salvelinus* fishes have been taxonomically split and merged in numerous ways by many researchers. In systems that support genetically distinct sympatric morphs, researchers have debated at what point such morphs warrant species status (e.g., Skulason et al. 1999; Klemetsen 2010). From an Inuit knowledge perspective in Kugluktuk, the biological species concept fails to translate, as do many of the other recognized species concepts. Fishers in Kugluktuk differentiate char based on their behavior, appearance, availability, and value (e.g., taste) to the subsistence fishery (Chapter 4); the scientific definition of species is not used. This was illustrated by many fishers' uncertainty when asked if they had ever caught Dolly Varden (Chapter 4), and by their recognition of the species upon being shown photographs. One participant who was asked if he had different names for the longer, skinnier char (Dolly Varden, from a species perspective) and the fatter char (Arctic char, from a species perspective) commented that the skinnier char was "still just a char," and remarked that the variation between the two photographs I had shown him might be due to differences in behavior or life history. In a system and a subsistence fishery with both Arctic char and Dolly Varden, perhaps what is most pressing from a conservation standpoint is that we use and build upon our newfound knowledge of char species diversity to understand how morphologically distinct chars vary in their habitat use, prey resources, migration timing, and spawning locations, as this knowledge will advance conservation and management.

5.3 Concluding remarks

In this thesis, data from advanced, next-generation techniques confirm long-held speculations and assertions – often based on limited data or anecdotal information – that contemporary Dolly Varden populations are present in the central Canadian Arctic east of the

Mackenzie River. This is also the first detailed description of genetic and morphological characteristics of sympatric anadromous Arctic char and anadromous Dolly Varden in the Canadian Arctic. I showed that Arctic char and Dolly Varden both exist in systems in the central Canadian Arctic, that the two species can be differentiated using meristics, morphometrics, and genomics, and that western scientific data aligns with observations of changes documented by fishers and elders in the community of Kugluktuk, Nunavut. The ability to use meristics and morphometrics to distinguish between two species may allow further cost-effective, feasible development and advancement of community-based monitoring and management of subsistence char fisheries. The char situation in the central Canadian Arctic remains complex. By incorporating multiple methods and different forms of knowledge, this research advances our understanding of *Salvelinus* fishes in the central Canadian Arctic, while contributing to ongoing efforts to conserve critical subsistence fisheries.

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Appendices

A: Research Ethics

The research presented in chapters 2 and 3 was conducted under University of Waterloo Animal Care Committee animal use protocol #30071. The research presented in Chapter 4 was conducted under Nunavut Research Institute scientific research licenses 04 023 23R-M (2021), 04 011 22R-M (2022), and 04 004 23R-M (2023). Additional approval for the research presented in Chapter 4 came from University of Waterloo Human Research Ethics protocol #41574.

B: Supplementary Information for Chapter 1

Table B.1: *Information on the life history characteristics, ecology, and evolutionary history of three forms of Dolly Varden: northern form Dolly Varden (*S. m. malma*), Miyabe char (*S. m. miyabei*), and stone char (*S. m. kuznetzovi*).*

Species (Scientific Name)	***Salvelinus malma***						
Predicted Origin	Asia/Western Pacific						
mtDNA Lineage	Bering, Arctic				Bering		Bering
Subspecies	*S. m. malma*				*S. m. miyabei*		*S. m. kuznetzovi*
Common Name	Northern form Dolly Varden				Miyabe char		Stone char*
Alternative Scientific Names/Classifications^	N/A				N/A		*S. kuznetzovi*
Location	Asia; North America north of the Alaska Peninsula and east to the Mackenzie River				Shikaribetsu Lake, Japan		Kamchatka River basin
Life History Type	Anadromous	Stream/riverine-resident	Isolated stream-resident	Lacustrine	Lake-run	Stream-resident	Riverine
Sex	M/F	M (precocious; more common)/F (less common but have been documented in some rivers)	M/F	M/F	M/F	M (rarely, females may be found)	M/F

Unique Physical Characteristics		Paedomorphic; smaller than anadromous individuals	Paedomorphic; variegation along body	Variable head and body shape; morph-specific, with morphs adapted to particular depths and feeding regimes	Paedomorphic; males develop secondary sexual characteristics and spawning colors	Paedomorphic; smaller than lake-run individuals; darker-colored bodies than lake-run fish	Distinctive marbling of skin
General Habitat Preferences	High-gradient, pristine rivers; estuaries; nearshore and offshore marine habitats	High-gradient, pristine rivers that do not freeze through in winter	Small headwater streams				
Age of First Migration~	3-5	N/A	In some systems, individuals may migrate to more productive lower reaches of rivers to feed on Pacific salmon eggs	N/A		N/A	
Timing of Outmigration	Spring (predominantly late June - July)	N/A	N/A	N/A		N/A	
Age of Sexual Maturity+	4-9	2-6, depending on sex and system	2-4 in small streams; 4-6 in larger streams and rivers	3-6, depending on morph	3-4	1-2	

Prey Preferences	Juveniles: midges, mayflies, insects, small crustaceans Adults and anadromous juveniles: amphipods, mysids, smaller freshwater and anadromous fish	Allochthonous and autochthonous invertebrates	Opportunistic benthic feeders; Pacific salmon eggs; aquatic insects	Morph-specific, but includes invertebrates, insects, and fish	Zooplankton; salmonid eggs; juvenile char; insect larvae		Ambush predator; prey include rainbow trout and salmonid eggs
Overwintering Habitat	Groundwater-fed rivers that do not freeze through in winter	Groundwater-fed rivers that do not freeze through in winter	Deep pools and/or deep areas near tributary mouths		Lake	Streams	
Spawning Time	Fall (late August - October)	Fall (~September) - winter	Fall (September - October; 2 - 3 weeks after anadromous Dolly Varden in lower reaches of rivers); individuals in some populations may spawn in late summer	Morph-specific; lake spawning has been documented in January - February, while lake tributary spawning has been observed from August - October; spring spawning may occur	Fall (September - November)	Fall (September - November)	Fall, peaking in mid-September

Spawning Habitat	Springs and groundwater-fed rivers that do not freeze through in winter; locations with strong currents	Groundwater-fed rivers that do not freeze through in winter	Sandy or gravel-bottomed habitat	Lakes and lake tributaries	Inlet streams	Inlet streams	Dark-colored water in coniferous taiga zone; substrate covered with conifer needles
Annual or Alternate-year Spawners?	Annual or alternate year	Annual	Annual or alternate year	Alternate year	Annual spawning/feeding migration between lake and inlet streams		
Notes on Spawning or Overwintering		Residual males ("sneakers") spawn with anadromous females. Individuals may make long-distance movements between spawning and overwintering sites within the river.	Females rarely construct redds; males develop secondary sexual characteristics before spawning. Females in most populations are iteroparous, though in some populations females are likely semelparous.	Individuals spawning in lake tributaries migrate from the lake in late summer	Small stream-resident males spawn with larger lake-run females. Multiple males attempt to spawn with any given female. Females appear to prefer males that are larger than themselves.		Females construct gravel redds upstream of riffles. When sympatric with Dolly Varden, stone char spawn when water temperatures are warmer.

Additional Notes	Generally prefer nearshore marine areas, but can and do undertake long-distance ocean migrations. After returning to freshwater to overwinter, individuals may skip migration.	Sympatric with anadromous *S. malma*. Abundance of resident individuals may correlate with abundance of Pacific salmon in rivers.	Isolation is either physical (e.g., due to waterfalls or dams) or as a result of distance to the marine environment. Migrants can be produced, but migrants are unable to return to the natal stream.	Very rarely documented in North America and Asia. Most Asian populations were isolated due to volcanic activity. Populations may contain multiple morphs.	Forms are sympatric, and whether a male adopts a stream resident or a lake-run life history is likely due to a combination of genetic and environmental factors. Early sexual maturation, typical of stream-resident char, may prevent individuals from making future migrations into lakes.	
References	Armstrong and Morrow 1980, DeCicco 1992, Kowalchuk et al. 2010, Reist and Sawatzky 2010, Courtney et al. 2018	McCart and Craig 1973; Armstrong and Morrow 1980; Gruzdeva et al. 2017, Power and Reist 2018; Gallagher et al. 2019	Armstrong and Morrow 1980, Esin 2015	Armstrong and Morrow 1980, Kowalchuk et al. 2010, Markevich et al. 2018	Maekawa 1978, Maekawa 1983, Maekawa and Onozato 1986, Yoshiyama et al. 2017	Melnik et al. 2020

Table B.2: *Information on the life history characteristics, ecology, and evolutionary history of two forms of Dolly Varden: southern form Dolly Varden (*S. m. lordi*) and southern Asian Dolly Varden (*S. m. kraschenninikovi*).*

Species (Scientific Name)	***Salvelinus malma***						
Predicted Origin	Asia/Western Pacific						
mtDNA Lineage	Bering						
Subspecies	*S. m. kraschenninikovi*		*S. m. lordi*				
Common Name	Southern form Dolly Varden; Asian Southern form Dolly Varden		Southern form Dolly Varden				
Alternative Scientific Names/Classifications^	*S. kraschenninikovi; S. curilus; S. m. curilus; S. gritzenkoi; S. vasiljevae*		N/A				
Location	Asian islands and mainland		North America south of the Alaska Peninsula to Washington state				
Life History Type	Anadromous (northern portion of the range)	Riverine-resident and lacustrine (southern portion of the range)	Anadromous (from stream-lake systems)	Stream/riverine-resident	Isolated riverine-resident	Adfluvial	Lacustrine
Sex	M/F	M/F	M/F	M/F	M/F	M/F	M/F

Unique Physical Characteristics	Systems support multiple morphs, which may diverge along depth and or size axes	Deep, cone-shaped head		Often paedomorphic	Paedomorphic		
General Habitat Preferences		Headwaters of rivers	Juveniles utilize diverse stream habitats				
Age of First Migration~	3-4		2-4	N/A	N/A	Migration into lake at ~2 years of age	N/A
Timing of Outmigration		Migration into river tributaries from August - September	May-June, September-November	N/A	N/A	N/A	N/A
Age of Sexual Maturity+	5-6	3-4	4-7	1-4		3+	
Prey Preferences	Benthos; fish eggs; decaying salmon carcasses; plankton	Large benthos; fish eggs; decaying salmon carcasses; plankton	Opportunistic feeders; aquatic insects; fish eggs and young; crustaceans	Opportunistic feeders; aquatic insects; invertebrates		Zooplankton (offshore group); benthic insects and worms (inshore group); invertebrates; fish; fish eggs	
Overwintering Habitat			Lakes or, uncommonly, large rivers (adults); warmer, spring-fed tributaries (juveniles)		N/A	Warmer, spring-fed tributaries	N/A
Spawning Time		October - December and January - February	Fall (September - November)	Fall		Summer (August), fall	

Spawning Habitat	Lake tributaries	Lakes; lake tributaries (morph-specific)	Streams	Streams and springs that do not freeze through in winter		Streams	Unknown location in lakes
Annual or Alternate-year Spawners?		Annual; individuals in some populations may be semelparous	Annual or alternate year	Annual	Annual	Annual	Annual
Notes on Spawning or Overwintering		In some populations, spawning individuals do not feed during the spawning period.	Overwinter in natal systems. Downstream summer migration consists of smolts, non-spawners, and spawners. Spawners that overwintered in non-natal systems move directly to natal (or, if strayers, non-natal spawning) systems without entering other freshwater systems along the way. Individuals enter and leave freshwater systems between July and November, looking for a system suitable for overwintering. Spawning generally occurs in natal streams, though straying can and does occur.	Residual males ("sneakers") spawn with anadromous females. Individuals may make long-distance movements between spawning and overwintering sites within the river.		Spawning fish move from the lake back into the natal stream. Summer-spawning fish spend the summer in the stream.	

Additional Notes	Thought to have a range distribution farther south than that of *S. m. malma. S. m. krascheninnikovi* may be used in the literature to refer to anadromous char, while *S. m. curilus* is at times used to refer to freshwater-resident char.		After returning to freshwater to overwinter, individuals may skip migration.	Sympatric with anadromous *S. malma*. Stream-resident individuals are slow-growing and have a comparatively short lifespan, and are rarely documented.	Isolation is either physical (e.g., due to waterfalls or dams) or as a result of distance to the marine environment. Migrants can be produced, but migrants are unable to return to the natal stream.	More common than lacustrine *S. m. malma*, but still rare compared to anadromous, isolated, and residual *S. malma.* After moving into the lake, populations may diverge into an offshore group and an inshore group.	Uncommon
References	Oleinik et al. 2007, Pichugin et al. 2008, Esin and Markevich 2018, Yamamoto et al. 2021		Armstrong 1974, Armstrong and Morrow 1980, Armstrong 1984	Armstrong and Morrow 1980; Kowalchuk et al. 2010	Kowalchuk et al. 2010	Armstrong and Morrow 1980	Armstrong and Morrow 1980, Kowalchuk et al. 2010

Table B.3: *Information on the life history characteristics, ecology, and evolutionary history of Arctic char.*

Species (Scientific Name)	***Salvelinus alpinus***							
Predicted Origin	Europe				Arctic Ocean; Siberia		Arctic Ocean; Lake El'gygytgyn, Siberia, western Alaska	
mtDNA Lineage	Arctic, Atlantic		Atlantic	Acadia	Arctic, Atlantic, Siberia		Arctic, Siberia	
Subspecies	*S. a. alpinus*		*S. a. salvelinus*	*S. a. oquassa*	*S. a. erythrinus*		*S. a. taranetzi*	
Common Name	Arctic char		Arctic char	Sunapee; blueback; red trout	Arctic char; Davatchan char		Arctic char; Taranets char	
Alternative Scientific Names/Classifications^	N/A		*S. umbla*	*S. marstoni; S. aureolus*	Increasingly used synonymously with *S. a. taranetzi*, see Osinov et al. 2015		*S. taranetzi*; *S. neiva*; *S. drjagini*; *S. boganidae*; *S. elgyticus*; *S. czerskii*; *S. krogiusae*; *S. andriashevi*; increasingly used synonymously with *S. a. erythrinus*, see Osinov et al. 2015	
Location	northern Europe	Landlocked, isolated lakes in Europe and Russia; Iceland	central Europe	Maine; Quebec; New Brunswick	Canadian Arctic; Siberia	northern Alaska; Transbaikalia	Siberia, Chukotka Peninsula to Dejnev's Bay	eastern Siberia
Life History Type	Anadromous	Lacustrine		Relict lacustrine	Anadromous	Isolated lacustrine	Anadromous	Lacustrine
Sex	M/F	M/F	M/F	M/F	M/F	M/F	M/F	M/F
Unique Physical Characteristics		Highly variable coloration and morphology		Generally < 40 cm in length; variable coloration				Generally larger than sympatric *S. m. malma*

General Habitat Preferences				Deep, spring-fed, oligotrophic lakes		Alpine lakes		Lakes in the permafrost zone
Age of First Migration~		N/A		N/A	2-11	N/A	3-6	N/A
Timing of Outmigration		N/A		N/A		N/A		N/A
Age of Sexual Maturity+		3-7, depending on morph		Males: 2-4 Females: 4+		4-8	5-8	3-6
Prey Preferences		Benthos; plankton; fish		Plankton; aquatic and terrestrial insects/insect larvae; invertebrates; fish; benthos	Invertebrates; fish, including smaller Arctic char; dependent on predator size	Zooplankton (small form); smaller fishes (large form)		Plankton; benthos; fish
Overwintering Habitat		N/A		N/A	Lakes, deep rivers that do not freeze through			
Spawning Time	Generally fall, but some populations spawn in spring	Generally fall, but some populations spawn in spring	Generally fall, but some populations spawn in spring	Fall (October - November)	Fall (September - October)	Late fall - winter (~November - January)	Late summer - early winter	Winter - spring
Spawning Habitat		Dwarf forms: shallow areas of lake shores		Rocky shoals; cobble or gravel substrate	Lakes with gravel substrate	Variable (has been documented on gravel and cobble substrate and on silty substrate, depending on the system)	Most commonly lakes; two populations have been identified as riverine spawners	Lakes

Annual or Alternate-year Spawners?					Annual or alternate year, depending on the characteristics of the spawning and overwintering systems.	Small form: annual Large form: alternate		
Notes on Spawning or Overwintering				Spawning individuals generally do not construct redds. Spawning behavior is system-specific, and is a plastic response to habitat/environmental conditions. Spawning/success of spawning activities in a given year is dependent on water levels.		In systems with high female fecundity, females spawn with one or few males and guard their eggs after spawning. Where females have lower fecundity and lay fewer, larger eggs, females spawn with multiple males and do not remain at the spawning grounds to guard their eggs. Spawning in some systems happens rapidly (e.g., over the course of just one week), while in other systems, individuals spawn over a period of months.	After spawning, individuals may cease migrating and remain as lake-residents for the remainder of their lives.	

Additional Notes	Populations may contain multiple morphs; each morph may display only one color form or consume a limited variety of prey.		Populations may contain multiple morphs; each morph may display only one color form or consume a limited variety of prey.	Found in systems without lake trout. When found in systems with brook trout, the two species occupy distinct habitats.		Populations support small and large morphs.		No divergence in mtDNA haplotypes between populations.
References	Behnke 1980, Behnke 1984	Klemetsen and Grotnes 1980	Armstrong and Morrow 1980, Lobón-Cerviá et al. 2019	Everhart and Waters 1965, Kircheis 1980, Kornfield et al. 1981, Frost 2001, Michaud et al. 2008	Pavlov et al. 1994, Osinov et al. 2015, Markevich and Esin 2019		Osinov et al. 2015, Esin et al. 2017, Power and Reist 2018, Markevich and Esin 2019	

^ Alternative names may be used widely, or may represent populations endemic to one or few systems.

* Markevich and Esin (2019) suggest that this is inaccurate, and that *S. m. kuznetzovi* are instead fluvial Dolly Varden.

~ In many/most char populations, migration and sexual maturity are driven by size rather than age.

(1) We note that the classification of species and subspecies is subjective and that, while this table represents the most common subspecies in the literature, it is not comprehensive as different authors may classify populations and subspecies differently. We also note that some of these details will vary between systems depending on the species composition of the system in question and the precise niche occupied by the char species, subspecies, or morph.

(2) Many intra-specific populations of Arctic char and Dolly Varden support sympatric morphs. Additional information on common morphs and examples of systems that support discrete morphs can be found in-text.

C: Supplementary Information for Chapter 2

Table C.1: *Data included in the meristic analyses presented in Chapter 2, including the results of the LDA. Each row represents a population average, according to the morphs, forms, or life history types distinguished in the original paper. Populations that were misclassified when performing the LDA (n = 14) are indicated in red.*

Paper	General location	System	Coordinates*	Species (as presented in original paper)	Species Code	Morph, form, or life history type	Species (following Morrow 1980)	Total gill rakers	Pyloric caeca	Correctly classified?
Alekseyev et al. 2013	Russia	Lake Bol'shoe Leprindo	56°37'25.2"N, 117°31'53.7"E	*Salvelinus alpinus*	ARCH	dwarf	ARCH	40.8	38.1	T
Alekseyev et al. 2013	Russia	Lake Bol'shoe Leprindo	56°37'25.2"N, 117°31'53.7"E	*Salvelinus alpinus*	ARCH	large	ARCH	36	47	T
Alekseyev et al. 2013	Russia	Lake Maloe Leprindo	56°36'50.3"N, 117°22'02.4"E	*Salvelinus alpinus*	ARCH	dwarf	ARCH	40.5	37.1	T
Alekseyev et al. 2013	Russia	Lake Maloe Leprindo	56°36'50.3"N, 117°22'02.4"E	*Salvelinus alpinus*	ARCH	large	ARCH	34.8	45.1	T
Alekseyev et al. 2013	Russia	Lake Maloe Leprindo + Bol'shoe	56°36'50.3"N, 117°22'02.4"E	*Salvelinus alpinus*	ARCH	small	ARCH	40.2	37.6	T
Alekseyev et al. 2014	Russia	Lake Kamkanda	57°05.5’ N, 119°48.5’ E	*Salvelinus alpinus*	ARCH	large	ARCH	36	47.8	T
Alekseyev et al. 2014	Russia	Lake Kamkanda	57°05.5’ N, 119°48.5’ E	*Salvelinus alpinus*	ARCH	dwarf	ARCH	34.3	51.4	T
Alekseyev et al. 2014	Russia	Lake Kamkanda	57°05.5’ N, 119°48.5’ E	*Salvelinus alpinus*	ARCH	small	ARCH	39	56.1	T
Alekseyev et al. 2019	Russia	Lake Kiryalta-3	57°08.5’N, 119°27’E	*Salvelinus alpinus*	ARCH	small	ARCH	41.1	38.5	T
Alekseyev et al. 2019	Russia	Lake Kiryalta-3	57°08.5’N, 119°27’E	*Salvelinus alpinus*	ARCH	large	ARCH	36.1	45.4	T

