Assessing reasons for changes in the condition of Deception Bay Arctic charr

(*Salvelinus alpinus*)

By

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The Raglan Mine sport fishing program has collected biological fish data in Deception Bay, Nunavik, Québec, Canada since 1998 in collaboration with local committees, small scale sampling programs, and government agencies and since 2004 there has been a documented and continued decline in the somatic condition of anadromous Deception Bay Arctic charr. Anadromous Arctic charr in Deception Bay support subsistence, recreational, and commercial fisheries, but research focused on this population of Arctic charr is limited, dated, and summer specific. In an effort to address the concerns of neighbouring communities regarding the observed declines in the somatic condition and to improve the overall available data on anadromous Nunavik Arctic charr populations, this research investigated seasonal variation in fish condition measures (lipid analysis and bomb calorimetry) and contaminant levels (arsenic, cadmium, chromium, copper, mercury, nickel, lead, and zinc) and their potential linkages with biological variables and indicators of feeding behaviour in Arctic charr returning from the marine environment (Deception Bay – summer 2016) and during the post-winter season (Deception River headwater lakes, Duquet and Françoys-Malherbe – spring 2017).

Biological information (fork-length, whole-weight, age, somatic condition), stable isotope values (δ^{13}C, % carbon, δ^{15}N, and % nitrogen), and dorsal muscle % lipid values, caloric densities, and total mercury concentrations were assessed to determine the seasonal variability of these parameters in this population of anadromous Arctic charr. Significant reductions in somatic condition and % nitrogen, consistent with prolonged periods of non-feeding, existed for post-winter captured Arctic charr, but % lipid and caloric values were significantly greater in dorsal muscle tissue of fish collected during this season. Significant correlations between data from these analyses and fork-length, whole-weight, age, somatic condition, δ^{13}C, % carbon, δ^{15}N, and % nitrogen were seasonally dependent and only existed between some of the tested variables.

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Total mercury concentrations also varied seasonally, with concentrations being significantly greater in the tissue collected from summer returning marine migrants. Similar to observations with lipid and caloric values, significant relationships were seasonally dependent and only existed between total mercury concentrations and some, but not all, of the tested variables. Total mercury concentration data also had limited relationships with fish condition measures, only significantly declining with increasing % lipid values in Arctic charr sampled in the marine environment. Biological descriptors and stable isotope values, in addition to season, were incorporated into multi-predictor variable models that better explained variations in the data than individual parameters. Season, condition, and stable isotope values (% carbon and % nitrogen) were the best indicators of % lipid content and caloric densities, while total mercury concentration data were best supported by whole-weight measurements, somatic condition, and $\delta^{13}C$. Seasonal variation in fish condition measures and results from total mercury analysis may be indicative of a condition selective mortality effect on this population, while winter diet subsidization is less plausible due to the observed absence of short term feeding and depletion of % nitrogen values. Future research must consider the implications of the phenomenon on mature fish, particularly in extreme environments, such as the Arctic.

Dorsal muscle and liver concentrations of arsenic, cadmium, chromium, copper, nickel, lead, and zinc were also quantified to examine possible organotropism, seasonal variation, and relationships with biological variables (fork-length, age, and condition) and stable isotopes (carbon and nitrogen). Metal organotropism favouring elevation in liver tissues was exhibited by cadmium, copper, nickel, and zinc, while arsenic, chromium and lead exhibited no significant organotropic variation. Seasonal differences in concentrations were metal and tissue dependent, but generally increased in tissues collected from post-winter sampled Arctic charr. Significant

correlations with biological and trophic descriptors were also determined to be element and tissue dependent. These parameters, in addition to season, were incorporated into multi-predictor variable models that better explained variations in the data. Variation in trace metal concentration data were often best supported when season, somatic condition, and trophic descriptors were included and these variables dominated as the parameters of greatest relative importance across all considered metals and tissue types. Fork-length also appeared as a variable of high relative importance for essential metals, while age and $\delta^{15}N$ were of greater relative importance to non-essential metals. These findings suggest that seasonally linked processes have the greatest influence on trace metal concentrations in anadromous Arctic charr and future metals related research on Arctic charr and other northern fish species should further consider these variables when evaluating elemental accumulation.

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Chapter 1: General Introduction

Arctic charr (*Salvelinus alpinus*)

Arctic charr (*Salvelinus alpinus* (L.)) is the most northerly distributed freshwater fish species on earth and exhibit diverse life history strategies (Jonsson *et al.* 1988). They are generally long lived with age-at-maturity varying with latitude throughout their circumpolar distribution (Johnson 1983; Johnson 1989; Klemetsen *et al.* 2003a; Power *et al.* 2008). There are anadromous, resident, and lacustrine populations, with Arctic charr being considered habitat generalists, occupying lakes, streams, rivers, and marine environments depending on the time of year and life history form (Power *et al.* 2008). Marine migrations of anadromous Arctic charr begin after ice break up in the spring and last between 6 to 8 weeks (Johnson 1983; Klemetsen *et al.* 2003a; Power *et al.* 2008). First time migrants can be anywhere from 3 to 8 years of age and both sexually mature and immature fish perform migrations (Nordeng 1983; Johnson 1989). The degree of anadromy may vary based on river parameters (Kristoffersen 1994; Moore *et al.*, 2016) or geographic location (Johnson, 1980), yet at the northern extreme of their distribution lacustrine residency is favoured regardless of access to the marine environment (Power *et al.* 2008). It is during the period of marine residency that fish feed opportunistically on zooplankton, amphipods, pelagic and benthic fishes, and occasionally surface insects (Grønvik and Klemetsen 1987; Dempson *et al.* 2002; Power *et al.* 2008).

Anadromous Arctic charr overwinter in freshwater and sub-optimal environmental and physiological conditions all suggest a prolonged period of fasting during the ice-covered months (Boivin and Power, 1990; Jobling 1994; Sæther *et al.* 1996 Mazur and Beauchamp 2003; Turesson and Brönmark, 2007; Mulder *et al.* 2017). While resident Arctic charr populations continually feed throughout the entire winter season (Eloranta *et al.* 2013; Klemetsen *et al.*

2003a; Power *et al.* 2009; Svenning *et al.* 2007), this period for anadromous Arctic charr is generally thought to be characterized by lipid and protein loss between 30% - 46% (Dutil 1986; Jørgensen, *et al.* 1997). However, the over-wintering ecology of anadromous Arctic charr has been poorly described in the literature beyond noting cessation of feeding (Sprules 1952; Moore and Moore, 1974; Dutil 1986; Boivin and Power, 1990; Jørgensen, *et al.* 1997; Rikardsen *et al.* 2003). Opportunistic maintenance winter diet subsidization and pursuit of hooks and baits have been noted (Boivin 1987) and suggested (Mulder *et al.* 2017), although the consequences of such feeding is under-studied. In general, winter mortality remains low for Arctic charr populations (Klemetsen *et al.* 2003b; Byström *et al.* 2006; Svenning *et al.* 2007; Aundsen and Knudsen, 2009; Siikavuopio *et al.* 2009) despite difficult winter conditions and ice-cover exceeding ten months (Svenning and Gullestad, 2002; Klemetsen *et al.* 2003ab).