Alekseyev et al. 2019	Russia	Lake Kiryalta-4	57°06.5'N, 119°28'E	*Salvelinus alpinus*	ARCH	small	ARCH	41.3	39.8	T
Alekseyev et al. 2019	Russia	Lake Kiryalta-4	57°06.5'N, 119°28'E	*Salvelinus alpinus*	ARCH	large	ARCH	39.3	40.1	T
Armitage 1973	North American Pacific Coast	Dickson Lake	49°19'0"N, 122°5'30"W	*Salvelinus malma*	DVCH	lacustrine	DVCH	17.5	25.9	T
Backus 1957	Eastern North America	Sunapee Lake	43°23'10.3"N, 72°03'17.8"W	*Salvelinus alpinus aureolus*	ARCH		ARCH	20.5	44	T
Barsukov 1960	Russia	Lake Estikhet		*Salvelinus malma (synonymous with S. alpinus)*	DVCH	lake char	ARCH	23.7	36.6	T
Barsukov 1960	Russia	Lavrentiya Bay near settlement of Pinakul		*Salvelinus malma (synonymous with S. alpinus)*	DVCH	lake char	ARCH	23.1	46.6	T
Barsukov 1960	Russia	Lavrentiya Bay near settlement of Pinakul		*Salvelinus malma*	DVCH	sea-run char	DVCH	23.4	26.4	T
Behnke 1980	Eastern North America	lake near Nain	56°32'26.4"N, 61°41'51.5"W	*Salvelinus alpinus oquassa*	ARCH		ARCH	24.5	33	F
Behnke 1980 (Chereshnev)	Russia	Lake Estikhet		*Chukotsk char*	ARCH		ARCH	25	42	T
Behnke 1980 (Savvaitova 1976)	Russia	Lake Dalneye		*ambiguous Salvelinus*	ARCH	lacustrine	ARCH	24.8	48	T
Behnke 1980 (Savvaitova 1976)	Russia	Lake Nachikin		*ambiguous Salvelinus*	ARCH	lacustrine	ARCH	26.7	48.8	T
Borisov 1931, in Savvaitova 1961	Russia	Aranastakh Lake, delta of Lena River		*Salvelinus jacuticus*	ARCH		ARCH	23.9	36.6	T

Cavender 1978	North American Pacific Coast	Aleutian Islands	52°13'00.4"N, 174°12'25.5"W	*Salvelinus malma*	DVCH		DVCH	16.5	25.3	T
Cavender 1978	North American Pacific Coast	Coastal	51°53'57.9"N, 128°25'20.1"W	*Salvelinus malma*	DVCH		DVCH	18	26.7	T
Cavender 1978	North American Pacific Coast	Gulf of Alaska Coastal Drainages and Islands	59°41'04.5"N, 145°41'18.7"W	*Salvelinus malma*	DVCH		DVCH	18.9	27.8	T
Cavender 1978	North American Pacific Coast	Puget Sound, Skagit River	48°22'16.8"N, 122°29'41.7"W	*Salvelinus malma*	DVCH		DVCH	17.7	26.9	T
Cavender 1978	North American Pacific Coast	Skeena River Basin	55°45'17.1"N, 127°57'27.2"W	*Salvelinus malma*	DVCH		DVCH	18.9	29	T
Cavender 1978	North American Pacific Coast	Soleduck River, Washington	47°57'01.8"N, 123°48'55.1"W	*Salvelinus malma*	DVCH		DVCH	17.5	22.1	T
Cavender 1978	North American Pacific Coast	Taku River	58°34'48.1"N, 133°39'11.6"W	*Salvelinus malma*	DVCH		DVCH	18.6	27.6	T
Cavender 1980	North Pacific	North Pacific		*Salvelinus alpinus*	ARCH		ARCH	24.7	41.1	T
Cavender 1980	North Pacific	North Pacific		*Salvelinus malma*	DVCH	southern form	DVCH	18	23.1	T
Cavender 1980	North Pacific	North Pacific		*Salvelinus malma*	DVCH	western Pacific form	DVCH	21.3	26.8	T
Cavender 1980	North Pacific	North Pacific		*Salvelinus malma*	DVCH	northern form	DVCH	20.9	27.3	T

Cavender 1980	North Pacific	North Pacific		*Salvelinus anaktuvukensis*	DVCH		DVCH	21.1	27.6	T
DeLacy and Morton 1943	North American Pacific Coast	Karluk Lake		*Salvelinus alpinus*	ARCH		ARCH	23.4	45.6	T
DeLacy and Morton 1943	North American Pacific Coast	Karluk Lake		*Salvelinus malma*	DVCH		DVCH	18.1	28.8	T
Esin 2015	Russia	Apachinskii Stream	52°56'11"N, 157°2'53"E	*Salvelinus malma*	DVCH	resident	DVCH	22.1	26.7	T
Esin 2015	Russia	Falshivaya River	52°29'58"N, 158°14'19"E	*Salvelinus malma*	DVCH	resident	DVCH	23.2	28.3	T
Esin 2015	Russia	Kavavlya River	56°1'6" N, 159°9'39" E	*Salvelinus malma*	DVCH	resident	DVCH	22.9	28.4	T
Esin 2015	Russia	Nachilova River	52°7'4"N, 156°51'59"E	*Salvelinus malma*	DVCH	anadromous (dwarf males)	DVCH	23.9	29.4	T
Esin 2015	Russia	Nizhnekoshelevskii Stream	51°22'6"N, 156°35'34"E	*Salvelinus malma*	DVCH	resident	DVCH	21.7	24.7	T
Esin 2015	Russia	Ponomarskii Stream	56°11'36"N, 161°46'18"E	*Salvelinus malma*	DVCH	resident	DVCH	20	28.8	T
Esin and Markevich 2019	Russia	Lake Bol'shoe	54°33'31"N, 159°39'25"E	*Salvelinus malma*	DVCH	northern, landlocked	DVCH	21.2	27.5	T
Esin and Markevich 2019	Russia	Lake Dal'nee	54°30'28"N, 160°2'23"E	*Salvelinus malma*	DVCH	northern, landlocked	DVCH	21.1	29.1	T
Esin and Markevich 2019	Russia	Lake Goltsovoe	53°4'34"N, 157°16'33"E	*Salvelinus malma*	DVCH	northern, landlocked	DVCH	25.6	25.7	T
Esin and Markevich 2019	Russia	Lake Krokur	54°41'56"N, 160°22'8"E	*Salvelinus malma*	DVCH	northern, landlocked	DVCH	22.1	28.9	T

Esin and Markevich 2019	Russia	Lake Snejnoe	55°34'18"N, 158°17'51"E	*Salvelinus malma*	DVCH	northern, landlocked	DVCH	21.3	26.8	T
Esin and Markevich 2019	Russia	Lake Topolovoe	52°48'23"N, 158°16'57"E	*Salvelinus malma*	DVCH	northern, landlocked	DVCH	21.7	28.1	T
Esin et al. 2017	Russia	Lake Ayaogytgyn	59°13.7'N, 160°50.0'E	*Salvelinus taranetzi*	ARCH	lacustrine	ARCH	26.9	41.5	T
Esin et al. 2017	Russia	Lake Bolshoy Sokoch	53°15.1'N, 157°45.1'E	*Salvelinus taranetzi*	ARCH	lacustrine	ARCH	24.1	42	T
Esin et al. 2017	Russia	Lake Dal'neye	52°56.0'N, 158°20.9'E	*Salvelinus taranetzi*	ARCH	lacustrine	ARCH	26.6	48.6	T
Esin et al. 2017	Russia	Lake Dvukhyurtochnoye	56°48.7'N, 160°3.5'E	*Salvelinus taranetzi*	ARCH	lacustrine	ARCH	26.5	48.8	T
Esin et al. 2017	Russia	Lake Kopyl'ye	55°23.2'N, 157°58.2'E	*Salvelinus taranetzi*	ARCH	lacustrine	ARCH	25.9	39.5	T
Esin et al. 2017	Russia	Lake Nachikinskoye	52°59.8'N, 157°51.0'E	*Salvelinus taranetzi*	ARCH	lacustrine	ARCH	24.6	43.8	T
Esin et al. 2017	Russia	Lake B. Sokoch	53°15.1'N, 157°45.1'E	*Salvelinus malma*	DVCH		DVCH	21.5	23.3	T
Esin et al. 2017	Russia	Lake Dal'neye	52°56.0'N, 158°20.9'E	*Salvelinus malma*	DVCH		DVCH	22.3	24.2	T
Esin et al. 2017	Russia	Lake Dvukhyurtochnoye	56°48.7'N, 160°3.5'E	*Salvelinus malma*	DVCH		DVCH	23.7	28.4	T
Esin et al. 2017	Russia	Lake Kopyl'ye	55°23.2'N, 157°58.2'E	*Salvelinus malma*	DVCH		DVCH	22.8	25.9	T
Esin et al. 2017	Russia	Lake Nachikinskoye	52°59.8'N, 157°51.0'E	*Salvelinus malma*	DVCH		DVCH	22.4	27.8	T
Frohne 1973	North American Pacific Coast	Aleutian Islands		*Salvelinus malma*	DVCH		DVCH	18.6	27.2	T
Frohne 1973	North American Pacific Coast	Southeast Alaska		*Salvelinus malma*	DVCH		DVCH	17.8	28.4	T

Frohne 1973	Russia	Siberia		*Salvelinus malma*	DVCH		DVCH	20.4	29.4	T
Frohne 1973	Western North America	Interior Alaska		*Salvelinus alpinus*	ARCH		ARCH	22.3	46.5	T
Frohne 1973	Western North America	Brooks Range		*Salvelinus anaktuvukensis*	DVCH		DVCH	20.5	28.3	T
Frohne 1973	Western North America	Interior Alaska		*Salvelinus malma*	DVCH	interior Alaska	DVCH	20.7	25.2	T
Frohne 1973	Western North America	Northern Alaska		*Salvelinus malma*	DVCH	northern Alaska	DVCH	20.8	25.9	T
Gritsenko 1970, in Pichugin et al. 2008	Russia	Longari River		*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	19.6	24	T
Gritsenko 1975, in Pichugin et al. 2008	Russia	Bogataya River		*Salvelinus malma krascheninnikovi*	DVCH	migratory	DVCH	20.6	21.4	T
Gritsenko 1975, in Pichugin et al. 2008	Russia	Kirpichnyi Brook (Tym)		*Salvelinus malma krascheninnikovi*	DVCH	brook	DVCH	18.7	21.6	T
Gritsenko 1975, in Pichugin et al. 2008	Russia	Poronai River	50°12'41.6"N, 142°54'10.9"E	*Salvelinus malma krascheninnikovi*	DVCH	migratory	DVCH	21.4	25.5	T
Gritsenko 1975, in Pichugin et al. 2008	Russia	Tym River	50°28'31.3"N, 142°51'45.6"E	*Salvelinus malma krascheninnikovi*	DVCH	migratory	DVCH	21.6	22.3	T
Gritsenko 1975, in Pichugin et al. 2008	Russia	Tym River	50°28'31.3"N, 142°51'45.6"E	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	21.4	22.8	T
Groening 2008	North American Pacific Coast	Bear Creek		*Salvelinus malma*	DVCH	intermediate form	DVCH	20.5	27.1	T

Groening 2008	North American Pacific Coast	Cleo Creek		*Salvelinus malma*	DVCH	intermediate form	DVCH	20.1	29.7	T
Groening 2008	North American Pacific Coast	Ruth Arm		*Salvelinus malma*	DVCH	intermediate form	DVCH	20	23.6	T
Groening 2008	Western North America	Babbage River	68.34, -139.19	*Salvelinus malma*	DVCH	northern form	DVCH	20.5	22.3	T
Groening 2008	Western North America	Blackstone River	64.77, -138.37	*Salvelinus malma*	DVCH	intermediate form	DVCH	20.3	26.3	T
Groening 2008	Western North America	Canoe River	68.46, -138.44	*Salvelinus malma*	DVCH	northern form	DVCH	21.5	28.7	T
Groening 2008	Western North America	Klutina River	62.45, -145.45	*Salvelinus malma*	DVCH	southern form	DVCH	18.4	26.2	T
Groening 2008	Western North America	Nome River	64.67, -165.33	*Salvelinus malma*	DVCH	intermediate form	DVCH	21.7	28.1	T
Hammar et al. 1991	Eastern North America	Fraser River	56°39'N, 63°10'W	*Salvelinus alpinus*	ARCH		ARCH	24.5	36.5	T
Havens 1988	North American Pacific Coast	Big Lake		*Salvelinus alpinus*	ARCH		ARCH	25	47	T
Havens 1988	North American Pacific Coast	Eklutna Lake		*Salvelinus malma*	DVCH		DVCH	18	22	T
Hesthagen et al. 1995	Norway	Lake Sirdalsvatn	58°25'N, 6°40'E	*Salvelinus alpinus*	ARCH	dwarf	ARCH	26.5	28.2	F

Hesthagen et al. 1995	Norway	Lake Sirdalsvatn	58°25'N, 6°40'E	*Salvelinus alpinus*	ARCH	normal	ARCH	34.4	24.9	F
MacDonald 1996	North American Pacific Coast	Heart Lake		*Salvelinus alpinus*	ARCH		ARCH	24	46	T
MacDonald 1996	Western North America	Upper Togiak Lake	59°50'05.9"N, 159°28'46.6"W	*Salvelinus alpinus*	ARCH		ARCH	21	42	T
MacDonald 1996	Western North America	High Lake		*Salvelinus malma*	DVCH		DVCH	22	30	T
MacDonald 1996	Western North America	West Togiak Lake	59°38'28.2"N, 159°38'27.4"W	*Salvelinus malma*	DVCH		DVCH	22	31	T
MacDonald 1996	Western North America	Ongivinuck Lake	59°34'01.6"N, 159°21'29.0"W	*Salvelinus alpinus*	ARCH		ARCH	22	49	T
McCart and Bain 1974	Western North America	Lower Cache Creek	68°33'N, 136°17'W	*Salvelinus alpinus*	ARCH		DVCH	21.1	28.2	T
McCart and Bain 1974	Western North America	Upper Cache Creek	68°33'N, 136°17'W	*Salvelinus alpinus*	ARCH	isolated	DVCH	21.7	26	T
McCart 1980	Western North America	Canning River	69°55'58.7"N, 146°18'35.1"W	*Salvelinus alpinus*	ARCH	anadromous western	DVCH	21.8	31.4	T
McCart 1980	Western North America	Canning Spring-1		*Salvelinus alpinus*	ARCH	anadromous western	DVCH	21.2	33.2	T
McCart 1980	Western North America	CT-41 Spring	69°24'38.5"N, 146°01'17.4"W	*Salvelinus alpinus*	ARCH	isolated western	DVCH	20.4	26.6	T
McCart 1980	Western North America	Echooka River	69°24'32.5"N, 148°02'08.4"W	*Salvelinus alpinus*	ARCH	anadromous western	DVCH	21.9	32.3	T

McCart 1980	Western North America	Firth River	69°21'55.0"N, 139°32'23.0"W	*Salvelinus alpinus*	ARCH	anadromous western	DVCH	22.1	30.6	T
McCart 1980	Western North America	Fish Creek	69°26'55.1"N, 140°22'18.2"W	*Salvelinus alpinus*	ARCH	anadromous western	DVCH	20.4	27.4	T
McCart 1980	Western North America	Fish Hole Creek	68°44'50.5"N, 138°44'34.5"W	*Salvelinus alpinus*	ARCH	anadromous western	DVCH	21.6	28	T
McCart 1980	Western North America	Hulahula River	69°59'37.8"N, 144°02'01.0"W	*Salvelinus alpinus*	ARCH	anadromous western	DVCH	21.5	30.8	T
McCart 1980	Western North America	Joe Creek	68°57'40.8"N, 140°40'11.6"W	*Salvelinus alpinus*	ARCH	anadromous western	DVCH	21.8	29.1	T
McCart 1980	Western North America	Kavik River	70°02'40.6"N, 147°19'47.2"W	*Salvelinus alpinus*	ARCH	anadromous western	DVCH	22.3	29.2	T
McCart 1980	Western North America	Kongakut River	69°41'05.8"N, 141°49'48.4"W	*Salvelinus alpinus*	ARCH	anadromous western	DVCH	21.1	29.5	T
McCart 1980	Western North America	Lower Babbage	69°12'42.6"N, 138°25'21.7"W	*Salvelinus alpinus*	ARCH	isolated western	DVCH	20.6	28.4	T
McCart 1980	Western North America	Lower Cache Creek	68°26'33.2"N, 135°57'45.0"W	*Salvelinus alpinus*	ARCH	anadromous western	DVCH	21.2	28.3	T
McCart 1980	Western North America	Sadlerochit Spring	69°48'48.0"N, 144°19'19.4"W	*Salvelinus alpinus*	ARCH	isolated western	DVCH	18.8	25.8	T
McCart 1980	Western North America	Shaviovik River	70°10'38.2"N, 147°18'06.1"W	*Salvelinus alpinus*	ARCH	anadromous western	DVCH	21.5	27	T
McCart 1980	Western North America	Shublik Spring	69°24'39.8"N, 145°55'52.7"W	*Salvelinus alpinus*	ARCH	isolated western	DVCH	22.8	29.9	T

McCart 1980	Western North America	Upper Babbage	69°12'42.6"N, 138°25'21.7"W	*Salvelinus alpinus*	ARCH	isolated western	DVCH	20.1	28.5	T
McCart 1980	Western North America	Upper Cache Creek	68°26'33.2"N, 135°57'45.0"W	*Salvelinus alpinus*	ARCH	isolated western	DVCH	21.5	26	T
McCart and Craig 1971	Western North America	Atigun lakes	68°07'40.8"N, 149°26'20.1"W	*Salvelinus alpinus*	ARCH	resident	ARCH	29.6	37	T
McCart and Craig 1971	Western North America	Campsite Drainage	68°13'39.7"N, 150°03'34.8"W	*Salvelinus alpinus*	ARCH	resident	ARCH	27.3	45.6	T
McCart and Craig 1971	Western North America	Galbraith Lake	68°27'38.6"N, 149°25'19.2"W	*Salvelinus alpinus*	ARCH	resident	ARCH	27.2	43.3	T
McCart and Craig 1971	Western North America	Accomplishment Creek	68°39'11.6"N, 148°46'59.7"W	*Salvelinus alpinus*	ARCH	anadromous	DVCH	21.7	28.9	T
McCart and Craig 1971	Western North America	Ribdon River	68°48'09.3"N, 148°47'46.3"W	*Salvelinus alpinus*	ARCH	anadromous	DVCH	22.4	31.7	T
McCart and Craig 1971	Western North America	Section Creek	68°38'53.7"N, 148°52'26.6"W	*Salvelinus alpinus*	ARCH	anadromous	DVCH	22.2	31	T
McPhail 1961	Central Canadian Arctic	Beechey Lake	65°12'N, 106°28'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	27.5	43	T
McPhail 1961	Central Canadian Arctic	Bernard Harbor	68°48'N, 116°10'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	27.4	45	T
McPhail 1961	Central Canadian Arctic	Bloody Falls	67°59'N, 115°30'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	26	46	T
McPhail 1961	Central Canadian Arctic	Kathawachaga Lake	66°11'N, 111°08'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	29	45	T

McPhail 1961	Central Canadian Arctic	Mould Bay	76°12'N, 119°09'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	27.7	44	T
McPhail 1961	Eastern North America	"Shona" Lake	63°30'N, 68°50'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	25	43.7	T
McPhail 1961	Eastern North America	Flaherty Island	55°59'N, 79°00'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	27	44.7	T
McPhail 1961	Eastern North America	Merewether Crat.	61°13'N, 73°40'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	27	36.9	T
McPhail 1961	Eastern North America	Nain	56°32'N, 61°40'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	25.7	42.6	T
McPhail 1961	Eastern North America	Nettilling Lake	66°18'N, 70°40'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	26.7	39	T
McPhail 1961	Eastern North America	Sapuladjuk	64°18'N, 76°30'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	26	42	T
McPhail 1961	Eastern North America	Armit Lake	64°06'N, 91°32'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	27	44	T
McPhail 1961	Eastern North America	Beverly Lake	64°35'N, 100°38'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	26	44	T
McPhail 1961	Eastern North America	Devon Island	76°00'N, 86°00'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	25	44.5	T
McPhail 1961	Eastern North America	King William Island	69°00'N, 98°10'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	26	46	T
McPhail 1961	Eastern North America	MacDougal Lake	65°59'N, 98°34'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	29	46	T

McPhail 1961	Eastern North America	Resolute Bay	74°43'N, 94°20'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	26	41	T
McPhail 1961	Eastern North America	Term Pt.	61°51'N, 93°00'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	26.7	41	T
McPhail 1961	Eastern North America	Victoria Lake	81°49'N, 70°30'W	*Salvelinus alpinus*	ARCH	eastern Arctic	ARCH	28	38	T
McPhail 1961	North American Pacific Coast	Brooks Lake	58°22'N, 156°00'W	*Salvelinus alpinus*	ARCH	Bristol Bay/Gulf of Alaska	ARCH	25	43	T
McPhail 1961	North American Pacific Coast	Brooks Lake	58°22'N, 156°00'W	*Salvelinus malma*	ARCH	northern form	DVCH	21.6	27.9	T
McPhail 1961	North American Pacific Coast	Fraser Lake	57°15'N, 154°10'W	*Salvelinus alpinus*	ARCH	Bristol Bay/Gulf of Alaska	ARCH	24	42.9	T
McPhail 1961	North American Pacific Coast	Karluk Lake	57°23'N, 154°09'W	*Salvelinus alpinus*	ARCH	Bristol Bay/Gulf of Alaska	ARCH	23.6	44.3	T
McPhail 1961	North American Pacific Coast	Adak I.	52°00'N, 176°40'W	*Salvelinus malma*	DVCH	southern North American form	DVCH	17	27.6	T
McPhail 1961	North American Pacific Coast	Chena Lake	61°32'N, 144°26'W	*Salvelinus malma*	DVCH	southern North American form	DVCH	19	24	T
McPhail 1961	North American Pacific Coast	Fraser Lake	57°15'N, 154°09'W	*Salvelinus malma*	DVCH	southern North American form	DVCH	15	35.4	T

McPhail 1961	North American Pacific Coast	Karluk Lake	57°23'N, 154°05'W	*Salvelinus malma*	DVCH	southern North American form	DVCH	18	28.1	T
McPhail 1961	North American Pacific Coast	Kenai River	60°28'N, 151°24'W	*Salvelinus malma*	DVCH	southern North American form	DVCH	20	27	T
McPhail 1961	North American Pacific Coast	Midarm Lake	58°11'N, 152°25'W	*Salvelinus malma*	DVCH	southern North American form	DVCH	18	27.8	T
McPhail 1961	North American Pacific Coast	Ocean Falls	52°40'N, 127°45'W	*Salvelinus malma*	DVCH	southern North American form	DVCH	16	24.2	T
McPhail 1961	North American Pacific Coast	Summit Lake	60°37'N, 149°31'W	*Salvelinus malma*	DVCH	southern North American form	DVCH	18	31	T
McPhail 1961	North American Pacific Coast	Taku River	58°32'N, 133°52'W	*Salvelinus malma*	DVCH	southern North American form	DVCH	17	27	T
McPhail 1961	North American Pacific Coast	Turnagain Arm	60°57'N, 149°21'W	*Salvelinus malma*	DVCH	southern North American form	DVCH	17	20.2	T
McPhail 1961	North American Pacific Coast	Upper Trail Lake	60°31'N, 149°24'W	*Salvelinus malma*	DVCH	southern North American form	DVCH	19.5	27.5	T
McPhail 1961	Western North America	Aleknagik Lake	59°15'N, 158°35'W	*Salvelinus alpinus*	ARCH	Bristol Bay/Gulf of Alaska	ARCH	24.1	52.5	T

McPhail 1961	Western North America	Nerka Lake	59°25'N, 159°00'W	*Salvelinus alpinus*	ARCH	Bristol Bay/Gulf of Alaska	ARCH	24.5	49	T
McPhail 1961	Western North America	Aklavik	68°30'N, 134°30'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	23	35	T
McPhail 1961	Western North America	Aniak River	61°35'N, 159°40'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	22	27	T
McPhail 1961	Western North America	Collison Point	69°35'N, 139°07'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	23.5	29.5	T
McPhail 1961	Western North America	Dry Creek	63°41'N, 144°00'W	*Salvelinus malma*	ARCH		DVCH	18	16	T
McPhail 1961	Western North America	Elson Lagoon	71°15'N, 156°10'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	22	29	T
McPhail 1961	Western North America	Hansen Creek	59°12'N, 158°35'W	*Salvelinus malma*	ARCH	northern form	DVCH	21.9	26.7	T
McPhail 1961	Western North America	Herschel Island	69°35'N, 139°00'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	23	32.3	T
McPhail 1961	Western North America	Nome River	64°28'N, 165°20'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	21	24	T
McPhail 1961	Western North America	Nulato River	64°40'N, 158°05'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	22.3	23	T
McPhail 1961	Western North America	Nunivak Island	60°00'N, 167°00'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	22.5	31.5	T
McPhail 1961	Western North America	Salmon Lake	64°50'N, 165°00'W	*Salvelinus malma*	ARCH	northern form	DVCH	21.8	28	T

McPhail 1961	Western North America	St. Lawrence Island	63°17'N, 169°00'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	22	28	T
McPhail 1961	Western North America	St. Matthews Island	61°20'N, 172°30'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	22	30	T
McPhail 1961	Western North America	Tolstoi Lake	63°10'N, 157°45'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	22.7	27.8	T
McPhail 1961	Western North America	Unalakleet River	63°52'N, 160°55'W	*Salvelinus alpinus*	ARCH	Bering Sea-western Arctic	DVCH	23.5	28	T
Melnik et al. 2020	Russia	Kamchatka River Basin	55.135797N, 159.158273E	*stone char*	DVCH		DVCH	23.7	28.5	T
Melnik et al. 2020	Russia	Kamchatka River Basin	55.135797N, 159.158273E	*Salvelinus malma*	DVCH	northern	DVCH	23.1	29.9	T
Mihkin 1955, in Savvaitova 1961	Russia	Taymyr Lake		*Salvelinus taimyricus*	ARCH		ARCH	28.7	41.8	T
Moore 1975	Eastern North America	Cumberland Sound, Baffin Island	66°25N, 66°29W; and 66°17N, 66°09W	*Salvelinus alpinus*	ARCH	anadromous	ARCH	27.3	40.1	T
Morrow 1980	North American Pacific Coast	Bear Creek	60°11'N, 149°22'W	*Salvelinus malma*	DVCH		DVCH	18.5	25	T
Morrow 1980	North American Pacific Coast	Karluk Lake	57°23'N, 154°03'W	*Salvelinus alpinus*	ARCH		ARCH	23.1	46.2	T
Morrow 1980	North American Pacific Coast	Agattu Island	52°25'30"N, 173°42'30"E	*Salvelinus malma*	DVCH		DVCH	17	25.5	T
Morrow 1980	North American	Agattu Island	52°25'30"N, 173°42'30"E	*Salvelinus malma*	DVCH		DVCH	19.3	27.6	T

	Pacific Coast								
Morrow 1980	North American Pacific Coast	Atka Island	52°07'N, 174°30'W	*Salvelinus malma*	DVCH	DVCH	18.2	25.4	T
Morrow 1980	North American Pacific Coast	Attu Island	52°55'N, 172°55'E	*Salvelinus malma*	DVCH	DVCH	19.7	31.7	T
Morrow 1980	North American Pacific Coast	Auke Bay	58°21'N, 134°41'W	*Salvelinus malma*	DVCH	DVCH	17.5	26	T
Morrow 1980	North American Pacific Coast	Hidden Creek	58°33'N, 155°50'W	*Salvelinus malma*	DVCH	DVCH	19.3	30.7	T
Morrow 1980	North American Pacific Coast	Juneau	58°18'15"N, 134°24'30"W	*Salvelinus malma*	DVCH	DVCH	19	24	T
Morrow 1980	North American Pacific Coast	Ketchikan area	55°20'30"N, 131°38'45"W	*Salvelinus malma*	DVCH	DVCH	18.6	28.9	T
Morrow 1980	North American Pacific Coast	Kiska Island	51°58'30"N, 177°30'E	*Salvelinus malma*	DVCH	DVCH	19.2	32	T
Morrow 1980	North American Pacific Coast	Kodiak Island	57°20'N, 153°22'W	*Salvelinus malma*	DVCH	DVCH	17.6	28.8	T
Morrow 1980	North American	Lake McDonald	55°58'N, 131°50'W	*Salvelinus malma*	DVCH	DVCH	17	26	T

	Pacific Coast								
Morrow 1980	North American Pacific Coast	Little Port Walter	56°23'00"N, 134°38'30"W	*Salvelinus malma*	DVCH	DVCH	17	25.8	T
Morrow 1980	North American Pacific Coast	Palmer Creek	60°51'15"N, 149°37'55"W	*Salvelinus malma*	DVCH	DVCH	18	23.5	T
Morrow 1980	North American Pacific Coast	Shumagin Islands	55°10'N, 160°00'W	*Salvelinus malma*	DVCH	DVCH	16.8	25.9	T
Morrow 1980	North American Pacific Coast	Sitka area		*Salvelinus malma*	DVCH	DVCH	17	29.3	T
Morrow 1980	North American Pacific Coast	Tutka Bay	59°27'30"N, 151°23'W	*Salvelinus malma*	DVCH	DVCH	17.8	26.5	T
Morrow 1980	North American Pacific Coast	Unalaska Island	52°35'N, 166°05'W	*Salvelinus malma*	DVCH	DVCH	18.1	26.3	T
Morrow 1980	North American Pacific Coast	Unalaska Island	52°35'N, 166°05'W	*Salvelinus malma*	DVCH	DVCH	19.3	28.4	T
Morrow 1980	Russia	Commander Islands	55°N, 166°E	*Salvelinus malma*	DVCH	DVCH	20.7	31.6	T
Morrow 1980	Russia	Icha River, Kamchatka	55°30'N, 156°E	*Salvelinus malma*	DVCH	DVCH	20	28	T
Morrow 1980	Russia	Petropavlovsk	52°30'N, 158°30'E	*Salvelinus malma*	DVCH	DVCH	18.3	22.8	T

Morrow 1980	Western North America	Elson Lagoon	71°15'N, 155°51'W	*Salvelinus malma*	DVCH	DVCH	23	39	F
Morrow 1980	Western North America	Lake Aleknagik	57°17'N, 158°37'W	*Salvelinus alpinus*	ARCH	ARCH	23.5	50.2	T
Morrow 1980	Western North America	Ponds near km 128, Mt. McKinley Park road	63°26'15"N, 150°45'W	*Salvelinus alpinus*	ARCH	ARCH	23.1	46.6	T
Morrow 1980	Western North America	Wonder Lake Mt. McKinley Natl. Park	63°28'30"N, 150°52'30"W	*Salvelinus alpinus*	ARCH	ARCH	21.5	46.5	T
Morrow 1980	Western North America	Berry Creek	63°42'10"N, 144°23'20"W	*Salvelinus malma*	DVCH	DVCH	19.7	21.7	T
Morrow 1980	Western North America	Contact Creek	68°09'N, 151°44'W	*Salvelinus malma*	DVCH	DVCH	21.3	28	T
Morrow 1980	Western North America	Contact Creek	68°08'N, 151°44'W	*Salvelinus malma*	DVCH	DVCH	20	30	T
Morrow 1980	Western North America	Dry Creek	63°42'N, 144°34'05"W	*Salvelinus malma*	DVCH	DVCH	21	24.4	T
Morrow 1980	Western North America	Golsova River	63°34'N, 161°04'W	*Salvelinus malma*	DVCH	DVCH	20.5	25.5	T
Morrow 1980	Western North America	Grant Creek	65°13'N, 152°56'W	*Salvelinus malma*	DVCH	DVCH	19	24	T
Morrow 1980	Western North America	Hutlinana Creek	65°00'N, 150°20'W	*Salvelinus malma*	DVCH	DVCH	20.4	25.2	T
Morrow 1980	Western North America	Ivishak River	69°30'N, 148°30'W	*Salvelinus malma*	DVCH	DVCH	21	28.4	T

Morrow 1980	Western North America	Kelly River	67°55'N, 162°21'W	*Salvelinus malma*	DVCH	DVCH	21.8	32	T
Morrow 1980	Western North America	Kobuk River	66°54'N, 156°38'W	*Salvelinus malma*	DVCH	DVCH	21	31	T
Morrow 1980	Western North America	Kotzebue	66°54'N, 162°35'W	*Salvelinus malma*	DVCH	DVCH	23	27.3	T
Morrow 1980	Western North America	Lake Aleknagik	59°19'N, 158°43'W	*Salvelinus malma*	DVCH	DVCH	18.6	25.4	T
Morrow 1980	Western North America	Little Minook Creek	65°27'30"N, 156°06'W	*Salvelinus malma*	DVCH	DVCH	20.6	25.6	T
Morrow 1980	Western North America	Little Tok River	63°05'N, 143°22'W	*Salvelinus malma*	DVCH	DVCH	17.9	22	T
Morrow 1980	Western North America	Point Barrow	71°23'29"N, 156°28'30"W	*Salvelinus malma*	DVCH	DVCH	21	26	T
Morrow 1980	Western North America	Prudhoe Bay	70°22'N, 148°22'W	*Salvelinus malma*	DVCH	DVCH	21.7	33.3	T
Morrow 1980	Western North America	Revine Creek	63°40'N, 148°40'W	*Salvelinus malma*	DVCH	DVCH	20.7	25.5	T
Morrow 1980	Western North America	Riley Creek	63°43'30"N, 148°53'W	*Salvelinus malma*	DVCH	DVCH	20	31	T
Morrow 1980	Western North America	Ruby Creek	65°24'30"N, 158°08'W	*Salvelinus malma*	DVCH	DVCH	22.3	24.7	T
Morrow 1980	Western North America	St Matthew Island	60°24'N, 172°42'W	*Salvelinus malma*	DVCH	DVCH	20	35	T

Morrow 1980	Western North America	Sunset Creek	64°32'N, 165°33'W	*Salvelinus malma*	DVCH		DVCH	21.4	26.6	T
Morrow 1980	Western North America	Tulugak Lake	68°17'N, 151°28'W	*Salvelinus malma*	DVCH		DVCH	20	26.1	T
Personal Communication	Central Canadian Arctic	Coppermine River 2020	67°46'48"N, 115°04'48"W	*Salvelinus alpinus*	ARCH	anadromous	ARCH	22.5	30.6	F
Personal Communication	Central Canadian Arctic	Fish Fence		*Salvelinus alpinus*	ARCH	anadromous	ARCH	19.3	25.5	F
Personal Communication	Central Canadian Arctic	Fubar Lake		*Salvelinus alpinus*	ARCH	landlocked	ARCH	18.7	29.7	F
Personal Communication	Central Canadian Arctic	Lake M		*Salvelinus alpinus*	ARCH	landlocked	ARCH	17.5	37	F
Personal Communication	Central Canadian Arctic	Nearly Nothing		*Salvelinus alpinus*	ARCH	landlocked	ARCH	21	34.3	F
Personal Communication	Central Canadian Arctic	Roberts Lake + Outflow		*Salvelinus alpinus*	ARCH	anadromous	ARCH	21.6	30.4	F
Personal Communication	Central Canadian Arctic	Bernard River 1993	73°31'48.0"N, 124°04'48.0"W	*Salvelinus alpinus*	ARCH		ARCH	25	33.6	F
Personal Communication	Central Canadian Arctic	Bernard River 1994	73°31'48.0"N, 124°04'48.0"W	*Salvelinus alpinus*	ARCH		ARCH	24.5	32.9	F
Personal Communication	Central Canadian Arctic	30 Mile Lake 1987	69°16'12"N, 108°W	*Salvelinus alpinus*	ARCH		ARCH	24.6	49	T
Personal Communication	Central Canadian Arctic	30 Mile Lake 1993	69°16'12"N, 108°W	*Salvelinus alpinus*	ARCH		ARCH	26	45.1	T

Personal Communication	Central Canadian Arctic	Bernard Harbour 2000	68°46’59.9 N, 114°46’59.9 W	*Salvelinus alpinus*	ARCH		ARCH	25.6	42.5	T
Personal Communication	Central Canadian Arctic	Bernard Harbour 2003	68°46’59.9N, 114°46’59.9 W	*Salvelinus alpinus*	ARCH		ARCH	25.9	45.2	T
Personal Communication	Central Canadian Arctic	Byron Bay 1987	69°04'12"N, 109°13'48"W	*Salvelinus alpinus*	ARCH		ARCH	28	45.5	T
Personal Communication	Central Canadian Arctic	Byron Bay 1996	69°04'12"N, 109°13'48"W	*Salvelinus alpinus*	ARCH		ARCH	26.4	44.5	T
Personal Communication	Central Canadian Arctic	Coppermine River 1994	67°46'48"N, 115°04'48"W	*Salvelinus alpinus*	ARCH		ARCH	25.2	41.3	T
Personal Communication	Central Canadian Arctic	Coppermine River 2003	67°46'48"N, 115°04'48"W	*Salvelinus alpinus*	ARCH		ARCH	25.3	38.6	T
Personal Communication	Central Canadian Arctic	Coppermine River 2019	67°46'48"N, 115°04'48"W	*Salvelinus alpinus*	ARCH	anadromous	ARCH	22.7	36	T
Personal Communication	Central Canadian Arctic	Darnley Bay	69°25'43.8"N 124°00'45.5"W	*Salvelinus alpinus*	ARCH		ARCH	25.7	33.8	T
Personal Communication	Central Canadian Arctic	Ekalluk River 1988	69°25'12"N, 106°16'48"W	*Salvelinus alpinus*	ARCH		ARCH	26.7	48.3	T
Personal Communication	Central Canadian Arctic	Ekalluk River 1990	69°25'12"N, 106°16'48"W	*Salvelinus alpinus*	ARCH		ARCH	26.8	47.1	T
Personal Communication	Central Canadian Arctic	Ekalluk River 1991	69°25'12"N, 106°16'48"W	*Salvelinus alpinus*	ARCH		ARCH	26.4	47.1	T
Personal Communication	Central Canadian Arctic	Ekalluk River 1992	69°25'12"N, 106°16'48"W	*Salvelinus alpinus*	ARCH		ARCH	24.9	43.8	T

Personal Communication	Central Canadian Arctic	Ekalluk River 1993	69°25'12"N, 106°16'48"W	*Salvelinus alpinus*	ARCH	ARCH	26.5	45.4	T
Personal Communication	Central Canadian Arctic	Ekalluk River 1994	69°25'12"N, 106°16'48"W	*Salvelinus alpinus*	ARCH	ARCH	26.8	44.6	T
Personal Communication	Central Canadian Arctic	Ferguson Lake 1987	69°22'12"N, 105°02'60"W	*Salvelinus alpinus*	ARCH	ARCH	26.8	48.6	T
Personal Communication	Central Canadian Arctic	Ferguson Lake 1996	69°22'12"N, 105°02'60"W	*Salvelinus alpinus*	ARCH	ARCH	25.5	44.8	T
Personal Communication	Central Canadian Arctic	Halovik River	69°05'24"N, 107°03'36"W	*Salvelinus alpinus*	ARCH	ARCH	27.1	49.5	T
Personal Communication	Central Canadian Arctic	Kagloryuak River 1989	70°17'60"N, 111°24'W	*Salvelinus alpinus*	ARCH	ARCH	27.1	40.4	T
Personal Communication	Central Canadian Arctic	Kagloryuak River 1998	70°17'60"N, 111°24'W	*Salvelinus alpinus*	ARCH	ARCH	23.8	45.2	T
Personal Communication	Central Canadian Arctic	Kitiga Lake	69°08'24"N, 105°22'12"W	*Salvelinus alpinus*	ARCH	ARCH	26.7	45.3	T
Personal Communication	Central Canadian Arctic	Kugaryuak River 2001	67°42'N, 113°17'24"W	*Salvelinus alpinus*	ARCH	ARCH	27.1	42.6	T
Personal Communication	Central Canadian Arctic	Kugaryuak River 2003	67°42'N, 113°17'24"W	*Salvelinus alpinus*	ARCH	ARCH	26.8	40.2	T
Personal Communication	Central Canadian Arctic	Kuujjua River	71°13'48"N, 116°31'48"W	*Salvelinus alpinus*	ARCH	ARCH	26	44.5	T
Personal Communication	Central Canadian Arctic	Kuuk River	70°34'12"N, 112°37'48"W	*Salvelinus alpinus*	ARCH	ARCH	26.7	41.4	T

Personal Communication	Central Canadian Arctic	Lauchlan River 1992	68°34'12"N, 108°19'12"W	*Salvelinus alpinus*	ARCH	ARCH	26.4	48.1	T
Personal Communication	Central Canadian Arctic	Lauchlin River 1993	68°34'12"N, 108°19'12"W	*Salvelinus alpinus*	ARCH	ARCH	27.5	47	T
Personal Communication	Central Canadian Arctic	Murky Lake		*Salvelinus alpinus*	ARCH	ARCH	22	40.8	T
Personal Communication	Central Canadian Arctic	Nalogayuk River	70°13'12"N, 112°13'12"W	*Salvelinus alpinus*	ARCH	ARCH	27.4	45.1	T
Personal Communication	Central Canadian Arctic	Rymer Point	69°01'12"N, 113°15'W	*Salvelinus alpinus*	ARCH	ARCH	26	47.4	T
Personal Communication	Central Canadian Arctic	Surrey Lake	69°40'12"N, 106°40'12"W	*Salvelinus alpinus*	ARCH	ARCH	25.8	47.6	T
Personal Communication	Central Canadian Arctic	Surrey River	69°16'12"N, 106°24'W	*Salvelinus alpinus*	ARCH	ARCH	26.4	46.9	T
Personal Communication	Central Canadian Arctic	Capron Lake	71°48'48"N, 124°13'12"W	*Salvelinus alpinus*	ARCH	ARCH	29.3	40.2	T
Personal Communication	Central Canadian Arctic	Carpenter Lake	71°49'12"N, 124°28'12"W	*Salvelinus alpinus*	ARCH	ARCH	26	42	T
Personal Communication	Central Canadian Arctic	Fish Lake 1993	71°49'48"N, 124°34'48"W	*Salvelinus alpinus*	ARCH	ARCH	27.3	43.3	T
Personal Communication	Central Canadian Arctic	Fish Lake 1998	71°49'48"N, 124°34'48"W	*Salvelinus alpinus*	ARCH	ARCH	26.3	44.1	T
Personal Communication	Central Canadian Arctic	Kuptan Lake 1992	71°50'60"N, 125°19'48"W	*Salvelinus alpinus*	ARCH	ARCH	30.1	41.7	T

Personal Communication	Central Canadian Arctic	Kuptan Lake 1994	71°50'60"N, 125°19'48"W	*Salvelinus alpinus*	ARCH	ARCH	29.5	43.4	T
Personal Communication	Central Canadian Arctic	Middle Lake	71°49'48"N, 125°19'48"W	*Salvelinus alpinus*	ARCH	ARCH	28.1	43.1	T
Personal Communication	Central Canadian Arctic	Raddi Lake	71°40'12"N, 123°45'W	*Salvelinus alpinus*	ARCH	ARCH	26.5	41	T
Personal Communication	Central Canadian Arctic	Sachs Harbour	71°58'12"N, 125°15'W	*Salvelinus alpinus*	ARCH	ARCH	28.5	41.3	T
Personal Communication	Central Canadian Arctic	Sachs River	71°58'12"N, 125°05'60"W	*Salvelinus alpinus*	ARCH	ARCH	28.5	43.5	T
Personal Communication	Central Canadian Arctic	Seal Camp Lake	71°47'60"N, 124°28'12"W	*Salvelinus alpinus*	ARCH	ARCH	30.9	38.6	T
Personal Communication	Central Canadian Arctic	Thompson River, Lake 305	73°04'48"N, 118°15'W	*Salvelinus alpinus*	ARCH	ARCH	28	43.4	T
Personal Communication	Central Canadian Arctic	Tree River		*Salvelinus malma*	DVCH	DVCH	23.5	29.6	T
Personal Communication	Eastern North America	Anderson Bay 1993	68°54'N, 104°15'W	*Salvelinus alpinus*	ARCH	ARCH	26.5	50.2	T
Personal Communication	Eastern North America	Anderson Bay L. 1994	68°54'N, 104°15'W	*Salvelinus alpinus*	ARCH	ARCH	26.5	50.1	T
Personal Communication	Eastern North America	Arrowsmith River	68°22'12"N, 90°19'48"W	*Salvelinus alpinus*	ARCH	ARCH	25.7	39.8	T
Personal Communication	Eastern North America	Becher River		*Salvelinus alpinus*	ARCH	ARCH	25	36.9	T