Arctic charr are often described as keystone predators integral to the structure and function of the ecosystems they occupy (Reist *et al.* 2006), in addition to also being considered a sentinel species for evaluating the impacts of a changing climate and spatial and temporal metal contaminant trends (Reist *et al.* 2006; Douglas et al., 2011). Arctic charr are a culturally important food resource (Condon 1994; Kuhnlein and Receveur, 2007) and an essential component of subsistence fisheries and the year-round diet of Indigenous people (AMAP, 2011). Thus, Arctic charr can assist in mitigating issues associated with northern food insecurity, to which Indigenous people are especially vulnerable (Lawn and Harvey, 2004; Sharma 2010; Huet *et al.* 2012). Arctic charr can also have significant impact on local economies through commercial and sport-fishing programs (Roux *et al.* 2011). However, Arctic charr and northern aquatic ecosystems are often threatened by demographic and economic expansion, as well as the anticipated changes associated with future climate changes (Schindler 2001; Reist *et al.* 2006;

Winfield Elliot and Elliot, 2010; Jeppensen *et al.* 2012; Murdoch and Power, 2013b; Reist *et al.* 2013). As a result, preservation and informed management of the species is required to ensure its continued contributions to northern cultural and socio-economic values.

Arctic charr in Deception Bay

The Raglan Mine, a large copper and nickel mining complex situated in the Nunavik region of Québec, Canada (Glencore 2016), has offered their employees a sport fishing program since 1998 in accordance with the local Hunting, Fishing, and Trapping Coordinating Committee (HFTCC) and the Ministère de la Forêt de la Faune et des Parcs (MFFP). Through a collaborative effort, biological data have been collected via the sport fishing program as a supplement to small scale environmental monitoring, which since 2004 has documented a continued decline in the somatic condition (K) of anadromous Deception Bay Arctic charr.

Anadromous Arctic charr in Deception Bay support subsistence fisheries in the neighbouring communities of Salluit and Kangiqsujuaq and an active commercial fishery in over-wintering lakes, Duquet and Françoys-Malherbe. Populations are also affected by recreational sport fisheries organized by the local mining operations. Nevertheless, research focused on the Deception Bay populations is limited, dated, and summer specific (Batterman and Cook 1981; Locke 1999; Locke 2001; Locke 2002). Additionally, the lack of data is part of a larger regional trend, as literature detailing resident and anadromous populations of Arctic charr in the Nunavik region of Québec remains scarce. Most of the available regional studies have focused on lacustrine Arctic charr, with a reduced set of studies having assessed anadromous populations (e.g., Boivin and Power, 1990; Murdoch and Power 2013a,b; van der Velden *et al.* 2013b), and only one study exists that directly examined issues related to over-wintering (Boivin and Power, 1990).

Preserving the sustainability of Arctic charr populations in Deception Bay is of critical importance, given the subsistence, commercial, and sport fishing importance of Arctic charr in the region. In an effort to address the concerns of the communities of Salluit and Kangiqsujuaq regarding the possible causes of the observed declines in the somatic condition of the Deception River Arctic charr population and to improve the overall scientific database on Nunavik Arctic charr populations, the HFTCC authorized the necessary scientific research hereafter outlined in this MSc. thesis.

Condition Indices

Given the apparent lack of literature associated with the impacts of over-wintering environmental conditions on anadromous Arctic charr in Nunavik, and the reported declines in somatic condition of Deception Bay Arctic charr, we examined known indices of fish condition that exhibit seasonal variation. Percent lipid (% lipid) analysis and bomb calorimetry for caloric content of dorsal muscle tissue were performed on both anadromous Arctic charr collected during summer (August 2016) and post-winter months (May 2017). The aforementioned methods yields data indicative of fish condition (Hoar 1939; Pinder and Eales, 1969; Naevdal *et al.* 1981; Herbinger and Friars, 1991; Dutil 1986; Thompson *et al.* 1991; Todd *et al.* 2008) and results of the two analyses are typically correlated (Weatherly and Gill, 1983; Soriguer *et al.* 1997; Anthony *et al.* 2000). Samples collected from Deception Bay, the marine environment where Arctic charr feed, and lakes Duquet and Françoys-Malherbe, where Arctic charr spawn and over-winter, quantified general lipid and caloric content of Deception Bay Arctic charr at distinctive points in the life-cycle, post-marine migration feeding and post-winter, and provided data for documenting the extent of seasonal variation.

Lipid analysis (%) was performed via lipid extraction employing methods as outlined in Folch *et al.* (1957) that provide accurate estimates of lipid content when lipids comprise greater than 2% of tissue (Iverson *et al.* 2001). Lipid content was calculated from the following equation:

$$\% \text{ Lipid } = \left(\left(\left(\frac{\text{Mass}_{\text{Dry}} \text{ (g)}}{\text{Mass}_{\text{Ground}} \text{ (g)}} \right) \right) * (1 - P_{\text{water}}) * 100\% * 20 \right);$$

and the procedure was duplicated to ensure accuracy and repeatability.

With bomb calorimetry, dorsal muscle tissue was dried and ground into a homogenate powder before being formed into pellets and ignited in a calorimeter that determined the sample's caloric content. Benzoic acid pellets were used to standardize the calorimeter and assess recovery (Washburn 1933). The data were examined in association with biological (fork-length, whole-weight, age, and somatic condition) and other analytical data (mercury concentrations and stable isotope values) as described in the following study objectives to assess seasonal variations and possible mechanisms driving condition indices.

Metal Analysis

Anthropogenic influence on the Deception River area include the Raglan Mine, Canadian Royalties Inc., and the historic Asbestos Hill Mine (Purtiniq). Mine personnel are present year round and a 95 kilometre road that closely follows the Deception River and its tributaries and connects Raglan Mine's main site Kattiniq with additional camps and a harbour in Deception Bay. Considering the close proximity of mining operations to Arctic charr habitat, the accumulation of metals was considered to be a possible stressor that had to be examined due to previously documented relationships with somatic condition in fish (Eastwood and Couture, 2002; Giguère *et al.* 2004; Maes *et al.* 2005; Pyle *et al.* 2005; Dehn et al 2006; Dittman and Driscoll, 2009; Swanson and Kidd, 2010) and the potential for metal accumulation in fish tissues

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to impact fish somatic condition and health (Sörensen 1991; Moiseenko and Kudryavtseva 2001; Couture and Kumar 2003; Pierron *et al.* 2011). Mining activity is one of the most prominent sources of pollution in aquatic ecosystems (Pannetier *et al.* 2015) and depending on the intensity and duration of the exposure, metal accumulation in somatic tissue can manifest as several pathologies. These can be inclusive of transcriptional changes (Pierron *et al.* 2011), reduced aerobic capacity in both muscle and whole fish (Couture and Kumar 2003), detrimental changes to the liver (e.g. changes in size and increased fragility) and pathologies associated with the kidneys (e.g. nephrocalcitosis and fibroelastosis) (Moiseenko and Kudryavtseva 2001). Additionally, metal accumulation in fish can interrupt ion regulation, disrupt the ability to perceive periphery events (i.e. the location of predators and prey), and reduced growth (Sörensen 1991) and condition (Eastwood and Couture, 2002; Giguère *et al.* 2004; Maes *et al.* 2005; Pyle *et al.* 2005; Dehn et al 2006; Dittman and Driscoll, 2009; Swanson and Kidd, 2010).

Most metals related metals research on Arctic charr has focused on mercury concentrations (Muir *et al.* 2005; Gantner *et al.* 2010; Swanson and Kidd, 2010; Swanson *et al.* 2011; Gantner *et al.* 2012; van der Velden *et al.* 2013a,b) and has generally neglected seasonal variation in tissue metal concentrations despite seasonal variation being reported for other species (e.g. European whitefish (*Coregonus lavaretus*) and Yellow perch (*Perca flavescens*)) and elements (e.g. cadmium, copper, mercury, nickel, lead, and zinc) (Köck *et al.* 1996; Eastwood and Couture, 2002; Kahilainen *et al.* 2016; Keva *et al.* 2017). For Arctic charr, seasonal migrations between freshwater and marine environments for summer feeding (Dutil 1986; Jonsson *et al.* 1988; Rikardsen *et al.* 2003; Power *et al.* 2008) have tended to result in habitat-related analyses because of the large differences in contamination that are observed

between marine and freshwater feeding conspecifics (Swason *et al.* 2011; van der Velden *et al.* 2012; van der Velden *et al.* 2013a,b).

For this thesis, analyses for total mercury (THg) dorsal muscle concentrations were completed using a Milestone Direct Mercury Analyzer (DMA) at the Institut National de la Recherche Scientifique (INRS) in Québec City, Québec, Canada as well as at the University of Waterloo in Waterloo, Ontario, Canada. The DMA permits assessment of mercury (Hg) concentrations via thermal decomposition employing temperatures up to 650°C followed by atomic absorption spectroscopy at a wavelength of 253.65 nm (Milestone 2010) using U.S. EPA method 7473 (**Fig. 1.1**). Arctic charr dorsal muscle and liver concentrations of arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) collected in summer from returning marine feeding fish and in winter from freshwater over-wintering fish were quantified by inductively coupled plasma mass spectrometry (ICP-MS). Concentrations of As, Cd, Cr, Cu, Ni, Pb, and Zn in samples were determined by digesting them with nitric acid followed by dilution with ultra-pure water, before ICP-MS analysis following methods outlined by the United States Geological Survey (2005) (**Fig. 1.2**). Certified reference materials from the National Research Council of Canada (NRCC) and blanks were subjected to identical analytical procedures and used to establish method precision and recovery.

Stable Isotope Analysis

When coupled with trace metal analysis, lipid analysis, and bomb calorimetry, stable isotope analysis can be useful for investigating patterns of accumulation. Additionally, stable isotope values can be used to infer relationships between food web metrics, including trophic position ($\delta^{15}N$), habitat use ($\delta^{13}C$), feeding relationships ($\delta^{13}C$ and $\delta^{15}N$), measures of fish condition (e.g., lipid and caloric content) and body tissue metal concentrations. Unlike stomach

content analysis, which only documents recent feeding (i.e., hours to days), stable isotope analyses can describe trophic interactions over longer periods of time (Fry and Sherr 1984; Peterson and Fry 1987; Hesslein et al 1993) and relative abundances of carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$) can allow inferences to be made about fish habitat use (Murdoch and Power 2013b), geographic distribution (Campana *et al.* 2000), ontogenetic life history traits (Grey 2001) and feeding relationships (Kling *et al.* 1992; Vander Zanden *et al.* 1998; Bearhop *et al.* 1999).

Nitrogen stable isotope values can be used to indicate food web position (Cabana and Rasmussen, 1994; Post 2002) as values are consistently incremented with trophic transfer (DeNiro and Epstein, 1981; Minagawa and Wada, 1984), and can be correlated with metal concentrations to estimate biomagnification (Kidd *et al.* 1995; Atwell *et al.* 1998; van der Velden 2013a). While carbon stable isotope values remain relatively constant during trophic transfer (DeNiro and Epstein, 1981; Fry and Sherr, 1984; Vander Zanden and Rasmussen, 2001), they provide insight into feeding location or habitat use (Hecky and Hesslein, 1995; Power et al., 2002).

Study Objectives

This MSc. research consisted of both an assessment of returning migrants from the marine environment in Deception Bay and an examination of post-wintering Arctic charr from Deception River headwater lakes, Lake Duquet and Lake Françoys-Malherbe. After detailed examination of the historical condition data, further investigation into associations between reported somatic condition declines of anadromous Deception Bay Arctic charr and 2016 and 2017 collected data was discontinued owing to historically small sample sizes and non-standardized sampling times or methods. As a result, further analysis of the data collected for

this thesis focused on seasonal comparisons to ascertain the importance of season for measures

of % lipid, caloric densities, and metal concentrations, as well as the relationships between

results and co-measured biological information and stable isotopes in anadromous Arctic charr.

Chapter 2 investigated seasonal variation in fish condition measures and contaminant

levels using dorsal muscle tissue for % lipid analysis, bomb calorimetry and Hg analysis.