Personal Communication	Eastern North America	Char Lake	69°37'12"N, 103°34'48"W	*Salvelinus alpinus*	ARCH	ARCH	26.3	47.8	T
Personal Communication	Eastern North America	Diana River 1990	62°49'48"N, 92°22'12"W	*Salvelinus alpinus*	ARCH	ARCH	26	39.9	T
Personal Communication	Eastern North America	Diana River 1991	62°49'48"N, 92°22'12"W	*Salvelinus alpinus*	ARCH	ARCH	25.8	40.7	T
Personal Communication	Eastern North America	Ellice River	69°02'60"N, 103°58'48"W	*Salvelinus alpinus*	ARCH	ARCH	25.5	45.7	T
Personal Communication	Eastern North America	Family Lake	69°37'12"N, 103°34'48"W	*Salvelinus alpinus*	ARCH	ARCH	27.1	47.4	T
Personal Communication	Eastern North America	Freshwater Creek 1988	69°07'12"N, 105°W	*Salvelinus alpinus*	ARCH	ARCH	26.2	47	T
Personal Communication	Eastern North America	Freshwater Creek 1991	69°07'12"N, 105°W	*Salvelinus alpinus*	ARCH	ARCH	26.4	46.2	T
Personal Communication	Eastern North America	Freshwater Creek 1992	69°07'12"N, 105°W	*Salvelinus alpinus*	ARCH	ARCH	26.4	44	T
Personal Communication	Eastern North America	Freshwater Creek 1993	69°07'12"N, 105°W	*Salvelinus alpinus*	ARCH	ARCH	26.5	46	T
Personal Communication	Eastern North America	Freshwater Creek 1994	69°07'12"N, 105°W	*Salvelinus alpinus*	ARCH	ARCH	26.3	45.7	T
Personal Communication	Eastern North America	Greiner Lake	69°11'39.0"N, 104°54'20.0"W	*Salvelinus alpinus*	ARCH	ARCH	26.5	48	T
Personal Communication	Eastern North America	Jayco River 1990	69°43'12"N, 103°16'12"W	*Salvelinus alpinus*	ARCH	ARCH	26.3	45.9	T

Personal Communication	Eastern North America	Jayco River 1997	69°43'12"N, 103°16'12"W	*Salvelinus alpinus*	ARCH		ARCH	27.9	45.4	T
Personal Communication	Eastern North America	Keith Bay River	68°19'12"N, 88°16'12"W	*Salvelinus alpinus*	ARCH		ARCH	25.2	38.2	T
Personal Communication	Eastern North America	Kellett River	68°19'48"N, 90°04'48"W	*Salvelinus alpinus*	ARCH		ARCH	26	38.9	T
Personal Communication	Eastern North America	Meliadine River	62°52'48"N, 92°07'48"W	*Salvelinus alpinus*	ARCH		ARCH	24.9	39.6	T
Personal Communication	Eastern North America	Wishbone Lake	69°20'24"N, 104°05'60"W	*Salvelinus alpinus*	ARCH		ARCH	25.8	46.1	T
Personal Communication	Eastern North America	Sylvia Grinnell 2002	63°44'51.7"N, 68°34'30.3"W	*Salvelinus alpinus*	ARCH		ARCH	22.7	37.2	T
Personal Communication	Eastern North America	Sylvia Grinnell 2004	63°44'51.7"N, 68°34'30.3"W	*Salvelinus alpinus*	ARCH		ARCH	23.9	38.8	T
Personal Communication	Western North America	Tourist River		*Salvelinus alpinus*	ARCH		ARCH	24.7	38.3	T
Personal Communication	Western North America	Babbage River	68°44'50.5"N, 138°44'34.5"W	*Salvelinus malma*	DVCH	resident	DVCH	14.3	25.1	T
Personal Communication	Western North America	Babbage River	68°44'50.5"N, 138°44'34.5"W	*Salvelinus malma*	DVCH	anadromous	DVCH	19.5	27	T
Personal Communication	Western North America	Yukon		*Salvelinus malma*	DVCH		DVCH	14	23.6	T
Pichugin et al. 2008	Russia	Belaya River	47°25'N	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	20.6	19.6	T

Pichugin et al. 2008	Russia	Krasnaya River (Novoselka River)	47°40'N	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	20.4	22.1	T
Pichugin et al. 2008	Russia	Krasnaya River (Tym River)	50°36'N	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	21.4	24.3	T
Pichugin et al. 2008	Russia	Lake Mokhovoe	47°40'N	*Salvelinus malma krascheninnikovi*	DVCH	lacustrine	DVCH	22.4	21.2	T
Pichugin et al. 2008	Russia	Lake Mokhovoe	47°40'N	*Salvelinus malma krascheninnikovi*	DVCH	lacustrine	DVCH	22.5	23.2	T
Pichugin et al. 2008	Russia	Lake Osochnoe	47°40'N	*Salvelinus malma krascheninnikovi*	DVCH	lacustrine	DVCH	22.4	21.2	T
Pichugin et al. 2008	Russia	Lake Osochnoe	47°40'N	*Salvelinus malma krascheninnikovi*	DVCH	lacustrine	DVCH	22.5	23.2	T
Pichugin et al. 2008	Russia	Longari River	50°36'N	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	21.8	22.3	T
Pichugin et al. 2008	Russia	Pochka River	47°40'N	*Salvelinus malma krascheninnikovi*	DVCH	lacustrine	DVCH	21.3	23	T
Pichugin et al. 2008	Russia	Rogatka River	47°00'N	*Salvelinus malma krascheninnikovi*	DVCH	brook	DVCH	20.1	19.1	T
Pichugin et al. 2008	Russia	Tym River	50°40'N	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	22.2	23.3	T
Reist 1989	Western North America	western Canadian Arctic		probably *Salvelinus malma malma*	DVCH		DVCH	21.4	29.2	T
Reist 1989	Western North America	Babbage River (upper)		probably *Salvelinus malma malma*	DVCH	isolated stream-resident	DVCH	20.6	23.1	T

					adult spawner				
Reist 1989	Western North America	Babbage River (upper)	*probably Salvelinus malma malma*	DVCH	isolated juvenile	DVCH	20.4	20.7	T
Reist 1989	Western North America	Cache Creek	*probably Salvelinus malma malma*	DVCH	anadromous adult spawner	DVCH	21.3	29.1	T
Reist 1989	Western North America	Cache Creek	*probably Salvelinus malma malma*	DVCH	anadromous large juvenile	DVCH	20.7	28.7	T
Reist 1989	Western North America	Cache Creek	*probably Salvelinus malma malma*	DVCH	small juvenile, likely anadromous	DVCH	21.4	29.7	T
Reist 1989	Western North America	Canoe River	*probably Salvelinus malma malma*	DVCH	anadromous adult spawner	DVCH	21.5	28.7	T
Reist 1989	Western North America	Firth River	*probably Salvelinus malma malma*	DVCH	anadromous adult spawner	DVCH	21.4	30.3	T
Reist 1989	Western North America	Joe Creek	*probably Salvelinus malma malma*	DVCH	anadromous adult spawner	DVCH	21.7	31.5	T
Reist 1989	Western North America	Joe Creek	*probably Salvelinus malma malma*	DVCH	residual adult spawner	DVCH	22	29.7	T
Reist 1989	Western North America	Rat River	*probably Salvelinus malma malma*	DVCH	anadromous adult resting	DVCH	20.8	29.7	T
Reist 1989	Western North America	Rat River	*probably Salvelinus malma malma*	DVCH	anadromous adult spawner	DVCH	21.4	31.7	T
Reist 1989	Western North America	Rat River	*probably Salvelinus malma malma*	DVCH	anadromous large juvenile	DVCH	21.4	29.7	T

Reist et al. 1995	Eastern North America	Lake Hazen	81°47'56.7"N, 71°00'40.0"W	*Salvelinus alpinus*	ARCH	small	ARCH	25.5	35.5	T
Reist et al. 1995	Eastern North America	Lake Hazen	81°47'56.7"N, 71°00'40.0"W	*Salvelinus alpinus*	ARCH	large	ARCH	25.7	38.2	T
Reist et al. 1997	Central Canadian Arctic	Cambridge Bay	69°06'30.6"N, 105°03'23.4"W	*Salvelinus alpinus*	ARCH		ARCH	26.4	48.4	T
Reist et al. 1997	Central Canadian Arctic	anadromous fish from rivers east of Mackenzie River		*Salvelinus alpinus*	ARCH		ARCH	27.1	42.8	T
Reist et al. 1997	Western North America	lacustrine char from west of Mackenzie River		*Salvelinus alpinus*	ARCH		ARCH	27.3	49.1	T
Reist et al. 1997	Western North America	residual char from west of Mackenzie River		*Salvelinus malma*	DVCH		DVCH	21.3	29.1	T
Reist et al. 1997	Western North America	anadromous fish from rivers west of Mackenzie River		*Salvelinus malma*	DVCH		DVCH	21.5	30.2	T
Reist et al. 1997	Western North America	isolated riverine char from west of Mackenzie River		*Salvelinus malma*	DVCH		DVCH	20.5	24.7	T
Reist et al. 1997	Western North America	Klutina River	61°57'19.1"N, 145°17'06.4"W	*Salvelinus malma*	DVCH		DVCH	18.4	26.3	T
Reist et al. 1997	Western North America	Nome River	64°29'03.1"N, 165°18'10.1"W	*Salvelinus malma*	DVCH		DVCH	21.7	28.1	T
Reshetnikov 1961	Russia	Lake Dalnii		*Salvelinus malma*	ARCH	lake resident	ARCH	26.7	48.4	T
Reshetnikov 1961	Russia	Paratunka River		*Salvelinus malma*	DVCH	lake and river	DVCH	21.8	32.8	T

Reshetnikov 1961	Russia	Paratunka River		*Salvelinus malma*	DVCH	diadromous	DVCH	22.1	28.9	T
Safronov and Skulyak 1996, in Pichugin et al. 2008	Russia	Anna River	47°05'21.2"N, 143°00'35.7"E	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	19.2	20.1	T
Safronov and Skulyak 1996, in Pichugin et al. 2008	Russia	Bakhura River	47°02'47.8"N, 143°01'56.3"E	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	18.8	19.9	T
Safronov and Skulyak 1996, in Pichugin et al. 2008	Russia	Bol'shaya Nyavan River	53°12'14.8"N, 141°50'24.4"E	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	19.5	22.5	T
Safronov and Skulyak 1996, in Pichugin et al. 2008	Russia	Irkir River upper reaches	53°12'14.8"N, 141°50'24.4"E	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	20.4	23	T
Safronov and Skulyak 1996, in Pichugin et al. 2008	Russia	Kashtanovka River		*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	20	19.8	T
Safronov and Skulyak 1996, in Pichugin et al. 2008	Russia	Lake Mokhovoe	47°50'33.2"N, 142°06'45.3"E	*Salvelinus malma krascheninnikovi*	DVCH	lacustrine	DVCH	21.4	22	T
Safronov and Skulyak 1996, in Pichugin et al. 2008	Russia	Lake Osochnoe	47°50'33.2"N, 142°06'45.3"E	*Salvelinus malma krascheninnikovi*	DVCH	lacustrine	DVCH	21.9	22	T
Safronov and Skulyak 1996, in Pichugin et al. 2008	Russia	Lake Skrytoe	54°45'28.3"N, 20°14'35.2"E	*Salvelinus malma krascheninnikovi*	DVCH	lacustrine	DVCH	20	21.1	T
Safronov and Skulyak 1996,	Russia	Mayakovka River	47°50'33.2"N, 142°06'45.3"E	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	22.1	24.2	T

in Pichugin et al. 2008										
Safronov and Skulyak 1996, in Pichugin et al. 2008	Russia	Shpakovka River		*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	20.3	17.9	T
Safronov and Skulyak 1996, in Pichugin et al. 2008	Russia	Yastrebok River	47°34'01.5"N, 141°58'02.7"E	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	21.1	24.4	T
Safronov and Zvezdov 2005, in Pichugin et al. 2008	Russia	Tengi River	52°35'09.6"N, 141°49'37.4"E	*Salvelinus malma krascheninnikovi*	DVCH	liman-riverine	DVCH	19.9	20.2	T
Safronov and Zvezdov 2005, in Pichugin et al. 2008	Russia	Tengi River	52°35'09.6"N, 141°49'37.4"E	*Salvelinus malma krascheninnikovi*	DVCH	riverine	DVCH	20.5	22.1	T
Safronov and Zvezdov 2005, in Pichugin et al. 2008	Russia	Tengi River	52°35'09.6"N, 141°49'37.4"E	*Salvelinus malma krascheninnikovi*	DVCH	migratory	DVCH	19.2	24	T
Samusenok et al. 2006	Russia	Lake Frolikha		*Salvelinus alpinus*	ARCH		ARCH	30.6	42.3	T
Samusenok et al. 2006	Russia	Lake Svetlinskoe		*Salvelinus alpinus*	ARCH	dwarf	ARCH	34.8	37.1	T
Samusenok et al. 2006	Russia	Lake Svetlinskoe		*Salvelinus alpinus*	ARCH	small	ARCH	33.7	41	T
Savvaitova 1961	Russia	western Chukotia sea		*Salvelinus alpinus*	ARCH		ARCH	23.5	33.6	F
Savvaitova 1961	Russia	Dalneye Lake		*Salvelinus alpinus*	ARCH	lake resident	ARCH	26.6	48.8	T
Savvaitova 1961	Russia	western Chukotia lake		*Salvelinus alpinus*	ARCH		ARCH	23.4	41.5	T
Savvaitova 1961	Russia	Lake-river systems in Kamchatka		*Salvelinus alpinus*	ARCH	lake-river	DVCH	22	32.2	T

Savvaitova 1961	Russia	Taryinskaya Bay		*Salvelinus alpinus*	ARCH	diadromous	DVCH	22.1	28.8	T
Savvaitova 1961	Russia	eastern Chukotia sea		*Salvelinus malma*	DVCH		DVCH	23.4	26.4	T
Savvaitova 1961, in Behnke 1980	Russia	lake on Aion Island		*ambiguous Salvelinus*	ARCH		ARCH	22.5	41.5	T
Savvaitova 1961, in Behnke 1981	Russia	lake near the sea in the Chanunsk region		*ambiguous Salvelinus*	ARCH		ARCH	23.4	37	T
Savvaitova 1961, in Behnke 1982	Russia	anadromous stock in Chanunsk region		*ambiguous Salvelinus*	DVCH	anadromous	DVCH	23.5	33.6	T
Savvaitova and Vasil'yev 1976	Russia	Lake Nachikinskoye		*Salvelinus alpinus*	ARCH	lake-river	DVCH	21.4	27	T
Savvaitova and Volobuyev 1978	Eastern North America	Ksewatin District, Chesterfield Inlet (museum collection)		*Salvelinus alpinus*	ARCH		ARCH	24.5	42	T
Savvaitova and Volobuyev 1978	North American Pacific Coast	Fern Creek (museum collection)		*Salvelinus malma*	DVCH		DVCH	19	32.5	T
Savvaitova and Volobuyev 1978	Western North America	Nelson Lake (museum collection)	66°29'34.1"N, 147°42'02.4"W	*Salvelinus alpinus*	ARCH		ARCH	24.3	33	F
Savvaitova and Volobuyev 1978	Western North America	Tolstoi Lake (museum collection)	62°57'12.1"N, 156°56'09.2"W	*Salvelinus alpinus*	DVCH		DVCH	22.1	27.7	T
Scanlon 2000	North American Pacific Coast	Becharof Lake Drainage	57°55'04.0"N, 156°26'01.2"W	*Salvelinus alpinus*	ARCH		ARCH	22.8	48.1	T
Scanlon 2000	North American Pacific Coast	Becharof Lake Drainage	57°55'04.0"N, 156°26'01.2"W	*Salvelinus malma*	DVCH		DVCH	20.7	26.9	T

Zhul'kov and Shershnev 1981, in Pichugin et al. 2008	Russia	Melkaya River	*Salvelinus malma krascheninnikovi*	DVCH	migratory	DVCH	21.2	22.6	T
Zhul'kov and Shershnev 1981, in Pichugin et al. 2008	Russia	Nerpichya River	*Salvelinus malma krascheninnikovi*	DVCH	migratory	DVCH	21.5	21.9	T
Zvezdov and Safronov 2003, in Pichugin et al. 2008	Russia	Lake Oktyabr'skoe	*Salvelinus malma krascheninnikovi*	DVCH	lacustrine-riverine	DVCH	17.2	23.6	T

D: Supplementary Information for Chapter 3

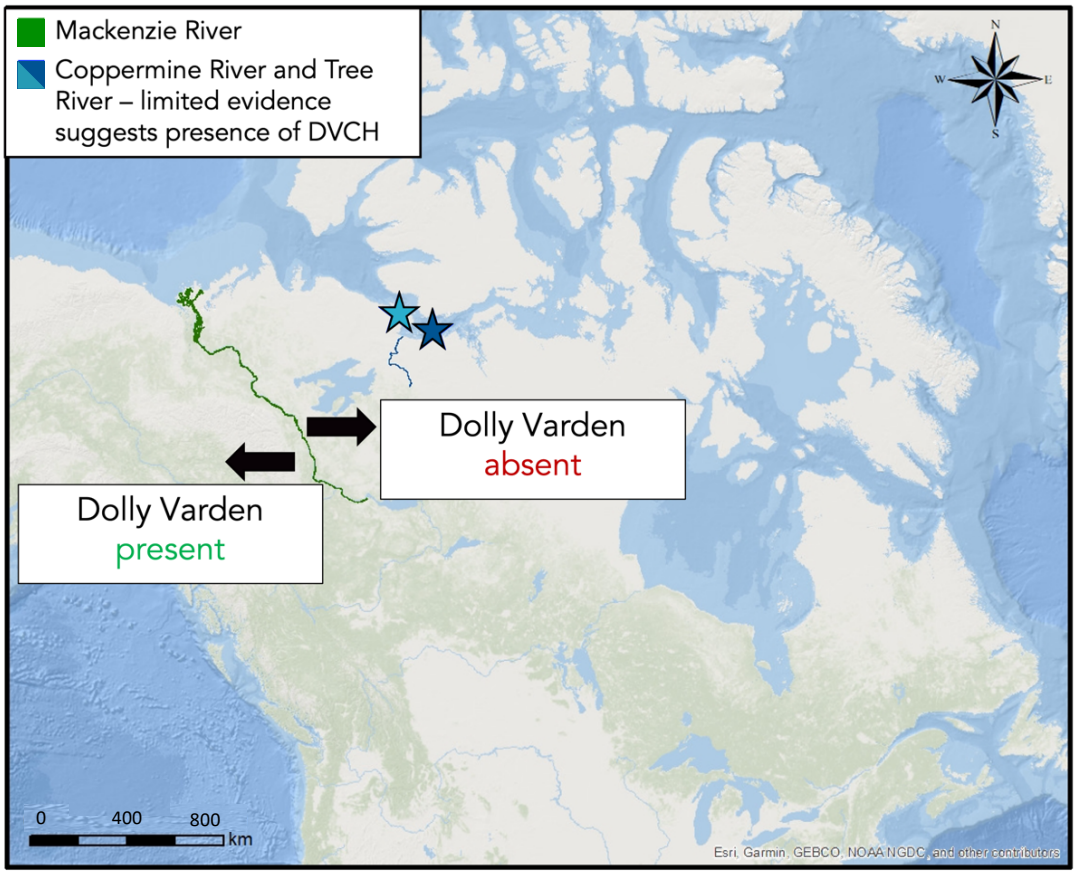


Figure D.1: *Map highlighting the Mackenzie River (green), the presumptive range boundary for Dolly Varden, and two populations east of the Mackenzie River, the Coppermine River (light blue) and Tree River (dark blue), where Dolly Varden have been suggested to occur.*



Figure D.2: *Example of char that have historically been caught in the Coppermine River (top) and char that are increasing in abundance in the system, as per fisher observations (bottom).*