Specifically, the chapter used data to test the hypotheses that: (i) biological variables associated

with over-wintering anorexia (e.g., whole-weight, somatic condition, and % nitrogen) would be

significantly reduced in post-winter fish; (Jøgensen *et al.* 1997; Jobling *et al.* 1998; Amundsen

and Knudsen, 2009; Power *et al.* 2009); (ii) % lipid and caloric content would be reduced in

Arctic charr collected during the post-winter sampling in comparison to fish captured during the

summer (Weatherly and Gill, 1983; Soriguer *et al.* 1997; Anthony *et al.* 2000), although % lipid

content and caloric value would remain positively correlated in both periods; (iii) dorsal muscle

% lipid and caloric densities would be positively correlated with biological variables (e.g. fork-

length, whole-weight, age, and somatic condition) (Hoar 1939; Pinder and Eales, 1969; Naevdal

et al. 1981; Harris *et al.* 1986; Herbinger and Friars, 1991; Dutil 1986; Thompson *et al.* 1991;

Anthony *et al.* 2000; Todd *et al.* 2008); and (iv) % lipid content and caloric density would be

positively correlated with carbon and nitrogen stable isotope values, % carbon, and % nitrogen

(Tieszen and Boutton, 1989; Pinnegar and Polunin, 1999; Post *et al.* 2007; Renkawitz *et al.*

2015).

Data were further used to test contamination hypotheses that: (v) total mercury (THg)

concentrations would be significantly higher during the post-winter sampling period as a result

of fasting-induced lipid and protein loss prompting subsequently higher concentrations of THg in

the remaining tissues; vi) THg concentrations would be negatively correlated with somatic

condition (Dittman and Driscoll, 2009; Swanson and Kidd, 2010); (vii) THg concentrations would be positively correlated with trophic position (δ^{15}N) and % nitrogen (Power *et al.* 2002; Muir *et al.* 2005; van der Velden *et al.* 2013a), but negatively correlated with the % carbon and the carbon stable isotope ratios, represented by δ^{13}C (Power *et al.* 2002); and (viii) THg concentrations would decline with increasing dorsal muscle % lipid and caloric density (Eisler 1987; Wiener *et al.* 2002; Swanson and Kidd, 2010; Kahilainent *et al.* 2016).

Additionally, we aimed to determine whether variation in dorsal muscle % lipid content, caloric density, and THg concentrations could be better described by multi-predictor variable statistical models inclusive of combinations of the previously mentioned variables and their interactions. Thus data were used to test the hypotheses: that (ix) fish condition (Fulton's K), as well as season, are most strongly related to % lipid and caloric content values determined from dorsal muscle tissue (Hoar 1939; Pinder and Eales, 1969; Naevdal *et al.* 1981; Herbinger and Friars, 1991; Dutil 1986; Thompson *et al.* 1991; Klemetsen *et al.* 2003b; Todd *et al.* 2008; Amundsen and Knudsen, 2009); and (x) variables associated with bioaccumulation (fork-length, weight, and/or age and trophic position represented by δ^{15}N) (Cizdziel *et al*., 2002; Power *et al.* 2002; Muir *et al.* 2005; Trudel and Rasmussen, 2006; van der Velden *et al.* 2013a), as well as season (Köck *et al.* 1996; Cizdziel *et al*., 2002; Cizdziel *et al.* 2003; Kahilainent *et al.* 2016; Keva *et al.* 2017), would be most indicative of THg concentrations (Weiner *et al.* 2002; Kahilainent *et al.* 2016).

Chapter 3 required collection of dorsal muscle and liver tissues from both Arctic charr sampled during the return summer migration and post-winter period to assess concentrations of As, Cd, Cr, Cu, Ni, Pb, and Zn with co-measured stable isotopes. Specifically, the data were used in the chapter to test hypotheses that: (i) concentrations of essential (Cu and Zn) and non-

essential metals (As, Cd, Cru, Ni, and Pb) would vary significantly by tissue type (Roméo *et al.* 1999; Andres *et al.*2000; Canli and Atli, 2003; Agah *et al.* 2009); (ii) concentrations would vary seasonally and be elevated in samples collected during the winter months (Köck *et al.* 1996; Cizdziel *et al.*, 2002; Cizdziel *et al.* 2003; Kahilainent *et al.* 2016; Keva *et al.* 2017); (iii) concentrations would be positively correlated with fork-length and age (Cizdziel *et al.*, 2002; Power *et al.* 2002; Trudel and Rasmussen, 2006) but decline with greater somatic condition values (Swanson and Kidd, 2010; Dittman and Driscoll, 2009); (iv) concentrations would be positively correlated with trophic position (Power *et al.* 2002; Muir *et al.* 2005; van der Velden *et al.* 2013a), but negatively correlated with carbon isotope values (Power *et al.* 2002); (v) models including information on trophic position or feeding strategies as represented by $\delta^{15}N$ and $\delta^{13}C$, in addition to season, best describe essential metal (Cu and Zn) concentration data due to uptake and handling processes associated with these metals (Shears and Fletcher, 1983; Handy 1996; Hardy *et al.* 1987; Glover and Hostrand, 2002; Kamunde *et al.* 2002a,b; Bury *et al.* 2003) and the dominance of seasonal summer feeding by anadromous Arctic charr; and, (vi) concentrations of non-essential metals would be best described by models inclusive of biological descriptors of bioaccumulation (fork-length and/or age and trophic position, as represented by $\delta^{15}N$, (Cizdziel *et al.*, 2002; Power *et al.* 2002; Muir *et al.* 2005; Trudel and Rasmussen, 2006; van der Velden *et al.* 2013a),) as well as season (Köck *et al.* 1996; Cizdziel *et al.*, 2002; Cizdziel *et al.* 2003; Kahilainent *et al.* 2016; Keva *et al.* 2017), as these variables are known to significantly influence measured metal concentrations in fish tissue (Weiner *et al.* 2002; Kahilainent *et al.* 2016).

Drying Period (160°C)
1 min

↓

Decomposition Period 1 (650°C)
2 min

↓

Decomposition Period 2 (650°C)
1 min

↓

Purge Time
240 sec
(This step in analysis predicates the initiation of THg concentration measurement)

↓

Amalgamation Time
12 sec
(Time required to release Hg to the absorption cells)

↓

Recording Time
30 sec

Total time: 8.7 min

Fig. 1.1. The program employed by the DMA-80 for determination of THg concentrations in anadromous Deception River Arctic charr tissues.

Sample Introduction

↓

Nebulization or Electrothermal Vapourization
Samples must be introduced to the torch in a gaseous form,
so liquid samples must be nebulized by argon gas, while
solid samples are rapidly vapourized before being swept into
the inductively coupled plasma (ICP) torch via argon gas

↓

ICP Torch (6000°C) Atomization
The aerosoal sample enters the high temperature plasma
where it is subsequently dried to a solid, before being
atomized to a gaseous product

↓

ICP Torch (6000°C) Ionization
The atomized product continuously travels through the
plasma, absorbing energy until the atoms release an
electron, becoming ionized

↓

Interface
The sample from the inductively coupled plasma is
introduced to mass spectrometry (MS). The interface allows
a coupling of the ICP and MS portions of the machine

↓

Mass Spectrometry
MS provides information on the elemental composition of
the specified sample

↓

Detection
The detector separates the signal ions of interest from
background noise, before data is sent to an accompanying
computer for processing

Fig. 1.2. The process used by an ICP-MS to determine the elemental composition of dorsal muscle and liver tissue samples from anadromous Deception River Arctic charr.

Chapter 2: Seasonal variation of total mercury and condition indices of Arctic charr

(*Salvelinus alpinus*) in Northern Québec, Canada

Introduction

Arctic charr (*Salvelinus alpinus*) are the most northerly distributed freshwater fish species on earth and exhibit diverse life history strategies (Jonsson *et al.* 1988) that include anadromous and non-anadromous types. Anadromous Arctic charr overwinter in freshwater with seaward migrations beginning after ice break up in the spring (Johnson 1983; Klemetsen *et al.* 2003a). It is during this period of marine residency that fish feed opportunistically and grow rapidly (Grønvik and Klemetsen 1987; Dempson *et al.* 2002). Historically, studies of anadromous Arctic charr have focused on the period of marine residency and its consequences for growth and maturation (Mathisen and Berg 1968; Berg and Berg, 1989; Finstad and Heggberget 1993; Jørgensen, *et al.* 1997; Power *et al.* 2008, Murdoch *et al.* 2015), but have been traditionally lacking winter data (Mulder *et al.* 2018). Available over-wintering data have focused on resident lacustrine Arctic charr condition, diet, and habitat during the ice-covered months (Knudsen *et al.* 1996; Svenning *et al.* 2007; Klemetsen *et al.* 2003b; Amundsen and Knudsen, 2009; Power *et al.* 2009; Eloranta *et al.* 2013), but the ecology of over-wintering anadromous Arctic charr has been poorly described in the literature beyond the noted cessation of feeding and resulting reduced condition (e. g. Sprules 1952; Moore and Moore, 1974; Dutil 1986; Boivin and Power, 1990; Jørgensen, *et al.* 1997; Rikardsen *et al.* 2003).

Winter for anadromous Arctic charr is a stressful period characterized by periods of ice cover that can exceed ten months (Svenning and Gullestad, 2002; Klemetsen *et al.* 2003a,b). During winter lipid and protein body reserves have been reported to decline by up to 30% for non-reproductive individuals and 35-46% for post-spawning Arctic charr (Dutil 1986, Jørgensen,

et al. 1997). Yet documented over-winter mortality rates appear to be low (Klemetsen *et al.* 2003b; Byström *et al.* 2006; Svenning *et al.* 2007; Aundsen and Knudsen, 2009; Siikavuopio *et al.* 2009). The minimization of movement, use of colder water temperatures to reduce metabolism (Mulder *et al.* 2018), lack of suitable prey (Boivin and Power, 1990), and the implications of light restrictions on prey capture efficiency (Mazur and Beauchamp 2003; Turesson and Brönmark, 2007) all suggest significantly reduced feeding or fasting during the winter months. In lacustrine resident populations of Arctic charr, winter feeding has been documented to some extent in the literature (e.g., Klemetsen *et al.* 2003b, Svenning *et al.* 2007, Power *et al.* 2009, Eloranta *et al.* 2013), but has only been inferred for anadromous individuals based on activity and habitat use (Boivin 1987; Mulder *et al.* 2018).

In addition to losses in lipids and overall reductions in condition, prolonged periods of reduced feeding can have other significant consequences for over-wintering fish. Critical among those effects are the possible associated changes in tissue contaminant levels. Methylmercury (MeHg) is one contaminant of specific concern due to its neurologically toxic health effects (Mergler *et al.* 2007) and its ability to bioaccumulate in aquatic food webs to reach high concentrations in predatory fish (Kidd *et al.* 1995; Muir *et al.* 2005; Power *et al.* 2002; Evans *et al.* 2005; Lockhart *et al.* 2005; Gantner *et al.* 2010; van der Velden *et al.* 2013a). In fish, MeHg concentrations are typically greater than 90% of total mercury (THg) (Hall *et al.* 1997; Lockhart *et al.* 2005; Eagles-Smith *et al.* 2016) making MeHg levels in fish of particular concern to Inuit peoples who consume large quantities of fish (Lemire *et al.* 2015). Measured concentrations of THg are often related to numerous biological variables such as: fish size, age, trophic position (δ^{15}N), feeding strategies and habitat use (δ^{13}C) , growth, and somatic condition (Kidd *et al.* 1995; Greenfield *et al.* 2001; Weiner *et al.* 2002; Power *et al.* 2002; Trudel and Rasmussen,

2006; Crump and Trudeau, 2009; Dittman and Driscoll, 2009; Weis, 2009), but also have been shown to be dependent on lipid content and protein (Eisler 1987; Wiener *et al.* 2002; Swanson and Kidd, 2010; Kahilainent *et al.* 2016). While THg in fish tissues is derived almost exclusively from prey consumption (Hall *et al.* 1997), lipid and protein loss prompted by a cessation of feeding during the winter months can result in a phenomenon known as starvation – concentration (Cizdziel et al., 2002, Cizdziel *et al.* 2003) that condenses mercury in remaining tissues (Kahilainent *et al.* 2016) resulting in higher THg during the ice-covered period (Keva *et al.* 2017). While seasonal variations in THg have been reported in lacustrine resident Arctic charr, as well as other fish species (Kahilainent *et al.* 2016; Keva *et al.* 2017), they are still relatively understudied and have yet to be documented for anadromous Arctic charr. Quantifying seasonal variations in THg concentrations in anadromous Arctic charr may further help determine differences in seasonal risks for capture and consumption associated with the winter fishery for Arctic charr that provides an important component of the year-round diet of the Inuit throughout the Nunavik region (e.g., Boivin and Power, 1990).