Figure D.3: *Orientation of char for photographs and subsequent morphometrics.*

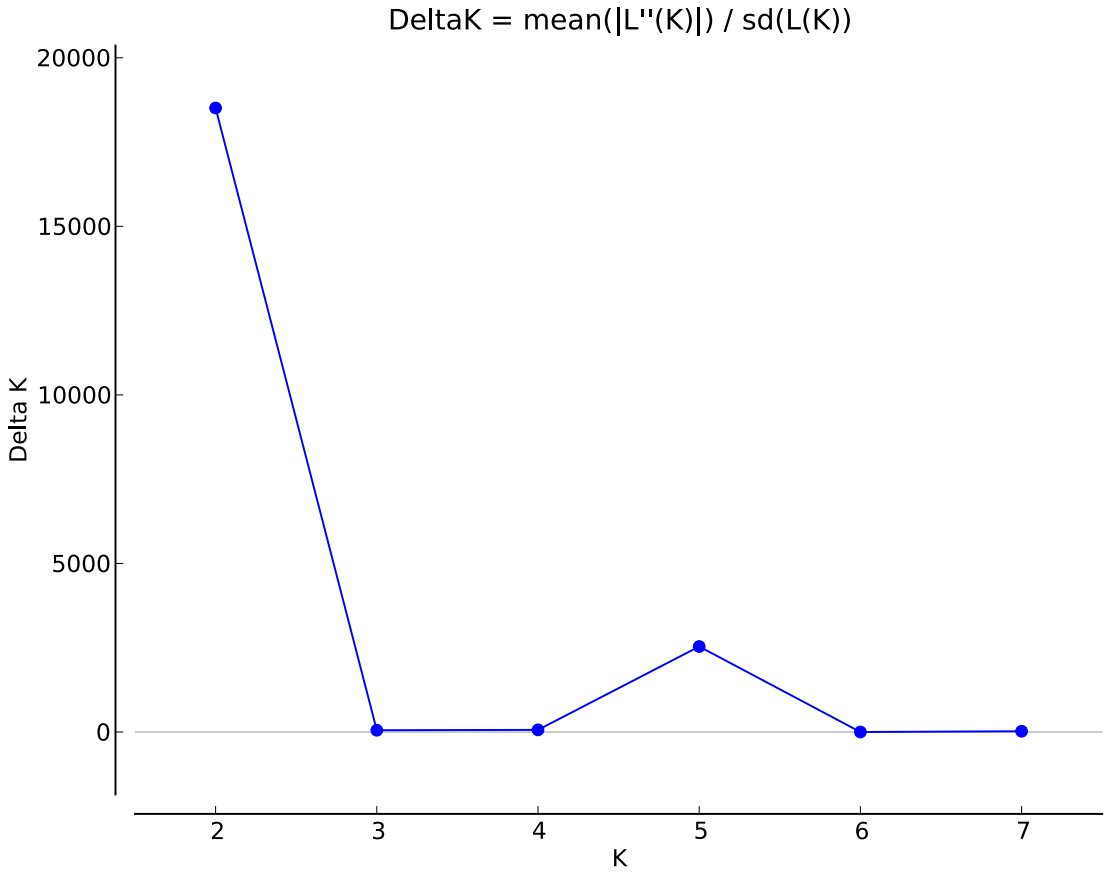


Figure D.4: *Delta K values used to select the best K value for our data.*

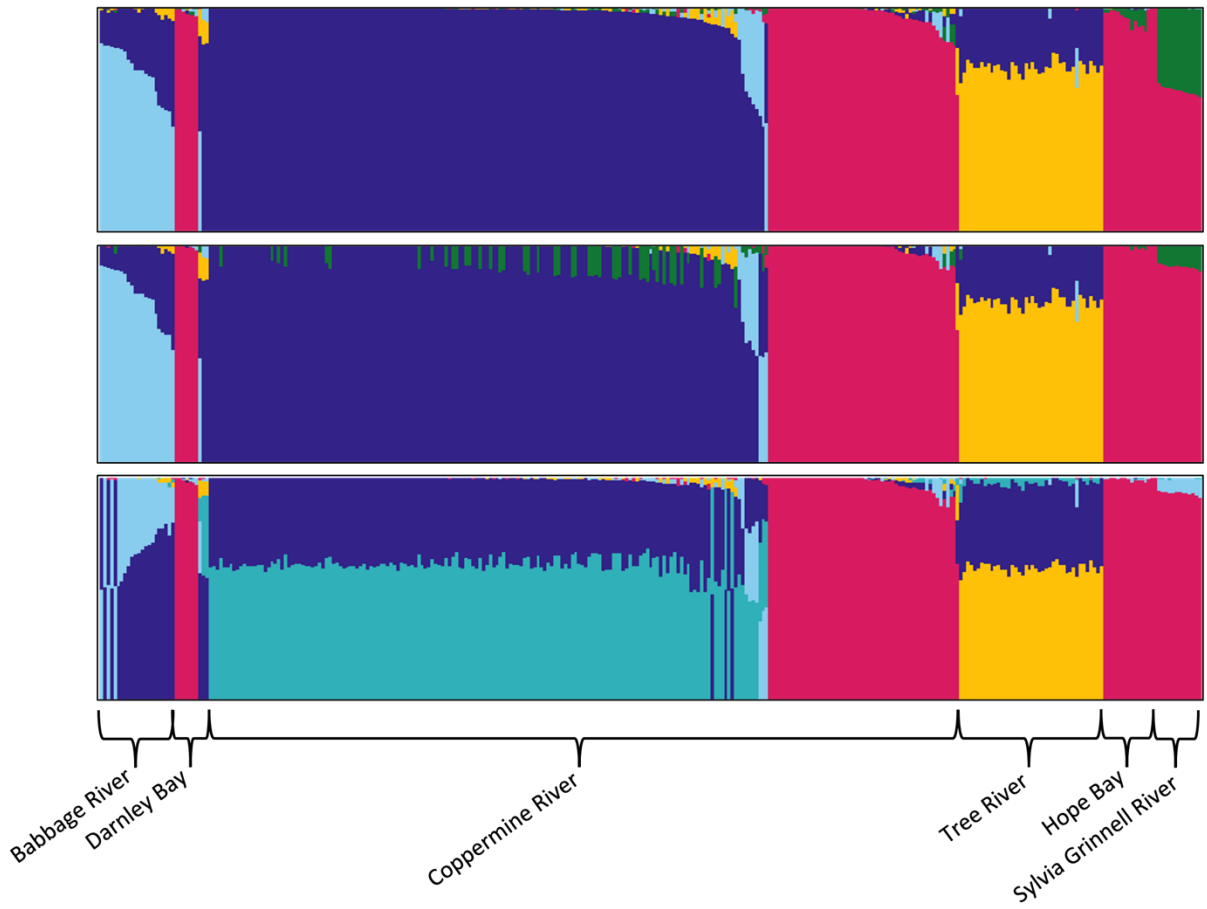


Figure D.5: *Three runs of STRUCTURE for K = 5, showing consistency in classifying samples as either Arctic char or Dolly Varden. Sample order is consistent across runs.*

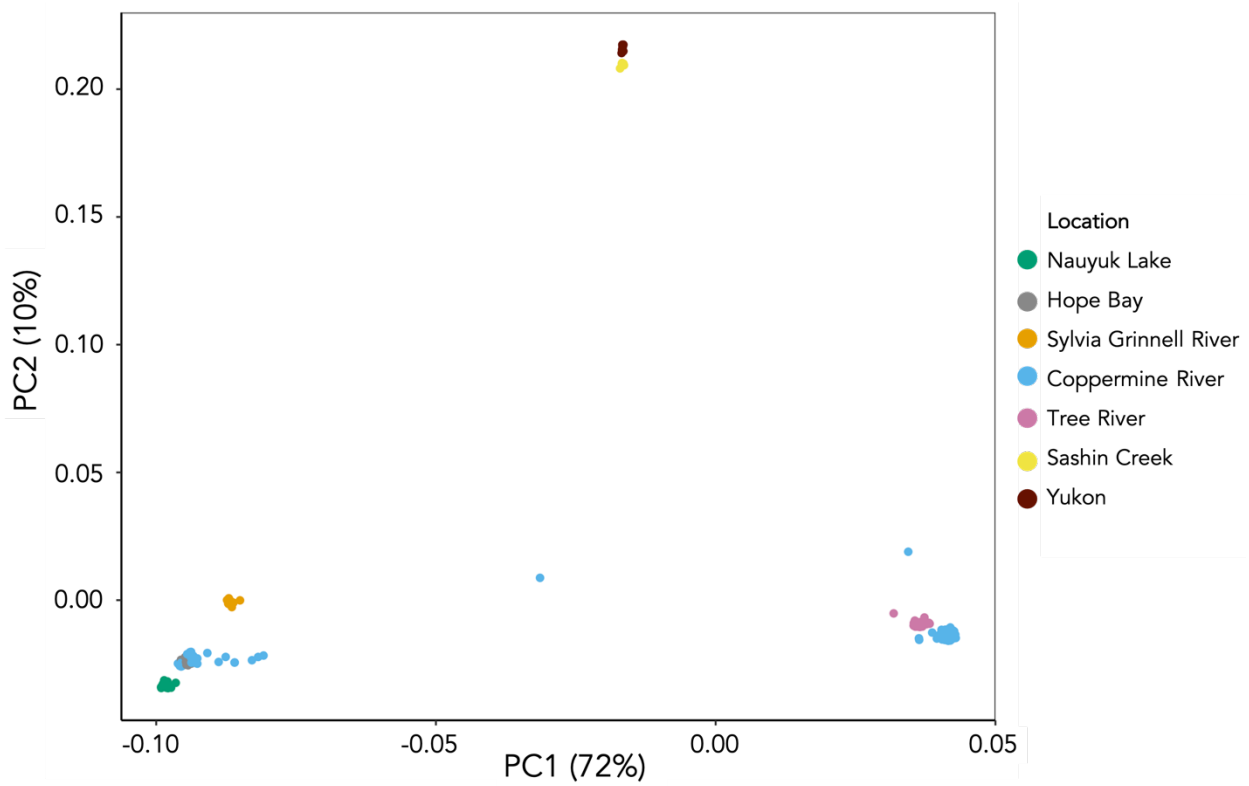


Figure D.6: *PCA showing that Dolly Varden from the Coppermine River (blue; right hand side) and Tree River (pink) are genetically distinct from southern form Dolly Varden (top center; Sashin Creek, yellow, and Yukon, maroon). Subsequent analyses with additional data confirmed that the Dolly Varden from the Coppermine and Tree rivers are northern form Dolly Varden.*

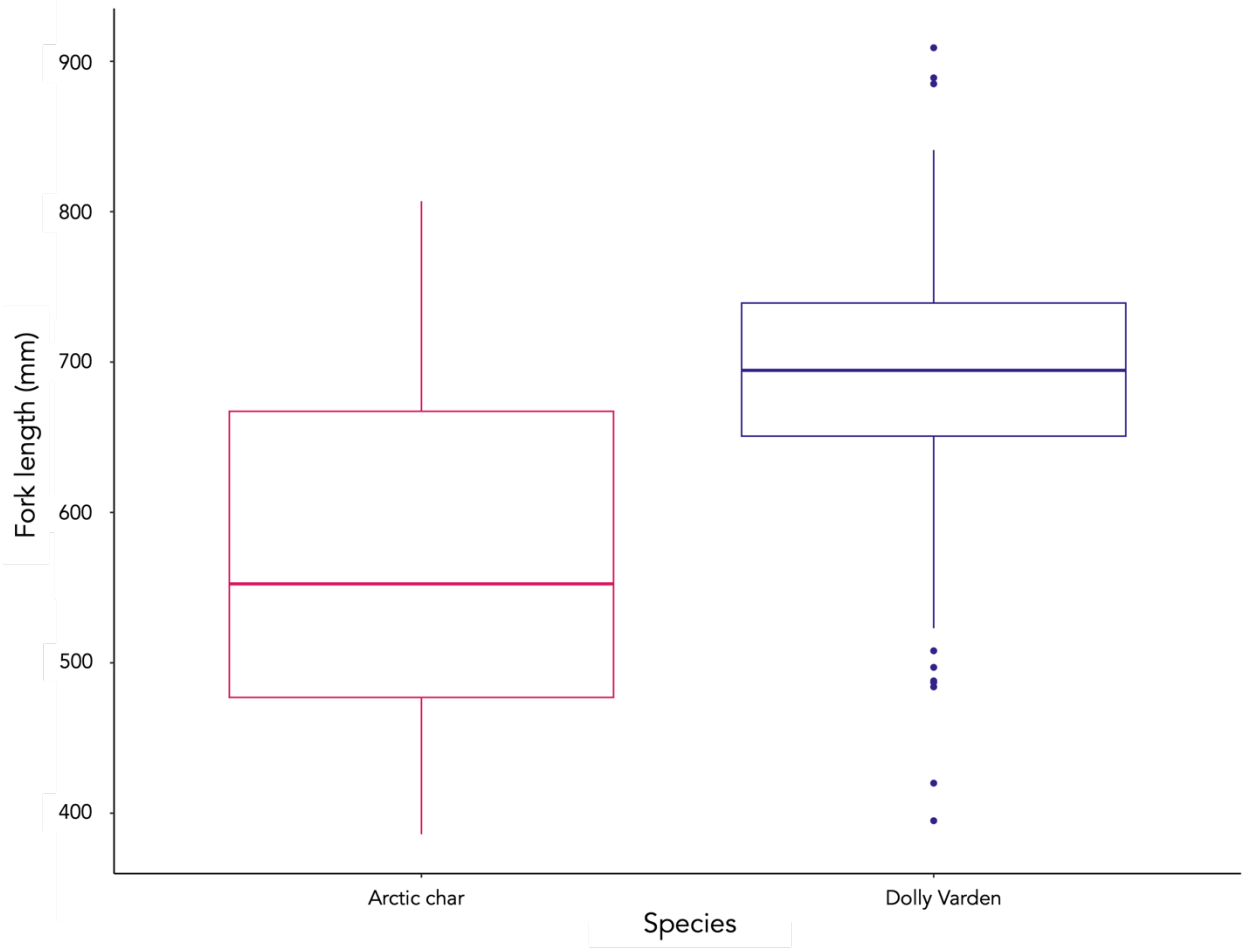


Figure D.7: *Differences in fork length between Arctic char and Dolly Varden, as identified using genomics, in the Coppermine River.*

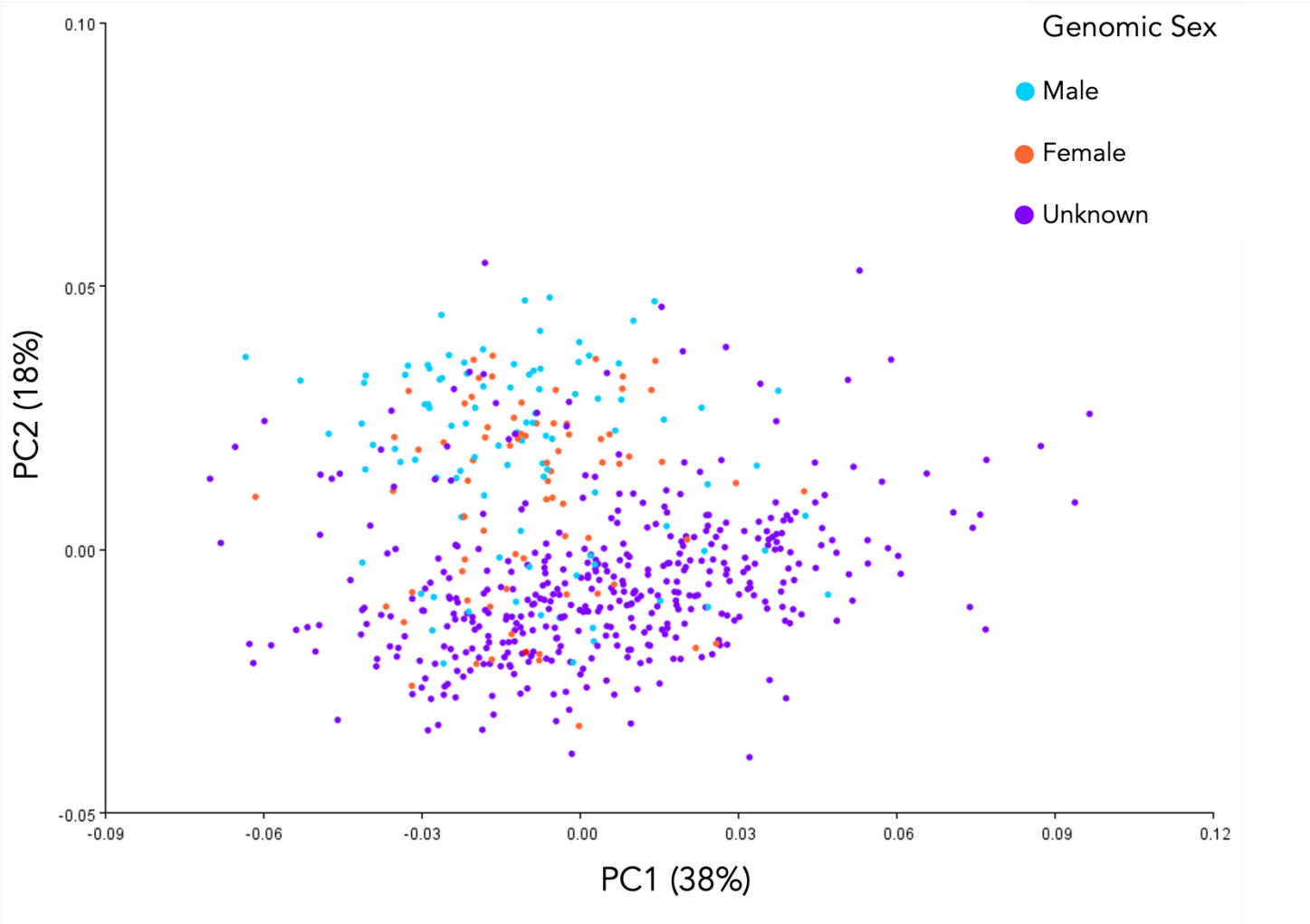


Figure D.8: *Principal component analysis on partial warp scores of 586 Arctic char and Dolly Varden. Neither variation on PC1 nor variation on PC2 appears to be driven by sex-specific differences.*

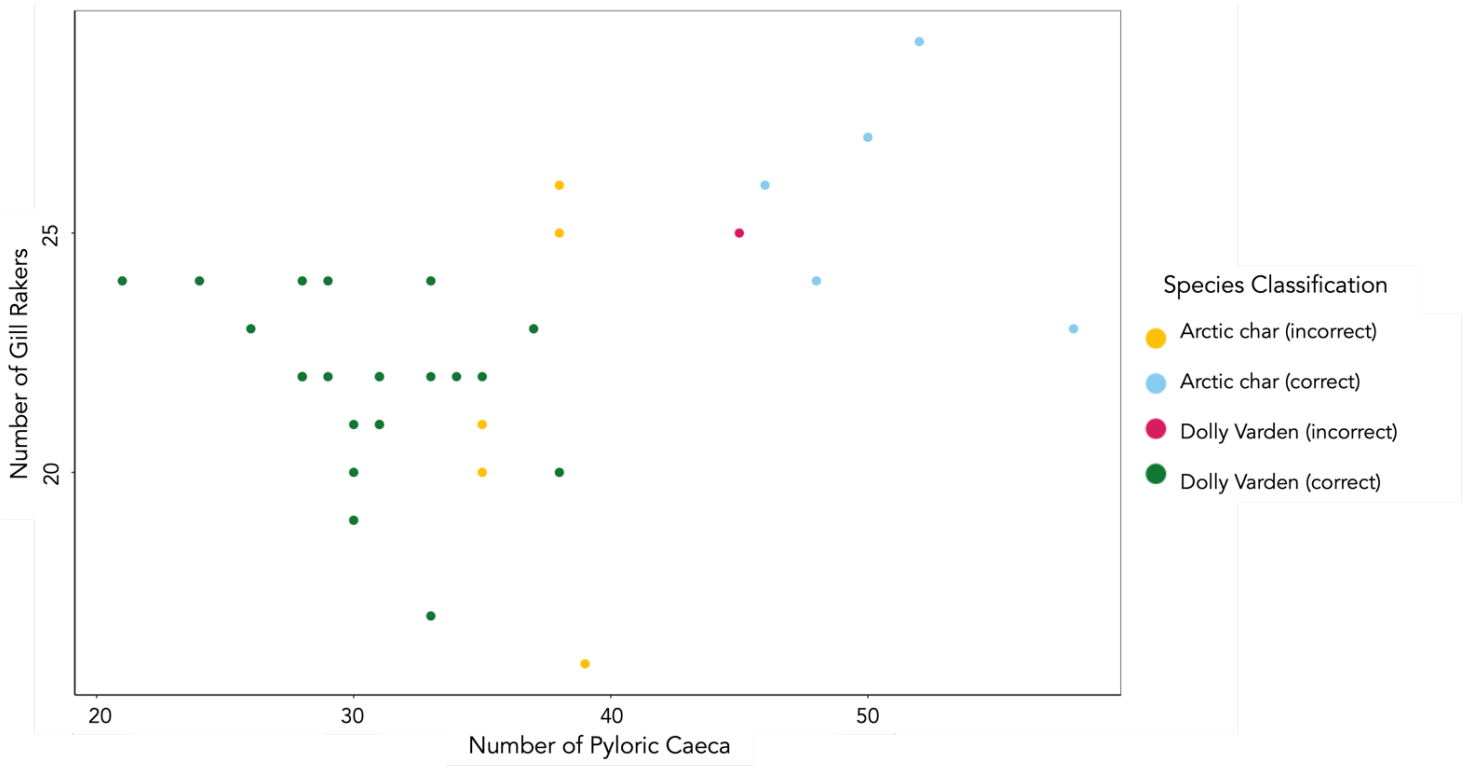


Figure D.9: *Individual meristics data for 34 Coppermine River char with corresponding genomics data. Symbol colors represent correct or incorrect LDA classification.*

Table D.1: *Number of samples available from each reference population of Arctic char and Dolly Varden included in this study.*

Species	Location	Number of Samples Available
Arctic char	Hope Bay	247
Arctic char	Darnley Bay	17
Arctic char	Sylvia Grinnell River	338
Dolly Varden	Babbage River	24

Table D.2: *Number of samples analyzed from each population of Arctic char and Dolly Varden included in this study, separated by DNA extraction method used.*

Location	Extraction Method	Tissue Type	Preservation Method	Number of Samples
Babbage River	Salt precipitation	Fin	Ethanol	24
Hope Bay	Salt precipitation	Skin	Frozen	8
Hope Bay	Qiagen DNeasy Blood and Tissue Kit	Skin	Frozen	8
Sylvia Grinnell River	Qiagen DNeasy Blood and Tissue Kit	Fin	Dried	13
Coppermine River	Phenol-chloroform	Fin	Dried (n = 6); ethanol (n = 2)	8
Coppermine River	Qiagen DNeasy Blood and Tissue Kit	Fin	Dried (n = 124); ethanol (n = 55)	179
Coppermine River	Salt precipitation	Fin	Dried (n = 40); ethanol (n = 4)	44
Darnley Bay	Salt precipitation	Fin	Ethanol	10
Tree River	Qiagen DNeasy Blood and Tissue Kit	Fin	Ethanol	15
Tree River	Salt precipitation	Fin	Ethanol	29