Similar to other areas of Arctic Canada, anadromous Arctic charr in Deception Bay, Nunavik, Québec, form the basis of important subsistence fisheries in local communities (e.g., Salluit and Kangiqsujuaq). In addition, there is an active commercial fishery in Deception Bay and Lakes Duquet (Tasialujjuaq) and Françoys-Malherbe (Pangaligiak), as well as a recreational sport fishery organized by the local mining operations. Despite the cultural and economic importance of Arctic charr to the local Indigenous communities, literature on resident and anadromous populations of Arctic charr in the Nunavik region of Québec remains scarce (e.g Murdoch and Power, 2013b), with most of the available regional studies having focused on lacustrine Arctic charr. A reduced set of studies does examine anadromous populations (e.g.,

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Boivin and Power, 1990; Murdoch and Power 2013a,b; van der Velden *et al.* 2013b), with only one directly examining issues related to seasonal changes in condition (Boivin and Power, 1990). Given the cultural and economic importance of anadromous Arctic charr in Nunavik, Québec, the lack of understanding regarding possible seasonal variations in THg in captured fish represents an important knowledge gap that needs to be addressed.

Here samples collected from Deception Bay, where Arctic charr migrate and feed, and lakes Duquet and Françoys-Malherbe, where Arctic charr spawn and over-winter, are used to investigate patterns of seasonal change in both fish condition measures and THg concentrations. Specifically, data were used to test the following condition hypotheses that: (i) biological variables descriptive of over-wintering anorexia and prolonged periods of fasting (e.g., whole-weight, somatic condition, and % nitrogen) would be significantly reduced in post-winter fish as compared to late summer captured fish; (Jøgensen *et al.* 1997; Jobling *et al.* 1998; Amundsen and Knudsen, 2009; Power *et al.* 2009); (ii) percent lipid (% lipid) and caloric content would be reduced in Arctic charr collected during the post-winter sampling period as compared to the late summer sampling period as a result of the mobilization of stored lipid and protein to meet metabolic demands during the over-wintering period, with % lipid content correlating positively with caloric value measures (Weatherly and Gill, 1983; Soriguer *et al.* 1997; Anthony *et al.* 2000); (iii) dorsal muscle % lipid and caloric densities would be positively correlated with biological descriptors fork-length, whole-weight, age, and somatic condition (Hoar 1939; Pinder and Eales, 1969; Naevdal *et al.* 1981; Harris *et al.* 1986; Herbinger and Friars, 1991; Dutil 1986; Thompson *et al.* 1991; Anthony *et al.* 2000; Todd *et al.* 2008); and (iv) positively correlated with carbon and nitrogen stable isotope values, % carbon, and % nitrogen (Tieszen and Boutton, 1989; Pinnegar and Polunin, 1999; Post *et al.* 2007; Renkawitz *et al.* 2015).

Data were further used to test the following contamination hypotheses that: (v) THg concentrations would be higher during the post-winter sampling period than the late summer sampling period as a result of fasting-induced lipid and protein loss and the subsequent condensation of mercury in the remaining tissues; (vi) THg concentrations would be negatively correlated with somatic condition (Dittman and Driscoll, 2009; Swanson and Kidd, 2010); (vii) THg concentrations would be positively correlated with trophic position and % nitrogen (Power *et al.* 2002; Muir *et al.* 2005; van der Velden *et al.* 2013a), but negatively correlated with the % carbon and the carbon stable isotope gradient (Power *et al.* 2002); and (viii) THg concentrations would decline with rising dorsal % lipid and caloric density (Eisler 1987; Wiener *et al.* 2002; Swanson and Kidd, 2010; Kahilainen *et al.* 2016).

In addition, we aimed to determine whether dorsal muscle % lipid content, caloric density, and THg concentrations could be better described by multi-predictor variable statistical models inclusive of combinations of the above tested variables and their interactions. Thus data were used to test the hypotheses: that (ix) season and/or fish condition (Fulton's K) would best describe % lipid values and caloric content (Hoar 1939; Pinder and Eales, 1969; Naevdal *et al.* 1981; Herbinger and Friars, 1991; Dutil 1986; Thompson *et al.* 1991; Todd *et al.* 2008); and (x) variables associated with bioaccumulation (fork-length, weight and/or age and trophic position represented by δ^{15}N) (Cizdziel *et al*., 2002; Power *et al.* 2002; Muir *et al.* 2005; Trudel and Rasmussen, 2006; van der Velden *et al.* 2013a), as well as season (Köck *et al.* 1996; Cizdziel *et al*., 2002; Cizdziel *et al.* 2003; Kahilainent *et al.* 2016; Keva *et al.* 2017), would be most indicative of THg concentrations as these variables are known to significantly influence measured THg concentrations in fish tissue (Weiner *et al.* 2002; Kahilainent *et al.* 2016).
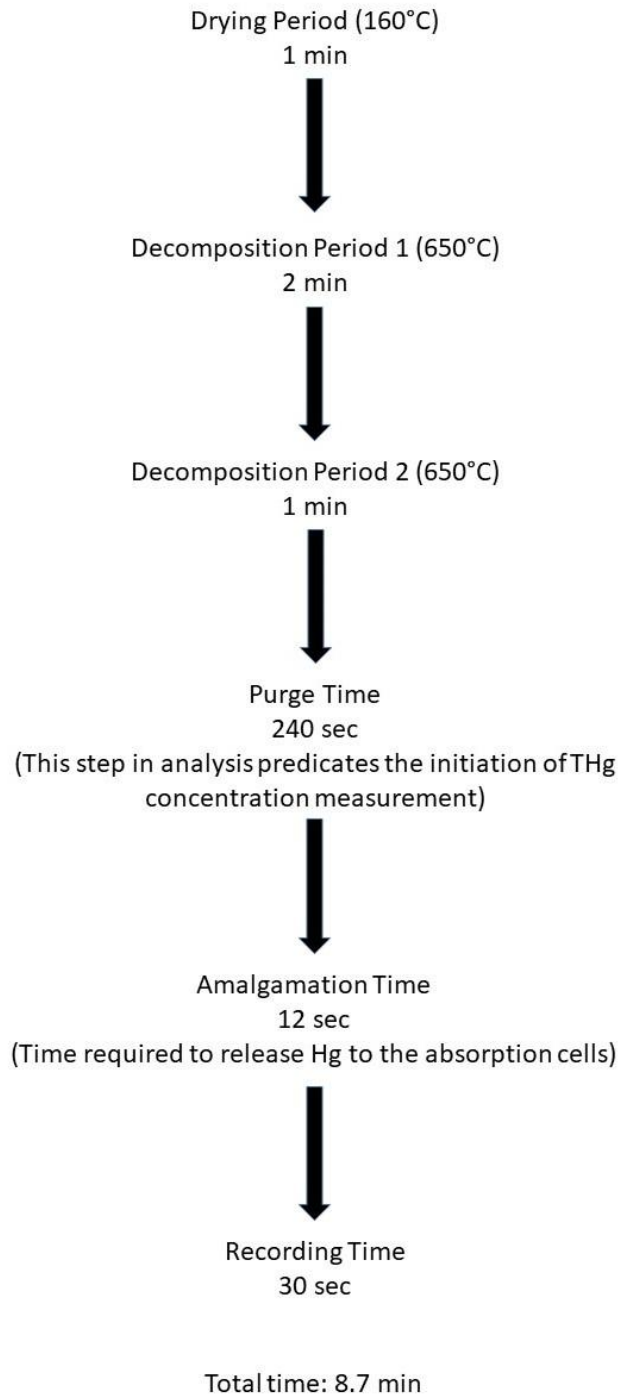
Methods