Table D.3: *Axiom Analysis Suite threshold settings, altered to retain full data set for downstream analyses.*

Name	Settings
species-type	Diploid
cr-cutoff	0
fld-cutoff	0
het-so-cutoff	-0.1
hom-ro-1-cutoff	0
hom-ro-2-cutoff	0
hom-ro-3-cutoff	-1

Table D.4: *Summary data on fork length, weight, and meristic characters for Coppermine River samples analyzed for genomics, and corresponding classification results for meristic and morphometric analyses.*

Sampling Location	Sample ID	Fork Length (mm)	Weight (g)	Genomic Species ID	Number of Pyloric Caeca	Number of Gill Rakers	Correctly Clustered - Meristics?	Photograph Included in Morphometric Analyses?	Correctly Classified - Morphometrics?
Coppermine River/ Coronation Gulf	8293	564	2200	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8535	626	2200	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8536	653	2700	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8537	618	2200	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8538	633	2500	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8539	718	2800	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8540	640	2500	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8545	604	2100	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8548	702	3100	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8549	680	3300	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8550	746	4300	DVCH	NA	NA	NA	N	NA

Coppermine River/ Coronation Gulf	8551	686	3000	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8553	746	3700	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8554	714	3400	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8555	683	2900	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8556	783	4700	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8559	716	4000	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8561	630	3100	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8566	679	2900	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8568	733	3300	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8569	735	3600	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8570	735	3800	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8573	885	6900	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8574	716	3500	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8847	662	3600	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8852	668	3100	DVCH	NA	NA	NA	N	NA

Coppermine River/ Coronation Gulf	8871	711	4600	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8877	684	3230	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8912	628	3590	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8913	674	2900	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8917	810	5460	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8925	682	3270	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8926	732	4020	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8927	539	1850	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9200	740	3550	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9201	707	3580	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9202	628	2690	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9203	644	2890	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9204	692	3550	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9205	781	3950	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9206	732	3700	DVCH	NA	NA	NA	Y	Y

Coppermine River/ Coronation Gulf	9207	729	3710	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9209	497	1070	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9210	728	3940	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9211	743	3660	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9214	702	2720	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9215	671	2650	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9216	716	3300	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9217	473	1120	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9218	386	540	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9220	741	3910	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9221	681	2390	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9222	667	2860	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9224	722	3840	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9225	645	2830	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9226	755	4160	DVCH	NA	NA	NA	Y	Y

Coppermine River/ Coronation Gulf	9227	701	3250	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9228	686	3190	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9229	658	3050	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9230	676	2800	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9231	695	2360	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9232	635	2180	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9233	590	1700	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9234	759	2890	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9235	650	2630	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9237	681	2870	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9238	810	5148	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9239	725	3200	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9240	787	4536	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9242	776	4800	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9243	663	3400	DVCH	NA	NA	NA	Y	Y

Coppermine River/ Coronation Gulf	9244	835	5140	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9245	685	3388	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9247	739	5044	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9248	565	1837	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9250	488	1297	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9251	395	1792	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9252	759	3900	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9254	707	3500	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9255	685	3000	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9256	546	1570	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9259	523	1680	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9260	909	7040	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9262	687	3270	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9263	670	3170	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9268	575	1820	DVCH	NA	NA	NA	Y	Y

Coppermine River/ Coronation Gulf	9270	688	3590	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9271	591	2040	DVCH	NA	NA	NA	Y	N
Coppermine River/ Coronation Gulf	9274	726	3150	DVCH	NA	NA	NA	Y	N
Coppermine River/ Coronation Gulf	9276	677	3380	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9279	650	2760	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9281	620	3020	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9283	696	3340	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9286	671	3370	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9289	487	1260	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9292	544	1730	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9293	508	1330	DVCH	35	22	Y	Y	Y
Coppermine River/ Coronation Gulf	9294	729	4020	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9295	684	2720	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9305	785	5150	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9306	718	3800	DVCH	NA	NA	NA	Y	Y

Coppermine River/ Coronation Gulf	9307	700	3150	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9312	462	1050	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9313	476	1070	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9314	469	1070	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9317	414	650	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9318	468	1180	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9320	688	3070	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9321	660	3260	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9333	471	1150	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9339	656	2810	DVCH	30	20	Y	N	NA
Coppermine River/ Coronation Gulf	9342	730	4100	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9343	542	1750	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9346	651	2620	DVCH	31	22	Y	N	NA
Coppermine River/ Coronation Gulf	9347	717	3090	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9348	740	3540	DVCH	NA	NA	NA	N	NA

Coppermine River/ Coronation Gulf	9352	712	4170	ARCH	52	29	Y	Y	Y
Coppermine River/ Coronation Gulf	9353	559	1740	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9354	495	1310	ARCH	58	23	Y	Y	Y
Coppermine River/ Coronation Gulf	9355	760	4510	DVCH	38	20	N	N	NA
Coppermine River/ Coronation Gulf	9357	750	4110	DVCH	33	17	Y	N	NA
Coppermine River/ Coronation Gulf	9358	803	5000	DVCH	30	19	Y	Y	Y
Coppermine River/ Coronation Gulf	9359	703	3790	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9360	572	1920	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9362	480	1040	ARCH	35	21	N	Y	Y
Coppermine River/ Coronation Gulf	9364	491	1120	ARCH	38	25	Y	Y	Y
Coppermine River/ Coronation Gulf	9365	452	1070	ARCH	39	16	Y	Y	Y
Coppermine River/ Coronation Gulf	9368	791	4700	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9369	817	4040	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9372	662	3720	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9375	715	3870	ARCH	50	27	Y	Y	Y

Coppermine River/ Coronation Gulf	9376	889	5530	DVCH	28	24	Y	Y	Y
Coppermine River/ Coronation Gulf	9377	757	4550	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9379	802	4520	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9381	752	4020	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9385	739	4360	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9387	730	4100	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9390	690	2960	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9392	586	2020	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9394	738	3970	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9397	709	5060	DVCH	24	24	Y	Y	Y
Coppermine River/ Coronation Gulf	9398	750	4050	DVCH	21	24	Y	Y	Y
Coppermine River/ Coronation Gulf	9399	569	1910	ARCH	48	24	Y	Y	Y
Coppermine River/ Coronation Gulf	9400	737	3980	DVCH	29	22	Y	Y	Y
Coppermine River/ Coronation Gulf	9404	669	3320	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9406	781	4510	DVCH	34	22	Y	Y	Y

Coppermine River/ Coronation Gulf	9407	749	4570	DVCH	37	23	Y	Y	Y
Coppermine River/ Coronation Gulf	9408	481	1010	ARCH	38	26	Y	Y	Y
Coppermine River/ Coronation Gulf	9415	766	4840	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9416	773	5250	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9417	813	4780	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9420	684	3900	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9421	536	1850	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9422	591	2060	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9429	480	1100	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9431	841	4280	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9432	730	3690	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9433	694	2670	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9436	800	5260	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9438	807	6810	ARCH	NA	NA	NA	Y	N
Coppermine River/ Coronation Gulf	9441	587	2120	ARCH	NA	NA	NA	Y	Y

Coppermine River/ Coronation Gulf	9442	740	3550	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9457	529	1340	DVCH	30	21	Y	Y	Y
Coppermine River/ Coronation Gulf	9461	667	2430	DVCH	26	23	Y	Y	Y
Coppermine River/ Coronation Gulf	9467	545	1670	DVCH	31	21	Y	Y	Y
Coppermine River/ Coronation Gulf	9472	546	1040	ARCH	35	20	N	Y	Y
Coppermine River/ Coronation Gulf	9478	575	1780	DVCH	33	24	Y	Y	Y
Coppermine River/ Coronation Gulf	9482	579	1730	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9486	643	1960	DVCH	28	22	Y	Y	Y
Coppermine River/ Coronation Gulf	9487	420	610	DVCH	28	22	Y	Y	Y
Coppermine River/ Coronation Gulf	9493	767	3510	DVCH	33	22	Y	Y	Y
Coppermine River/ Coronation Gulf	9502	604	2000	DVCH	28	22	Y	Y	Y
Coppermine River/ Coronation Gulf	9512	484	1060	DVCH	29	24	Y	Y	Y
Coppermine River/ Coronation Gulf	9517	680	2520	DVCH	31	22	Y	Y	Y
Coppermine River/ Coronation Gulf	8265	689	NA	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8267	700	NA	DVCH	NA	NA	NA	N	NA

Coppermine River/ Coronation Gulf	8268	669	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8270	824	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8272	611	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8273	689	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8275	684	NA	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8279	786	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8281	857	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8286	710	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8287	693	NA	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8290	658	NA	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8291	688	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8296	637	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8297	725	NA	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8298	779	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8299	721	NA	DVCH	NA	NA	NA	N	NA

Coppermine River/ Coronation Gulf	8300	664	NA	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8301	645	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8302	762	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8303	663	NA	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8306	638	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8310	720	NA	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8315	651	NA	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8318	679	NA	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	8945	776	NA	DVCH	31	21	Y	N	NA
Coppermine River/ Coronation Gulf	9212	700	NA	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9213	750	NA	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9223	NA	NA	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9253	NA	NA	DVCH	45	25	N	Y	Y
Coppermine River/ Coronation Gulf	9297	684	NA	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9298	545	NA	DVCH	NA	NA	NA	Y	Y

Coppermine River/ Coronation Gulf	9300	676	NA	DVCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9302	450	NA	ARCH	NA	NA	NA	Y	Y
Coppermine River/ Coronation Gulf	9363	392	650	HYBR	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9426	475	NA	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9454	NA	2370	ARCH	46	26	Y	Y	Y
Coppermine River/ Coronation Gulf	9508	NA	2650	DVCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9533	NA	1120	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9534	NA	990	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9535	NA	850	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9539	NA	520	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9540	NA	580	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9541	NA	510	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9546	NA	280	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9547	NA	460	ARCH	NA	NA	NA	N	NA
Coppermine River/ Coronation Gulf	9552	NA	630	ARCH	NA	NA	NA	N	NA

Table D.5: Summary data for Babbage River, Darnley Bay, Hope Bay, and Sylvia Grinnell River, for samples included in genomic and/or morphometric analyses.

Sampling Location	Sample ID	Year Sampled	Fork Length (mm)	Weight (g)	Genomics Data?	Genomic Species ID	Inferred Species ID	Photograph Included in Morphometric Analyses?	Correctly Classified - Morphometrics?
Babbage	A_1	2018	337	264.9	N		DVCH	Y	Y
Babbage	A_2	2018	437	850	Y	DVCH		Y	Y
Babbage	A_3	2018	440	800	N		DVCH	Y	Y
Babbage	A_4	2018	390	618.6	N		DVCH	Y	Y
Babbage	A_5	2018	357	429.2	N		DVCH	Y	Y
Babbage	A_6	2018	597	2350	Y	DVCH		Y	Y
Babbage	A_7	2018	359	410.5	Y	DVCH		Y	Y
Babbage	A_8	2018	449	905.9	N		DVCH	Y	Y
Babbage	A_9	2018	324	321.9	Y	DVCH		Y	Y
Babbage	A_10	2018	421	873.2	N		DVCH	Y	Y
Babbage	A_11	2018	400	751.3	Y	DVCH		Y	Y
Babbage	A_12	2018	466	1000	N		DVCH	Y	Y
Babbage	A_13	2018	307	309.1	N		DVCH	Y	Y
Babbage	A_14	2018	683	3450	Y	DVCH		Y	Y
Babbage	R_01	2018	299	279.1	Y	DVCH		Y	Y
Babbage	R_02	2018	258	181.8	N		DVCH	Y	Y
Babbage	R_03	2018	118	63.9	N		DVCH	Y	Y
Babbage	R_04	2018	177	56.7	N		DVCH	Y	Y
Babbage	R_05	2018	187	74.2	N		DVCH	Y	Y
Babbage	R_06	2018	208	92.8	Y	DVCH		Y	Y

Babbage	R_07	2018	206	87.5	N		DVCH	Y	Y
Babbage	R_08	2018	231	123.4	N		DVCH	Y	Y
Babbage	R_09	2018	203	82.7	Y	DVCH		Y	Y
Babbage	R_10	2018	224	108.3	Y	DVCH		Y	Y
Babbage	R_11	2018	166	48.9	N		DVCH	Y	Y
Babbage	R_12	2018	168	43.4	N		DVCH	Y	Y
Babbage	R_13	2018	173	53.8	N		DVCH	Y	Y
Babbage	R_14	2018	168	48.6	N		DVCH	Y	Y
Babbage	R_15	2018	174	47	Y	DVCH		Y	Y
Babbage	R_16	2018	175	49.4	Y	DVCH		Y	Y
Babbage	R_17	2018	203	71.3	N		DVCH	Y	Y
Babbage	R_18	2018	244	130.1	N		DVCH	Y	Y
Babbage	R_19	2018	245	121.3	Y	DVCH		Y	Y
Babbage	R_20	2018	206	81.6	Y	DVCH		Y	Y
Babbage	R_21	2018	234	122.3	Y	DVCH		Y	Y
Babbage	R_22	2018	236	119	N		DVCH	Y	Y
Babbage	R_23	2018	238	124.7	Y	DVCH		Y	Y
Babbage	A_46	2019	645	2750	Y	DVCH		Y	Y
Babbage	A_48	2019	600	2350	Y	DVCH		Y	Y
Babbage	A_50	2019	640	2400	N		DVCH	Y	Y
Babbage	A_51	2019	378	567.5	Y	DVCH		Y	Y
Babbage	A_52	2019	308	328.5	Y	DVCH		Y	Y
Babbage	A_53	2019	342	411	N		DVCH	Y	Y
Babbage	A_54	2019	498	1300	N		DVCH	Y	Y
Babbage	A_56	2019	490	1100	N		DVCH	Y	Y
Babbage	A_62	2019	536	1525	Y	DVCH		Y	Y
Babbage	A_63	2019	450	901.5	Y	DVCH		Y	Y
Babbage	A_67	2019	393	659	N		DVCH	Y	Y

Darnley Bay	2	2017	560	1550	Y	ARCH	NA	Y	Y
Darnley Bay	3	2017	530	1500	Y	ARCH	NA	Y	Y
Darnley Bay	5	2017	740	4800	Y	DVCH	NA	Y	Y
Darnley Bay	11	2017	700	3500	Y	ARCH	NA	Y	Y
Darnley Bay	14	2017	630	2300	Y	ARCH	NA	Y	Y
Darnley Bay	22	2017	630	3250	Y	DVCH	NA	Y	N
Darnley Bay	24	2017	360	2200	Y	ARCH	NA	Y	Y
Darnley Bay	26	2017	510	1600	Y	ARCH	NA	Y	Y
Darnley Bay	35	2017	490	1200	Y	ARCH	NA	Y	Y
Darnley Bay	36	2017	440	1150	Y	DVCH	NA	Y	Y
Hope Bay	55	2006	688	2515	N		ARCH	Y	Y
Hope Bay	60	2006	582	1730	N		ARCH	Y	Y
Hope Bay	65	2006	742	4130	N		ARCH	Y	Y
Hope Bay	447	2006	670	3317	N		ARCH	Y	Y
Hope Bay	453	2006	374	621	N		ARCH	Y	Y
Hope Bay	764	2006	392	682	Y	ARCH	NA	N	NA
Hope Bay	768	2006	330	216	Y	ARCH	NA	N	NA
Hope Bay	778	2006	257	159	Y	ARCH	NA	N	NA
Hope Bay	802	2006	640	3272	Y	ARCH		Y	Y
Hope Bay	803	2006	600	2759	N		ARCH	Y	Y
Hope Bay	804	2006	483	1342	Y	ARCH		Y	Y
Hope Bay	805	2006	400	709	N		ARCH	Y	Y
Hope Bay	807	2006	379	564	N		ARCH	Y	Y
Hope Bay	808	2006	274	243	Y	ARCH		Y	Y
Hope Bay	887	2006	380	588	Y	ARCH	NA	N	NA
Hope Bay	888	2006	499	1245	Y	ARCH	NA	N	NA
Hope Bay	889	2006	420	764	Y	ARCH		Y	Y
Hope Bay	890	2006	456	1058	Y	ARCH	NA	N	NA

Hope Bay	1001	2007	249	115	Y	ARCH	NA	N	NA
Hope Bay	1004	2007	801	5700	N		ARCH	Y	Y
Hope Bay	1005	2007	225	101	Y	ARCH	NA	N	NA
Hope Bay	1006	2007	219	80	Y	ARCH	NA	N	NA
Hope Bay	1019	2007	695	3612	N		ARCH	Y	Y
Hope Bay	1104	2007	362	403	N		ARCH	Y	Y
Hope Bay	1105	2007	668	3385	N		ARCH	Y	Y
Hope Bay	1107	2007	725	3030	N		ARCH	Y	Y
Hope Bay	1108	2007	660	2975	N		ARCH	Y	Y
Hope Bay	1168	2007	495	907	N		ARCH	Y	Y
Hope Bay	1170	2007	385	613	N		ARCH	Y	Y
Hope Bay	1186	2007	502	1255	N		ARCH	Y	Y
Hope Bay	1187	2007	476	1360	N		ARCH	Y	Y
Hope Bay	1188	2007	495	1220	N		ARCH	Y	Y
Hope Bay	1196	2007	636	3115	N		ARCH	Y	Y
Hope Bay	1199	2007	582	2845	N		ARCH	Y	Y
Hope Bay	1200	2007	776	5535	N		ARCH	Y	Y
Hope Bay	1201	2007	712	3575	N		ARCH	Y	Y
Hope Bay	1202	2007	665	3565	N		ARCH	Y	Y
Hope Bay	1250	2007	820	5965	N		ARCH	Y	Y
Hope Bay	1254	2007	810	6070	N		ARCH	Y	Y
Hope Bay	1272	2007	450	875	N		ARCH	Y	Y
Hope Bay	1275	2007	451	950	N		ARCH	Y	Y
Hope Bay	1277	2007	425	806	N		ARCH	Y	Y
Hope Bay	1280	2007	370	530	N		ARCH	Y	Y
Hope Bay	1281	2007	356	465	Y	ARCH		Y	Y
Hope Bay	1284	2007	345	433	Y	ARCH	NA	N	NA
Hope Bay	1285	2007	295	252	N		ARCH	Y	Y

Hope Bay	1286	2007	360	446	Y	ARCH	NA	N	NA
Hope Bay	1289	2007	412	727	N		ARCH	Y	N
Hope Bay	3002	2011	665	2605	N		ARCH	Y	Y
Hope Bay	3004	2011	615	3080	N		ARCH	Y	Y
Hope Bay	3005	2011	712	4365	N		ARCH	Y	Y
Hope Bay	3026	2011	823	6420	N		ARCH	Y	Y
Hope Bay	3033	2011	501	1470	N		ARCH	Y	Y
Hope Bay	3045	2011	734	5610	N		ARCH	Y	Y
Hope Bay	3052	2011	440	1230	N		ARCH	Y	Y
Hope Bay	3055	2011	306	375	N		ARCH	Y	Y
Hope Bay	3057	2011	717	4150	N		ARCH	Y	Y
Hope Bay	3059	2011	412	855	N		ARCH	Y	Y
Hope Bay	3060	2011	347	460	N		ARCH	Y	Y
Hope Bay	3061	2011	381	720	N		ARCH	Y	Y
Hope Bay	3067	2011	422	945	N		ARCH	Y	Y
Hope Bay	3068	2011	366	550	N		ARCH	Y	Y
Hope Bay	3070	2011	379	600	N		ARCH	Y	Y
Hope Bay	3096	2011	608	2925	N		ARCH	Y	Y
Hope Bay	3097	2011	567	2060	N		ARCH	Y	Y
Hope Bay	3111	2011	665	3425	N		ARCH	Y	Y
Hope Bay	3122	2011	392	770	N		ARCH	Y	Y
Hope Bay	3132	2011	755	5250	N		ARCH	Y	Y
Hope Bay	3134	2011	737	4450	N		ARCH	Y	Y
Hope Bay	3135	2011	700	3825	N		ARCH	Y	Y
Hope Bay	3136	2011	589	2550	N		ARCH	Y	Y
Hope Bay	3139	2011	749	4420	N		ARCH	Y	Y
Hope Bay	3145	2011	670	3805	N		ARCH	Y	Y
Hope Bay	3146	2011	565	2245	N		ARCH	Y	Y

Hope Bay	3153	2011	755	4410	N	ARCH	Y	Y
Hope Bay	3162	2011	535	1795	N	ARCH	Y	Y
Hope Bay	3164	2011	464	1075	N	ARCH	Y	Y
Hope Bay	3166	2011	515	1945	N	ARCH	Y	Y
Hope Bay	3167	2011	560	2370	N	ARCH	Y	Y
Hope Bay	3173	2011	472	1090	N	ARCH	Y	Y
Hope Bay	3174	2011	460	1100	N	ARCH	Y	Y
Hope Bay	3190	2011	465	1250	N	ARCH	Y	Y
Hope Bay	3191	2011	500	1685	N	ARCH	Y	Y
Hope Bay	3192	2011	398	710	N	ARCH	Y	Y
Hope Bay	3198	2011	572	2310	N	ARCH	Y	Y
Hope Bay	3201	2011	445	940	N	ARCH	Y	Y
Hope Bay	3203	2011	505	1595	N	ARCH	Y	Y
Hope Bay	3204	2011	580	2420	N	ARCH	Y	Y
Hope Bay	3205	2011	820	5900	N	ARCH	Y	Y
Sylvia Grinnell River	8	2018	374	429	N	ARCH	Y	Y
Sylvia Grinnell River	10	2018	495	1111	N	ARCH	Y	Y
Sylvia Grinnell River	11	2018	540	1516	N	ARCH	Y	Y
Sylvia Grinnell River	12	2018	426	671	N	ARCH	Y	Y
Sylvia Grinnell River	13	2018	385	517	N	ARCH	Y	Y
Sylvia Grinnell River	14	2018	357	395	N	ARCH	Y	Y
Sylvia Grinnell River	15	2018	374	494	N	ARCH	Y	Y
Sylvia Grinnell River	20	2018	360	405	N	ARCH	Y	Y
Sylvia Grinnell River	21	2018	435	842	N	ARCH	Y	Y
Sylvia Grinnell River	22	2018	475	1352	N	ARCH	Y	Y
Sylvia Grinnell River	23	2018	510	1052	N	ARCH	Y	Y
Sylvia Grinnell River	24	2018	485	563	N	ARCH	Y	Y
Sylvia Grinnell River	25	2018	277	225	N	ARCH	Y	Y