Study Area

The Deception River and its tributaries (**Fig. 2.1**) are located east of Salluit, Québec (62°10'46 N, 75°40'13 W) and span an area 3 870 km^2 between latitudes 61°31'26" N and 62°11'01" N. The river flows into Deception Bay, which is associated with the Hudson Strait marine ecosystem (Goldsmit *et al.* 2014), a deep and wide channel that connects Hudson Bay and the Foxe Basin with the Labrador Sea and the Davis Strait (Drinkwater 1986). Average daily temperatures range from -25.6ºC in February, to 10.5ºC in August (Environment Canada 2011a,b), with a growing season of less than 120 days per year. In addition to traditional hunting and fishing, the area is impacted by two nickel and copper mining projects: the Raglan Mine and Canadian Royalties Inc., and is proximate to the now closed Asbestos Hill Mine (Purtiniq). A 95 kilometre road connects the main Raglan mining site with an additional camp and harbour in Deception Bay. Mine personnel are present year round and the road closely follows the Deception River and its tributaries for most of its length. Arctic charr spawn and overwinter in headwater lakes Duquet (62°03'18 N, 74°31'51 W) and Françoys-Malherbe (62°00'06 N, 74°15'25 W) from October to June. The lakes are located 2.5 km and 15 km, respectively, upstream of the river mouth. There is a commercial fishing permit active for both lakes, and a Raglan Mine sport fishing permit is active for Lake Françoys-Malherbe.

Sample Collection

Summer sample collection of anadromous Arctic charr was completed using multi-mesh experimental gill nets (25 – 150 mm X 120 m) set at eight locations in Deception Bay and from the mouth of the Deception River in August of 2016 coincident with the returning upstream migration period. A second post-winter sample of Arctic charr was obtained from lakes

Françoys-Malherbe (May 8th – 11th, 2017) and Duquet (May 12th – 13th, 2017), approximately a month prior to ice break-up (reported for the area by the Canadian Ice Service (2018) as June 26th, 2017). Post-winter samples were collected throughout the lakes with jigging lines by Nunavik Research Centre (NRC) staff in collaboration with the Elder's Spring Fishing Event hosted by Qaqqalik Landholding Corporation and supported by Raglan Mine.

In the laboratory, all summer and winter captured Arctic charr were weighed ($\pm$ 1 g) and measured for fork-length ($\pm$ 1 mm) and these measurements were used to calculate Fulton's condition factor ($K = 10^5 * W/L^3$). Isometric growth was determined by the slope of standardized weight-length regression (Deception Bay sampling – 3.12, post-winter sampling – 3. 03) (Ricker, 1975) and it was confirmed that the slope did not differ significantly from 3 (Deception Bay, t-test, $p = 0.4569$, post-winter sampling, t-test, $p = 0.2546$). A sample of dorsal muscle tissue ($\approx$10 g) was removed from above the lateral line and posterior to the dorsal fin on the left side of each Arctic charr (van der Velden 2013a) and frozen for subsequent laboratory analyses. A random sub-sample from each season was chosen for lipid analysis, bomb calorimetry, and THg analysis. Tissue for THg analysis were placed in acid washed (15% HNO_3) Eppendorf polypropylene tubes that had been rinsed seven times in ultrapure water before use in an effort to minimize accidental metal contamination. The upper gastrointestinal tract (e.g. esophagus and stomach) of all post-winter collected fish was examined to determine whether the presence of short term winter feeding could be identified. Anadromy of Arctic charr captured during this sampling period was also confirmed with $\delta^{34}S$ stable isotope analysis following methods described in Doucett *et al.* (1999). Aging of all sampled fish was completed by NRC staff, with fish ages determined by submersing the otolith in water and examining it with reflected light under a dissecting microscope (Chilton and Beamish 1982).

Stable Isotope Analysis

For stable isotope analyses, dorsal muscle tissue was dried at 50°C for 48 h and then pulverized into a homogenate powder with a mortar and pestle. After being weighed to 0.275 – 0.300 mg (UMX2, Mettler-Toledo GmbH, Greifensee, Switzerland), tissue was simultaneously analyzed for stable carbon and nitrogen stable isotope ratios ($\delta^{13}C$, $\delta^{15}N$) at the Environmental Isotope Laboratory, University of Waterloo, Ontario, Canada with a Delta Plus Continuous Flow Stable Isotope Ratio Mass Spectrometer (Thermo Finnigan, Bremen, Germany) coupled to a Carlo Erba Elemental Analyzer (CHNS-O EA1108, Carlo Erba, Milan, Italy) following methods described in van der Velden *et al.* (2013a). Elemental compositions were expressed in ‰ based on pre-analysis weights. All stable isotope measurements were expressed using standard delta notation (δ) as parts per thousand differences (‰) with respect to the international reference standards of Vienna Peedee Belemnite carbonate rock for $\delta^{13}C$ (Craig 1957) and nitrogen gas in the atmosphere for $\delta^{15}N$ (Mariotti 1983):

$$\delta R = \left[\frac{R_{sample} - R_{standard}}{R_{standard}}\right] x \; 1000$$

δR is the measured carbon ($^{13}C/^{12}C$) or nitrogen ($^{15}N/^{14}N$) isotope ratio expressed with respect to the appropriate international standard and % carbon and % nitrogen sample composition is obtained from the elemental analyzer and is measured coincidentally. Machine analytical precision was determined to be ± 0.2‰ for $\delta^{13}C$ and ± 0.3‰ for $\delta^{15}N$ and was established via repeat analysis of internal laboratory working standards (IAEA-N_1 + N_2, IAEA-CH_3 + CH_6) cross calibrated to International Atomic Energy Agency (IAEA) standards: CH_6 for $\delta^{13}C$ and N_1 and N_2 for $\delta^{15}N$. Internal standards were placed at the beginning, middle and end of every run of samples and repeatability was assessed by repeat analysis of 1 in 10 samples. As C:N ratios were consistently below the 4.0 threshold above which extraction is required (Logan *et al.* 2008;

Sanderson *et al.* 2009; Jardine *et al.* 2011), $\delta^{13}C$ values were not lipid extracted or mathematically normalized for lipid content.