Sylvia Grinnell River	26	2018	235	138	N	ARCH	Y	Y
Sylvia Grinnell River	27	2018	245	123	N	ARCH	Y	Y
Sylvia Grinnell River	28	2018	310	226	N	ARCH	Y	Y
Sylvia Grinnell River	30	2018	340	394	N	ARCH	Y	Y
Sylvia Grinnell River	31	2018	380	571	N	ARCH	Y	Y
Sylvia Grinnell River	32	2018	375	487	N	ARCH	Y	Y
Sylvia Grinnell River	33	2018	340	366	N	ARCH	Y	Y
Sylvia Grinnell River	34	2018	470	1025	N	ARCH	Y	Y
Sylvia Grinnell River	35	2018	410	709	N	ARCH	Y	Y
Sylvia Grinnell River	36	2018	430	871	N	ARCH	Y	Y
Sylvia Grinnell River	37	2018	380	572	N	ARCH	Y	Y
Sylvia Grinnell River	38	2018	395	633	N	ARCH	Y	Y
Sylvia Grinnell River	39	2018	395	561	N	ARCH	Y	Y
Sylvia Grinnell River	40	2018	315	275	N	ARCH	Y	Y
Sylvia Grinnell River	41	2018	325	312	N	ARCH	Y	Y
Sylvia Grinnell River	42	2018	345	377	N	ARCH	Y	Y
Sylvia Grinnell River	43	2018	455	948	N	ARCH	Y	Y
Sylvia Grinnell River	44	2018	495	1287	N	ARCH	Y	Y
Sylvia Grinnell River	45	2018	550	1640	N	ARCH	Y	Y
Sylvia Grinnell River	46	2018	580	2198	N	ARCH	Y	Y
Sylvia Grinnell River	47	2018	490	592	N	ARCH	Y	Y
Sylvia Grinnell River	48	2018	475	1028	N	ARCH	Y	Y
Sylvia Grinnell River	49	2018	355	429	N	ARCH	Y	Y
Sylvia Grinnell River	50	2018	350	420	N	ARCH	Y	Y
Sylvia Grinnell River	51	2018	390	576	N	ARCH	Y	Y
Sylvia Grinnell River	52	2018	360	419	N	ARCH	Y	Y
Sylvia Grinnell River	53	2018	335	374	N	ARCH	Y	Y
Sylvia Grinnell River	54	2018	377	470	N	ARCH	Y	Y

Sylvia Grinnell River	55	2018	340	365	N	ARCH	Y	Y
Sylvia Grinnell River	56	2018	340	399	N	ARCH	Y	Y
Sylvia Grinnell River	57	2018	320	297	N	ARCH	Y	Y
Sylvia Grinnell River	58	2018	250	146	N	ARCH	Y	Y
Sylvia Grinnell River	59	2018	255	151	N	ARCH	Y	Y
Sylvia Grinnell River	60	2018	220	108	N	ARCH	Y	Y
Sylvia Grinnell River	62	2018	436	840	N	ARCH	Y	Y
Sylvia Grinnell River	63	2018	435	817	N	ARCH	Y	Y
Sylvia Grinnell River	64	2018	470	1119	N	ARCH	Y	Y
Sylvia Grinnell River	65	2018	325	316	N	ARCH	Y	Y
Sylvia Grinnell River	66	2018	440	814	N	ARCH	Y	Y
Sylvia Grinnell River	67	2018	485	652	N	ARCH	Y	Y
Sylvia Grinnell River	68	2018	430	742	N	ARCH	Y	Y
Sylvia Grinnell River	69	2018	372	494	N	ARCH	Y	Y
Sylvia Grinnell River	70	2018	575	1349	N	ARCH	Y	Y
Sylvia Grinnell River	71	2018	347	346	N	ARCH	Y	Y
Sylvia Grinnell River	72	2018	350	389	N	ARCH	Y	Y
Sylvia Grinnell River	73	2018	330	368	N	ARCH	Y	Y
Sylvia Grinnell River	74	2018	452	721	N	ARCH	Y	Y
Sylvia Grinnell River	75	2018	383	525	N	ARCH	Y	Y
Sylvia Grinnell River	76	2018	420	670	N	ARCH	Y	Y
Sylvia Grinnell River	77	2018	374	466	N	ARCH	Y	Y
Sylvia Grinnell River	78	2018	340	355	N	ARCH	Y	Y
Sylvia Grinnell River	79	2018	336	332	N	ARCH	Y	Y
Sylvia Grinnell River	80	2018	330	336	N	ARCH	Y	Y
Sylvia Grinnell River	81	2018	356	437	N	ARCH	Y	Y
Sylvia Grinnell River	82	2018	315	264	N	ARCH	Y	Y
Sylvia Grinnell River	83	2018	366	438	N	ARCH	Y	Y

Sylvia Grinnell River	84	2018	277	212	N	ARCH	Y	Y
Sylvia Grinnell River	85	2018	327	318	N	ARCH	Y	Y
Sylvia Grinnell River	86	2018	326	333	N	ARCH	Y	Y
Sylvia Grinnell River	87	2018	360	459	N	ARCH	Y	Y
Sylvia Grinnell River	88	2018	312	261	N	ARCH	Y	Y
Sylvia Grinnell River	90	2018	270	176	N	ARCH	Y	Y
Sylvia Grinnell River	91	2018	260	156	N	ARCH	Y	Y
Sylvia Grinnell River	92	2018	553	1948	N	ARCH	Y	Y
Sylvia Grinnell River	93	2018	440	814	N	ARCH	Y	Y
Sylvia Grinnell River	94	2018	555	1146	N	ARCH	Y	Y
Sylvia Grinnell River	95	2018	179	54	N	ARCH	Y	Y
Sylvia Grinnell River	96	2018	376	489	N	ARCH	Y	Y
Sylvia Grinnell River	97	2018	330	371	N	ARCH	Y	Y
Sylvia Grinnell River	98	2018	306	278	N	ARCH	Y	Y
Sylvia Grinnell River	99	2018	319	292	N	ARCH	Y	Y
Sylvia Grinnell River	100	2018	355	399	N	ARCH	Y	Y
Sylvia Grinnell River	101	2018	332	318	N	ARCH	Y	Y
Sylvia Grinnell River	102	2018	313	305	N	ARCH	Y	Y
Sylvia Grinnell River	103	2018	384	475	N	ARCH	Y	Y
Sylvia Grinnell River	104	2018	430	882	N	ARCH	Y	Y
Sylvia Grinnell River	105	2018	436	766	N	ARCH	Y	Y
Sylvia Grinnell River	106	2018	314	273	N	ARCH	Y	Y
Sylvia Grinnell River	107	2018	334	346	N	ARCH	Y	Y
Sylvia Grinnell River	108	2018	315	293	N	ARCH	Y	Y
Sylvia Grinnell River	109	2018	250	203	N	ARCH	Y	Y
Sylvia Grinnell River	110	2018	250	178	N	ARCH	Y	Y
Sylvia Grinnell River	111	2018	356	410	N	ARCH	Y	Y
Sylvia Grinnell River	112	2018	516	1404	N	ARCH	Y	Y

Sylvia Grinnell River	113	2018	415	724	N	ARCH	Y	Y
Sylvia Grinnell River	114	2018	433	922	N	ARCH	Y	Y
Sylvia Grinnell River	115	2018	322	327	N	ARCH	Y	Y
Sylvia Grinnell River	116	2018	318	282	N	ARCH	Y	Y
Sylvia Grinnell River	117	2018	340	324	N	ARCH	Y	Y
Sylvia Grinnell River	118	2018	353	460	N	ARCH	Y	Y
Sylvia Grinnell River	119	2018	308	267	N	ARCH	Y	Y
Sylvia Grinnell River	120	2018	325	346	N	ARCH	Y	Y
Sylvia Grinnell River	121	2018	352	446	N	ARCH	Y	Y
Sylvia Grinnell River	122	2018	331	352	N	ARCH	Y	Y
Sylvia Grinnell River	123	2018	355	422	N	ARCH	Y	Y
Sylvia Grinnell River	124	2018	360	489	N	ARCH	Y	Y
Sylvia Grinnell River	125	2018	390	603	N	ARCH	Y	Y
Sylvia Grinnell River	126	2018	370	450	N	ARCH	Y	Y
Sylvia Grinnell River	127	2018	330	301	N	ARCH	Y	Y
Sylvia Grinnell River	128	2018	570	2201	N	ARCH	Y	Y
Sylvia Grinnell River	129	2018	484	1476	N	ARCH	Y	Y
Sylvia Grinnell River	130	2018	450	988	N	ARCH	Y	Y
Sylvia Grinnell River	131	2018	340	300	N	ARCH	Y	Y
Sylvia Grinnell River	132	2018	370	512	N	ARCH	Y	Y
Sylvia Grinnell River	133	2018	310	271	N	ARCH	Y	Y
Sylvia Grinnell River	134	2018	290	237	N	ARCH	Y	Y
Sylvia Grinnell River	135	2018	310	289	N	ARCH	Y	Y
Sylvia Grinnell River	136	2018	340	344	N	ARCH	Y	Y
Sylvia Grinnell River	137	2018	300	269	N	ARCH	Y	Y
Sylvia Grinnell River	138	2018	305	265	N	ARCH	Y	Y
Sylvia Grinnell River	139	2018	500	1504	N	ARCH	Y	Y
Sylvia Grinnell River	140	2018	562	1695	N	ARCH	Y	Y

Sylvia Grinnell River	141	2018	358	436	N		ARCH	Y	Y
Sylvia Grinnell River	142	2018	330	298	N		ARCH	Y	Y
Sylvia Grinnell River	143	2018	345	410	N		ARCH	Y	Y
Sylvia Grinnell River	144	2018	312	269	N		ARCH	Y	Y
Sylvia Grinnell River	145	2018	349	400	N		ARCH	Y	Y
Sylvia Grinnell River	146	2018	399	768	N		ARCH	Y	Y
Sylvia Grinnell River	147	2018	535	2056	N		ARCH	Y	Y
Sylvia Grinnell River	148	2018	360	5086	N		ARCH	Y	Y
Sylvia Grinnell River	149	2018	352	453	N		ARCH	Y	Y
Sylvia Grinnell River	150	2018	403	1615	N		ARCH	Y	Y
Sylvia Grinnell River	151	2018	234	107	N		ARCH	Y	Y
Sylvia Grinnell River	152	2018	351	347	N		ARCH	Y	Y
Sylvia Grinnell River	154	2018	231	142	N		ARCH	Y	Y
Sylvia Grinnell River	156	2018	487	1107	N		ARCH	Y	Y
Sylvia Grinnell River	1	2019	303	3056	Y	ARCH		Y	Y
Sylvia Grinnell River	2	2019	409	647.2	Y	ARCH		Y	Y
Sylvia Grinnell River	3	2019	332	331.2	Y	ARCH	NA	N	NA
Sylvia Grinnell River	4	2019	320	309.6	Y	ARCH		Y	Y
Sylvia Grinnell River	5	2019	260	189.9	Y	ARCH		Y	Y
Sylvia Grinnell River	6	2019	310	259.7	N		ARCH	Y	Y
Sylvia Grinnell River	7	2019	365	553	Y	ARCH		Y	Y
Sylvia Grinnell River	8	2019	296	231.2	Y	ARCH		Y	Y
Sylvia Grinnell River	9	2019	215	80.4	N		ARCH	Y	Y
Sylvia Grinnell River	10	2019	580	784.8	Y	ARCH	NA	N	NA
Sylvia Grinnell River	11	2019	290	249.3	N		ARCH	Y	Y
Sylvia Grinnell River	12	2019	350	441.3	Y	ARCH		Y	Y
Sylvia Grinnell River	13	2019	340	390.4	N		ARCH	Y	Y
Sylvia Grinnell River	14	2019	410	580.7	N		ARCH	Y	Y

Sylvia Grinnell River	15	2019	340	358.4	N		ARCH	Y	Y
Sylvia Grinnell River	16	2019	410	690.1	Y	ARCH		Y	Y
Sylvia Grinnell River	17	2019	390	660.6	N		ARCH	Y	Y
Sylvia Grinnell River	18	2019	330	400.3	N		ARCH	Y	Y
Sylvia Grinnell River	19	2019	290	247.5	Y	ARCH		Y	Y
Sylvia Grinnell River	20	2019	352	401.2	N		ARCH	Y	Y
Sylvia Grinnell River	21	2019	365	431	N		ARCH	Y	Y
Sylvia Grinnell River	23	2019	353	438.5	N		ARCH	Y	Y
Sylvia Grinnell River	24	2019	374	516.6	Y	ARCH		Y	Y
Sylvia Grinnell River	26	2019	325	328.2	N		ARCH	Y	Y
Sylvia Grinnell River	27	2019	290	259.2	N		ARCH	Y	Y
Sylvia Grinnell River	28	2019	530	1947.5	N		ARCH	Y	Y
Sylvia Grinnell River	29	2019	340	352.9	N		ARCH	Y	Y
Sylvia Grinnell River	30	2019	420	839.5	N		ARCH	Y	Y
Sylvia Grinnell River	31	2019	322	342.3	Y	ARCH		Y	Y
Sylvia Grinnell River	32	2019	394	602.2	N		ARCH	Y	Y
Sylvia Grinnell River	33	2019	500	1515.8	N		ARCH	Y	Y
Sylvia Grinnell River	34	2019	475	1434.4	N		ARCH	Y	Y
Sylvia Grinnell River	35	2019	320	334	N		ARCH	Y	Y
Sylvia Grinnell River	37	2019	494	1406	N		ARCH	Y	Y
Sylvia Grinnell River	38	2019	465	1450	N		ARCH	Y	Y
Sylvia Grinnell River	39	2019	522	1651	N		ARCH	Y	Y
Sylvia Grinnell River	40	2019	438	1028	N		ARCH	Y	Y
Sylvia Grinnell River	41	2019	431	973	N		ARCH	Y	Y
Sylvia Grinnell River	42	2019	467	1169	N		ARCH	Y	Y
Sylvia Grinnell River	43	2019	411	740	N		ARCH	Y	Y
Sylvia Grinnell River	44	2019	476	1355	N		ARCH	Y	Y
Sylvia Grinnell River	45	2019	429	880	N		ARCH	Y	Y

Sylvia Grinnell River	46	2019	506	1524	N	ARCH	Y	Y
Sylvia Grinnell River	47	2019	480	1417	N	ARCH	Y	Y
Sylvia Grinnell River	48	2019	530	2005	N	ARCH	Y	Y
Sylvia Grinnell River	49	2019	470	1233	N	ARCH	Y	Y
Sylvia Grinnell River	50	2019	431	1042	N	ARCH	Y	Y
Sylvia Grinnell River	51	2019	450	951	N	ARCH	Y	Y
Sylvia Grinnell River	52	2019	565	1200	N	ARCH	Y	Y
Sylvia Grinnell River	53	2019	403	817	N	ARCH	Y	Y
Sylvia Grinnell River	54	2019	450	1067	N	ARCH	Y	Y
Sylvia Grinnell River	55	2019	440	944	N	ARCH	Y	Y
Sylvia Grinnell River	56	2019	480	1201	N	ARCH	Y	Y
Sylvia Grinnell River	57	2019	455	966	N	ARCH	Y	Y
Sylvia Grinnell River	58	2019	460	1084	N	ARCH	Y	Y
Sylvia Grinnell River	59	2019	450	1053	N	ARCH	Y	Y
Sylvia Grinnell River	60	2019	415	717	N	ARCH	Y	Y
Sylvia Grinnell River	61	2019	390	744	N	ARCH	Y	Y
Sylvia Grinnell River	62	2019	430	875	N	ARCH	Y	Y
Sylvia Grinnell River	63	2019	545	2076	N	ARCH	Y	Y
Sylvia Grinnell River	64	2019	530	1576	N	ARCH	Y	Y
Sylvia Grinnell River	65	2019	494	1931	N	ARCH	Y	Y
Sylvia Grinnell River	66	2019	395	654	N	ARCH	Y	Y
Sylvia Grinnell River	67	2019	374	668	N	ARCH	Y	Y
Sylvia Grinnell River	68	2019	383	565	N	ARCH	Y	Y
Sylvia Grinnell River	69	2019	350	491	N	ARCH	Y	Y
Sylvia Grinnell River	70	2019	340	415	N	ARCH	Y	Y
Sylvia Grinnell River	71	2019	333	399	N	ARCH	Y	Y
Sylvia Grinnell River	72	2019	377	611	N	ARCH	Y	Y
Sylvia Grinnell River	73	2019	331	405	N	ARCH	Y	Y

Sylvia Grinnell River	74	2019	340	386	N	ARCH	Y	Y
Sylvia Grinnell River	75	2019	338	286	N	ARCH	Y	Y
Sylvia Grinnell River	76	2019	530	1733	N	ARCH	Y	Y
Sylvia Grinnell River	77	2019	470	1096	N	ARCH	Y	Y
Sylvia Grinnell River	78	2019	540	1483	N	ARCH	Y	Y
Sylvia Grinnell River	79	2019	420	793	N	ARCH	Y	Y
Sylvia Grinnell River	80	2019	385	609	N	ARCH	Y	Y
Sylvia Grinnell River	81	2019	333	369	N	ARCH	Y	Y
Sylvia Grinnell River	82	2019	410	803	N	ARCH	Y	Y
Sylvia Grinnell River	83	2019	470	1134	N	ARCH	Y	Y
Sylvia Grinnell River	84	2019	480	1385	N	ARCH	Y	Y
Sylvia Grinnell River	85	2019	440	935	N	ARCH	Y	Y
Sylvia Grinnell River	86	2019	400	639	N	ARCH	Y	Y
Sylvia Grinnell River	87	2019	368	959	N	ARCH	Y	Y
Sylvia Grinnell River	88	2019	316	325	N	ARCH	Y	Y
Sylvia Grinnell River	89	2019	500	1454	N	ARCH	Y	Y
Sylvia Grinnell River	90	2019	287	255	N	ARCH	Y	Y
Sylvia Grinnell River	91	2019	340	415	N	ARCH	Y	Y
Sylvia Grinnell River	92	2019	400	646	N	ARCH	Y	Y
Sylvia Grinnell River	93	2019	460	1142	N	ARCH	Y	Y
Sylvia Grinnell River	94	2019	540	1744	N	ARCH	Y	Y
Sylvia Grinnell River	95	2019	390	718	N	ARCH	Y	Y
Sylvia Grinnell River	96	2019	400	679	N	ARCH	Y	Y
Sylvia Grinnell River	97	2019	360	575	N	ARCH	Y	Y
Sylvia Grinnell River	98	2019	350	417	N	ARCH	Y	Y
Sylvia Grinnell River	99	2019	310	286	N	ARCH	Y	Y
Sylvia Grinnell River	101	2019	350	450	N	ARCH	Y	Y
Sylvia Grinnell River	103	2019	410	759	N	ARCH	Y	Y

Sylvia Grinnell River	104	2019	354	546	N	ARCH	Y	Y
Sylvia Grinnell River	105	2019	355	553	N	ARCH	Y	Y
Sylvia Grinnell River	106	2019	348	380	N	ARCH	Y	Y
Sylvia Grinnell River	107	2019	379	556	N	ARCH	Y	Y
Sylvia Grinnell River	108	2019	195	68	N	ARCH	Y	Y
Sylvia Grinnell River	109	2019	460	1124	N	ARCH	Y	Y
Sylvia Grinnell River	111	2019	400	712	N	ARCH	Y	Y
Sylvia Grinnell River	114	2019	354	460	N	ARCH	Y	Y
Sylvia Grinnell River	115	2019	333	392	N	ARCH	Y	Y
Sylvia Grinnell River	116	2019	300	268	N	ARCH	Y	Y
Sylvia Grinnell River	117	2019	310	332	N	ARCH	Y	Y
Sylvia Grinnell River	118	2019	250	178	N	ARCH	Y	Y
Sylvia Grinnell River	119	2019	290	244	N	ARCH	Y	Y
Sylvia Grinnell River	120	2019	250	179	N	ARCH	Y	Y
Sylvia Grinnell River	121	2019	240	128	N	ARCH	Y	Y
Sylvia Grinnell River	122	2019	370	512	N	ARCH	Y	Y
Sylvia Grinnell River	123	2019	340	400	N	ARCH	Y	Y
Sylvia Grinnell River	125	2019	335	375	N	ARCH	Y	Y
Sylvia Grinnell River	126	2019	420	721	N	ARCH	Y	Y
Sylvia Grinnell River	127	2019	380	401	N	ARCH	Y	Y
Sylvia Grinnell River	128	2019	298	272	N	ARCH	Y	Y
Sylvia Grinnell River	129	2019	332	375	N	ARCH	Y	Y
Sylvia Grinnell River	130	2019	282	229	N	ARCH	Y	Y
Sylvia Grinnell River	131	2019	390	721	N	ARCH	Y	Y
Sylvia Grinnell River	132	2019	480	1221	N	ARCH	Y	Y
Sylvia Grinnell River	133	2019	430	833	N	ARCH	Y	Y
Sylvia Grinnell River	134	2019	220	261	N	ARCH	Y	Y
Sylvia Grinnell River	135	2019	310	343	N	ARCH	Y	Y

Sylvia Grinnell River	136	2019	370	579	N	ARCH	Y	Y
Sylvia Grinnell River	137	2019	340	468	N	ARCH	Y	Y
Sylvia Grinnell River	138	2019	310	258	N	ARCH	Y	Y
Sylvia Grinnell River	139	2019	340	329	N	ARCH	Y	Y
Sylvia Grinnell River	140	2019	300	238	N	ARCH	Y	Y
Sylvia Grinnell River	141	2019	290	244	N	ARCH	Y	Y
Sylvia Grinnell River	142	2019	320	306	N	ARCH	Y	Y
Sylvia Grinnell River	143	2019	310	296	N	ARCH	Y	Y
Sylvia Grinnell River	144	2019	370	471	N	ARCH	Y	Y
Sylvia Grinnell River	145	2019	345	428	N	ARCH	Y	Y
Sylvia Grinnell River	146	2019	310	300	N	ARCH	Y	Y
Sylvia Grinnell River	147	2019	345	503	N	ARCH	Y	Y
Sylvia Grinnell River	148	2019	308	331	N	ARCH	Y	Y
Sylvia Grinnell River	149	2019	350	404	N	ARCH	Y	Y
Sylvia Grinnell River	150	2019	333	419	N	ARCH	Y	Y
Sylvia Grinnell River	151	2019	330	371	N	ARCH	Y	Y
Sylvia Grinnell River	152	2019	340	369	N	ARCH	Y	Y
Sylvia Grinnell River	153	2019	370	563	N	ARCH	Y	Y
Sylvia Grinnell River	155	2019	417	893	N	ARCH	Y	Y
Sylvia Grinnell River	156	2019	491	1408	N	ARCH	Y	Y
Sylvia Grinnell River	157	2019	354	488	N	ARCH	Y	Y
Sylvia Grinnell River	158	2019	510	1450	N	ARCH	Y	Y
Sylvia Grinnell River	159	2019	532	1667	N	ARCH	Y	Y
Sylvia Grinnell River	160	2019	287	253	N	ARCH	Y	Y
Sylvia Grinnell River	161	2019	298	263	N	ARCH	Y	Y
Sylvia Grinnell River	162	2019	526	1562	N	ARCH	Y	Y
Sylvia Grinnell River	164	2019	476	1403	N	ARCH	Y	Y
Sylvia Grinnell River	165	2019	480	1516	N	ARCH	Y	Y

Sylvia Grinnell River	166	2019	420	937	N	ARCH	Y	Y
Sylvia Grinnell River	167	2019	361	575	N	ARCH	Y	Y
Sylvia Grinnell River	168	2019	405	652	N	ARCH	Y	Y
Sylvia Grinnell River	170	2019	325	410	N	ARCH	Y	Y
Sylvia Grinnell River	171	2019	34	418	N	ARCH	Y	Y
Sylvia Grinnell River	172	2019	31	310	N	ARCH	Y	Y
Sylvia Grinnell River	173	2019	32	286	N	ARCH	Y	Y
Sylvia Grinnell River	174	2019	28	23.4	N	ARCH	Y	Y
Sylvia Grinnell River	176	2019	402	701	N	ARCH	Y	Y
Sylvia Grinnell River	177	2019	421	895	N	ARCH	Y	Y
Sylvia Grinnell River	178	2019	426	980	N	ARCH	Y	Y
Sylvia Grinnell River	179	2019	455	1068	N	ARCH	Y	Y
Sylvia Grinnell River	180	2019	320	328	N	ARCH	Y	Y
Sylvia Grinnell River	181	2019	290	237	N	ARCH	Y	Y
Sylvia Grinnell River	182	2019	310	282	N	ARCH	Y	Y
Sylvia Grinnell River	184	2019	180	55	N	ARCH	Y	Y
Sylvia Grinnell River	185	2019	440	1062	N	ARCH	Y	Y
Sylvia Grinnell River	186	2019	340	443	N	ARCH	Y	Y
Sylvia Grinnell River	187	2019	310	330	N	ARCH	Y	Y
Sylvia Grinnell River	188	2019	290	227	N	ARCH	Y	Y

Table D.6: *Summary data for Tree River samples included in genomic analyses.*

Sampling Location	Sample ID	Year Sampled	Fork Length (mm)	Weight (g)	Genomic Species ID
Tree River	5	2019			DVCH
Tree River	10	2019			DVCH
Tree River	8494	1995	778	6111	DVCH
Tree River	8495	1995	780	4713	DVCH
Tree River	8496	1995	790	5243	DVCH
Tree River	8497	1995	742	4634	DVCH
Tree River	8498	1995	807	6362	DVCH
Tree River	8500	1995	629	2892	DVCH
Tree River	8501	1995	635	3005	DVCH
Tree River	8502	1995	667	3072	DVCH
Tree River	8503	1995	657	2639	DVCH
Tree River	8504	1995	645	2869	DVCH
Tree River	8505	1995	782	5338	DVCH
Tree River	8506	1995	738	4230	DVCH
Tree River	8507	1995	799	4902	DVCH
Tree River	8508	1995	687	3999	DVCH
Tree River	8509	1995	855	5343	DVCH
Tree River	8510	1995	612	2388	DVCH
Tree River	8511	1995	746	3601	DVCH
Tree River	8512	1995	770	4556	DVCH
Tree River	8513	1995	682	3294	DVCH
Tree River	8514	1995	697	3011	DVCH
Tree River	8515	1995	648	3083	DVCH
Tree River	8516	1995	573	1858	DVCH
Tree River	8517	1995	812	5825	DVCH
Tree River	8518	1995	777	5358	DVCH
Tree River	8519	1995	691	3695	DVCH
Tree River	8520	1995	672	3011	DVCH
Tree River	8521	1995	790	5304	DVCH
Tree River	8522	1995	677	3970	DVCH
Tree River	8523	1995	719	3967	DVCH
Tree River	8524	1995	558	1521	DVCH
Tree River	8525	1995	655	2665	DVCH
Tree River	8526	1995	833	6528	DVCH
Tree River	8527	1995	630	3147	DVCH

Tree River	8528	1995	618	2826	DVCH
Tree River	8529	1995	663	3290	DVCH
Tree River	8530	1995	755	4553	DVCH
Tree River	8531	1995	647	2910	DVCH
Tree River	8532	1995	633	2743	DVCH
Tree River	8533	1995	606	2501	DVCH
Tree River	8534	1995	820	6305	DVCH

Table D.7: *Samples from Darnley Bay and Coppermine River included in morphometric analyses, but without corresponding genomic data. Species identifications were predicted by running a model using known samples as a training set, and the samples in this table as a predicted set.*

Sampling Location	Sample ID	Year Sampled	Predicted Species
Darnley Bay	1	2017	ARCH
Darnley Bay	4	2017	ARCH
Darnley Bay	6	2017	ARCH
Darnley Bay	7	2017	ARCH
Darnley Bay	9	2017	ARCH
Darnley Bay	10	2017	ARCH
Darnley Bay	12	2017	DVCH
Darnley Bay	13	2017	ARCH
Darnley Bay	15	2017	ARCH
Darnley Bay	16	2017	ARCH
Darnley Bay	17	2017	ARCH
Darnley Bay	18	2017	ARCH
Darnley Bay	19	2017	ARCH
Darnley Bay	20	2017	ARCH
Darnley Bay	21	2017	ARCH
Darnley Bay	23	2017	ARCH
Darnley Bay	25	2017	ARCH
Darnley Bay	27	2017	ARCH
Darnley Bay	28	2017	ARCH
Darnley Bay	29	2017	ARCH
Darnley Bay	31	2017	ARCH
Darnley Bay	32	2017	ARCH
Darnley Bay	33	2017	ARCH
Darnley Bay	34	2017	ARCH
Coppermine River/ Coronation Gulf	8246	2018	DVCH
Coppermine River/ Coronation Gulf	8277	2018	DVCH
Coppermine River/ Coronation Gulf	8278	2018	DVCH
Coppermine River/ Coronation Gulf	8284	2018	DVCH
Coppermine River/ Coronation Gulf	8292	2018	DVCH
Coppermine River/ Coronation Gulf	8294	2018	ARCH
Coppermine River/ Coronation Gulf	8308	2018	DVCH
Coppermine River/ Coronation Gulf	8316	2018	ARCH

Coppermine River/ Coronation Gulf	8557	2019	DVCH
Coppermine River/ Coronation Gulf	8558	2019	ARCH
Coppermine River/ Coronation Gulf	8562	2019	ARCH
Coppermine River/ Coronation Gulf	8861	2019	DVCH
Coppermine River/ Coronation Gulf	8867	2019	ARCH
Coppermine River/ Coronation Gulf	8872	2019	ARCH
Coppermine River/ Coronation Gulf	8917	2019	DVCH
Coppermine River/ Coronation Gulf	8924	2019	ARCH
Coppermine River/ Coronation Gulf	8945	2019	DVCH
Coppermine River/ Coronation Gulf	9219	2019	ARCH
Coppermine River/ Coronation Gulf	9246	2019	ARCH
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Coppermine River/ Coronation Gulf	9264	2019	DVCH
Coppermine River/ Coronation Gulf	9265	2019	DVCH
Coppermine River/ Coronation Gulf	9266	2019	DVCH
Coppermine River/ Coronation Gulf	9267	2019	DVCH
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Coppermine River/ Coronation Gulf	9272	2019	DVCH
Coppermine River/ Coronation Gulf	9273	2019	DVCH
Coppermine River/ Coronation Gulf	9275	2019	DVCH
Coppermine River/ Coronation Gulf	9277	2019	DVCH
Coppermine River/ Coronation Gulf	9278	2019	DVCH
Coppermine River/ Coronation Gulf	9280	2019	DVCH
Coppermine River/ Coronation Gulf	9282	2019	DVCH
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Coppermine River/ Coronation Gulf	9299	2019	DVCH
Coppermine River/ Coronation Gulf	9301	2019	DVCH
Coppermine River/ Coronation Gulf	9303	2019	DVCH
Coppermine River/ Coronation Gulf	9311	2019	ARCH
Coppermine River/ Coronation Gulf	9315	2019	ARCH
Coppermine River/ Coronation Gulf	9316	2019	ARCH
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Coppermine River/ Coronation Gulf	9330	2019	DVCH
Coppermine River/ Coronation Gulf	9331	2019	DVCH
Coppermine River/ Coronation Gulf	9332	2019	DVCH
Coppermine River/ Coronation Gulf	9334	2019	ARCH
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Coppermine River/ Coronation Gulf	9340	2019	DVCH
Coppermine River/ Coronation Gulf	9341	2019	DVCH
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Coppermine River/ Coronation Gulf	9349	2019	DVCH
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Coppermine River/ Coronation Gulf	9437	2019	DVCH
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Coppermine River/ Coronation Gulf	9500	2020	DVCH
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Coppermine River/ Coronation Gulf	9534	2021	ARCH
Coppermine River/ Coronation Gulf	9535	2021	ARCH
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Coppermine River/ Coronation Gulf	9537	2021	ARCH
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Coppermine River/ Coronation Gulf	9540	2021	ARCH
Coppermine River/ Coronation Gulf	9541	2021	ARCH
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Coppermine River/ Coronation Gulf	9544	2021	ARCH
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Coppermine River/ Coronation Gulf	9546	2021	ARCH
Coppermine River/ Coronation Gulf	9547	2021	ARCH
Coppermine River/ Coronation Gulf	9548	2021	ARCH
Coppermine River/ Coronation Gulf	9549	2021	ARCH
Coppermine River/ Coronation Gulf	9550	2021	ARCH

Coppermine River/ Coronation Gulf	9551	2021	ARCH
Coppermine River/ Coronation Gulf	9552	2021	ARCH

E: Supplementary Information for Chapter 4

Kugluktuk HTO Letter of Support

Kugluktuk Angoniatit Association ● Hunters' & Trappers' Organization
PO Box 309, Kugluktuk NU X0B 0E0 ● Phone: (867) 982-4908 Fax: (867) 982-5912
Email: kugluktuk@krwb.ca

30 October 2019

To Whom It May Concern:

The Kugluktuk Hunters and Trappers Organization is pleased to offer support for the Traditional Knowledge portion of a larger project "Movement and habitat use of anadromous Arctic char (*Salvelinus alpinus*) and Dolly Varden (*Salvelinus malma malma*) near Kugluktuk, Nunavut" led by researchers at the University of Waterloo. This Traditional Knowledge study is part of a larger, multi-year project that is aimed at investigating how chars use the Coppermine River, and how fish habitat may be enhanced through restoration efforts.

In Kugluktuk, we are witnessing changes to our critical Arctic char fishery. Climate change is disproportionately affecting the coastal Canadian Arctic, and since 2015 we have noticed a decline in the numbers of migratory char entering the Coppermine River each fall. Since 2017, we have collaborated with researchers at the University of Waterloo and Fisheries and Oceans Canada to identify migratory patterns and overwintering habitats of char in the Coppermine River, and to assess the diversity of chars present in the system. By evaluating the species composition of chars in the Coppermine River, we can determine how habitats and resources are being used, which will allow us to identify critical habitats and aid in prioritizing sites for restoration. Use of both traditional knowledge and western science methods is allowing us to formulate the most complete picture possible of an ecosystem that we rely on daily – as Inuit, we have knowledge that is not captured by western science methods, and this Traditional Knowledge study is critical to gaining a comprehensive understanding of char in the Coppermine River. We look forward to using this research to maintain and manage our subsistence fishery.

We are able to contribute in $10,000 in monetary support to this Traditional Knowledge study in the form of honoraria for interview participants.

Sincerely,

[redacted]

Larry Adjun
Chairperson, Kugluktuk Hunters and Trappers Organization

Interview Guide

Background questions

What is your name?

How old are you?

How long have you lived in Kugluktuk?

How long have you been fishing in this area?

What types of fish do you usually fish for?

Questions about char fishing

Why are char important to you?

When you go char fishing, what methods do you use to catch char?

Where do you usually fish for char? Can you show me these places on the map?

Why are these good places for catching char?

When are the best times for char fishing?

What do you do with the char after you catch them? I.e., preparation, trading/sharing, etc.

Have you noticed any changes to the char in the Coppermine River?

Can you describe these changes?

How long ago did you start observing these changes?

What are the causes of these changes?

Has the number of char you've caught annually changed?

Has the health of the fish changed? Do the fish look or taste different?

Can you describe a healthy looking char?

Have you noticed any changes in the environment that concern you?

Have these changes affected char?

Have these changes affected how you fish?

Questions about the presence of Dolly Varden in the Coppermine River and Coronation Gulf

Have you ever caught Dolly Varden in the Coppermine River [or other places nearby]?

If yes, when was the first time you caught a Dolly Varden?

When you go fishing, do you catch more Arctic char or more Dolly Varden? Has this changed over time?

If no, are there different types of char in the Coppermine River? What are the words/names for these different types of char?

How can you tell apart Arctic char and Dolly Varden?

Do Arctic char and Dolly Varden taste the same?

Do Arctic char and Dolly Varden have the same color flesh, or is the color different?

Does health differ between Arctic char and Dolly Varden?

Do you catch Arctic char and Dolly Varden in the same places or different places?

Can you mark on the map where you catch Arctic char? Dolly Varden?

Do you catch Arctic char and Dolly Varden at the same time or different times?

If different, ask follow-up questions.

When do Arctic char move downstream from the river into the ocean? When do Arctic char move upstream from the ocean into the river? Has this changed over time?

When do Dolly Varden move downstream from the river into the ocean? When do Dolly Varden move upstream from the ocean into the river? Has this changed over time?

Do Dolly Varden and Arctic char go to the same or different places out in the ocean, or when they are in the Coppermine River?

Can you show me on the map where Arctic char go? Dolly Varden?

Do Dolly Varden and Arctic char overwinter in the same places or different places?

Can you show me on the map where Arctic char overwinter? Dolly Varden?

Do Arctic char and Dolly Varden spawn at the same times or different times?

If they haven't caught Dolly Varden: when do Arctic char spawn?

Do Arctic char and Dolly Varden spawn in the same places or different places?

Can you show me on a map where Arctic char spawn? Dolly Varden?

Have spawning or overwintering places changed over time?

Concluding questions

Do you think more could be done to protect the fishery? Are there any changes that you would like to see happen?

What research would you like to see happen in the future?

I am now going to give you pictures of fish that were harvested during the 2019 and 2020 migration seasons. Can you put the fish into the category that matches what you would call it or what species you think it is (i.e. Arctic char, Dolly Varden, hybrid, other)?

Is there anything else you would like to tell me about Arctic char or Dolly Varden, or about your experiences fishing for char?

Follow-up questions for January 2023

How often do you go fishing?

Has this changed over time?

Do you fish as frequently as you used to?

Can you elaborate on char migration timing?

Who taught you how to fish?

Is your family from Kugluktuk area, or did they move here from somewhere else?

When did ice break-up used to occur?

In what months do you mainly fish?

Are you seeing the char population decline in every season or just during specific months?

Can you tell me about char movement in the summer and the fall?

Can you draw the different char that you catch?

What are the differences between the char, in terms of movement or behavior or what they eat?

Do different types of char enter and leave rivers at the same or different times?

Are there different Inuinnaqtun words for the different types of char?

Participant Consent Form

PARTICIPANT CONSENT FORM

Movement and habitat use of anadromous Arctic char (*Salvelinus alpinus*) and Dolly Varden (*Salvelinus malma malma*) near Kugluktuk, Nunavut

Principal Investigator:

Spencer Weinstein
Department of Biology, University of Waterloo
200 University Ave. W.
Waterloo, Ontario N2L 3G1
Email: spencer.weinstein@uwaterloo.ca

Project Background and Description:

Since 2017, researchers from the University of Waterloo and Department of Fisheries and Oceans (DFO) have worked with the Kugluktuk Hunters and Trappers Organization (HTO) to understand the causes for the recent decline in subsistence-caught char in the Coppermine River. As part of this research, we are investigating whether both Arctic char and the closely-related Dolly Varden char are present in the Coppermine River and Coronation Gulf. Part of our work addressing this question involves a Traditional Knowledge (TK) study on Arctic char and Dolly Varden in the Coppermine River. Approximately 10-20 Kugluktuk residents will be recruited to participate in a Traditional Knowledge study. Both elders and fishers with extensive knowledge of the local char fishery will be recruited for participation. The Kugluktuk HTO will help plan the study, approve its design and methodology, and recruit interview participants. An Inuktitut or Inuinnaqtun translator will be available upon request by participants.

I am a PhD student in the Department of Biology at the University of Waterloo, and I will be carrying out this study. You are being asked to participate in this Traditional Knowledge study on the diversity of char in the Coppermine River. The goal of this research is to understand recent changes in the Arctic char fishery in the Coppermine River, and whether both Arctic char and Dolly Varden are present in the river. Being a part of this study means participating in an in-person interview that will last for approximately one hour. The interview will be audio taped.

Participation:

Your participation in this study is voluntary. You have the right to decline to participate – there will be no consequences to those who do not participate. If you do choose to participate, you may withdraw your agreement at any time without penalty up to two weeks after the date of your interview. You may choose to have your answers recorded on paper but not recorded on tape. You may choose to not answer any questions that you do not wish to answer.

Confidentiality and Release of Information:

Unless your permission has been obtained in writing (see below), your name will not be linked with the audio recordings or written documents that are produced from this research; instead, a coded number will be used if quotes are included. All information present on audio recordings will be written out by the researcher, and the tapes will then be destroyed. Your name will never be linked to any other information, unless you have consented to being identified in any outputs that are returned and/or presented to the community. If you agree to be identified, your name will only be used in products that are presented and/or returned to the community. Any interview information used in academic spaces will remain strictly confidential.

All of the written documentation for this project will be placed in a locked cabinet in a locked room. This information will be kept for seven years after the study is published. Any report published as a result of this study will not use any information that could identify you. Researchers will not share any information on you with others and will follow the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans*. All interview information will be validated with participants, and you and the HTO will have the opportunity to review all collated information before publication or use in a thesis.

Honorarium:

The Kugluktuk HTO will provide you with a $150 honorarium in recognition of your time and contribution to this study.

Contact Information:

If you have any questions at any point during the study, you may contact the Kugluktuk HTO or Spencer Weinstein (contact information above) or Heidi Swanson (Spencer's supervisor) directly.

Kugluktuk HTO
Larry Adjun (Chairperson) and Amanda Dumond (Manager)
P.O. Box 309
Kugluktuk, Nunavut X0B 0E0
Phone: 867-982-4908
Email: kugluktuk@kitikmeothto.ca

Heidi Swanson
Department of Biology, University of Waterloo
200 University Ave. W.
Waterloo, Ontario N2L 3G1
Phone: 519-888-4567 ext. 37387
Fax: 519-746-0614
Email: heidi.swanson@uwaterloo.ca

UNIVERSITY OF WATERLOO

Consent:

I have been fully informed of the objectives of the project being conducted. I understand these objectives and consent to being interviewed for the project. I understand that steps will be undertaken to ensure that this interview will remain confidential unless I consent to being identified. I also understand that, if I wish to withdraw from the study, I may do so without any repercussions. I have read and understand the above information. I agree to participate in this study and to release my interview and associated data to the Kugluktuk HTO and associated University of Waterloo researchers.

Participant's name _____

Participant's signature _____

Date _____

Check one:

I wish to remain confidential ☐

I am okay with my name being used ☐

Check one:

I agree to have my interview taped ☐

I do not agree to have my interview taped ☐

Check one:

I agree to be photographed ☐

I do not agree to be photographed ☐

519-888-4567 | uwaterloo.ca | 200 UNIVERSITY AVENUE WEST, WATERLOO, ON, CANADA N2L 3G1