Lipid Analysis and Bomb Calorimetry

Lipid analysis and bomb calorimetry were performed at the University of Waterloo, Waterloo, Ontario, Canada. A modified version of the procedure outlined in Folch *et al.* (1957) was used for lipid extraction as this method provides accurate estimates of lipid content when lipids comprise greater than 2% of tissue (Iverson *et al.* 2001). After freeze drying (Freezone Plus 2.5 Liter Cascade Benchtop Freeze Dry Systems, Labconco, Kansas City, USA), Arctic charr dorsal muscle tissue was ground with a mortar and pestle and weighed to approximately 0.030 g ± 0.1 mg (XS205DU Analytical Balance, Mettler Toledo, Mississauga, Canada). 2 mL of a 2:1 chloroform-methanol solution and 1.6 mL of a 0.9% KCl solution were then added to the ground tissue. The resulting solution was then homogenized with a vortex (Fisherbrand Analog Vortex Mixer, Fisher Scientific, Hampton, USA) and centrifuged (Fisherbrand™ Centrific Model 225A Benchtop Centrifuge, Fisher Scientific, Hampton, USA) at 2000 RPM for 5 minutes until the KCl, tissue, and chloroform-methanol layers were completely separated. The lipid containing solution was then extracted via Pasteur pipette through the KCl and residual biomass layers. Three iterations of the procedure were performed until a final lipid solution of 8 mL was obtained. The lipid-containing solution was then evaporated to dryness. Once dry, an additional 2 mL of 2:1 chloroform-methanol solution were added to the dried material and two, 100 μL aliquots were then transferred to pre-weighed tin cups. The solution was evaporated at room temperature overnight until only dry lipids remained. Remains were weighed on a micro-balance (UMX2, Mettler-Toledo GmbH, Greifensee, Switzerland) to determine the percentage of lipid in the dorsal muscle tissue expressed as:

$$\% \text{ Lipid } = \left(\left(\left(\frac{\text{Mass}_{\text{Dry}} \text{ (g)}}{\text{Mass}_{\text{Ground}} \text{ (g)}} \right) \right) * (1 - \text{P}_{\text{Water}}) * 100\% * 20 \right);$$

where Mass_{Dry} is the weight of the dried lipid following the extraction procedure, $\text{Mass}_{\text{Ground}}$ is

the initial ground mass of the tissue preceding extraction, P_{Water} is the proportion of water in the

analyzed dorsal muscle tissue (wet tissue mass (g) – dry tissue mass (g)), and with 20

representing a correction as a result of using only a subset of the final extraction solution volume

for establishing the final dried mass (Folch *et al.* 1957).

For bomb calorimetry, Arctic charr dorsal muscle tissue was dried at 50°C for 48 hours

and ground to obtain a homogenized sample using a mortar and pestle. Pellets were formed (Parr

Pellet Press, Parr Instrument Company, Moline, USA) with weights not exceeding 0.5 mg ± 0.1

mg (XS205DU Analytical Balance, Mettler Toledo, Mississauga, Canada) before ignition in a

Parr Semi-micro Calorimeter 6725 (Parr Instrument Company, Moline, USA) to measure caloric

density (cal·g^{-1} dry mass). The wet mass caloric density was determined by multiplying the dry

mass caloric density by the proportion of final dry mass to original wet mass (Glover *et al.*

2010). Results were represented by wet weight (ww) caloric density means ± standard deviation.

Benzoic acid pellets with a caloric density of 6318.4 cal·g^{-1} dry weight (dw) were used to

standardize the calorimeter and assess recovery every 10th sample. Percent recovery ± standard

deviation of benzoic acid pellets ($n = 11$) was determined to be 100.35% ± 1.07%.

Mercury Analysis

Mercury analysis was performed at the Institut National de la Recherche Scientifique

(INRS) in Québec City, Québec, Canada and at the University of Waterloo in Waterloo, Ontario,

Canada. After freeze-drying (FTS Systems TMM, Kinetics Thermal Systems, Longueil, QC,

Canada; Freezone Plus 2.5 Liter Cascade Benchtop Freeze Dry Systems, Labconco, Kansas City,

USA), tissue was weighed to approximately 0.050 – 0.100 g ± 0.1 mg (Series 321 LT 220A

Balance, Precisa Gravimetrics AG, Dietikon, Switzerland; Mettler Toledo, Mississauga, Canada). Analysis was then performed with a direct mercury analyzer (DMA-80, Milestone Inc., Shelton, USA) which enables assessment of THg through thermal decomposition followed by atomic absorption spectroscopy as described in U.S. EPA method 7473 (U.S. Environmental Protection Agency, 2007). Results were converted from dry weight to wet weight using percent moisture calculations determined from weights ($\pm$ 0.1 mg) taken before and after lyophilisation (Eikenberry *et al.* 2015).

As past studies have indicated that age (van der Velden *et al.* 2013b) and/or length (Rigét et al., 2000; Swanson et al., 2011) are often strongly correlated with THg concentrations such that THg concentrations requires suitable age or length adjustment to permit comparisons among individuals, data were examined for evidence of significant length and/or age correlations using linear regression ($\log_{10}$THg vs. $\log_{10}$fork-length, fork-length, or age) (Tran *et al.* 2015). The effect of lipids on analytical results was examined by comparing differences in relationships obtained using raw and lipid corrected THg concentrations, with lipid corrected THg concentrations computed following methods described in Kahilainen *et al.* (2016).

Method detection limits and percent recoveries are reported as mean percentage of certified value $\pm$ standard deviation. Tissues were evaluated in triplicate with certified reference materials from the National Research Council of Canada (NRCC) (TORT-3, DOLT-4, and DOLT-5). Blanks were used every fifth sample in the same analytical cycle to establish accuracy and recovery rates. The method detection limit, determined as $3\times$ the standard deviation of blanks, was 2.91 ng Hg (approximately 0.003 ($mg \cdot kg^{-1}$)) and mean relative standard deviation of the triplicates was 5.53% ($n = 108$). Percent recoveries were determined to be 99.32 ± 7.42 ($n =$

52), 93.16 ± 9.04 (n = 47), and 88.95 ± 3.88 (n = 16) for TORT-3, DOLT-4, and DOLT-5 respectively.

Statistical Analysis

All statistical analyses were performed using JMP statistical software (v. 13.0.0, SAS Institute, CA) and Type I error was set to α = 0.05. Data consistency with normality and homoscedasticity assumptions were verified using residual diagnostic histograms, visual assessment of Q-Q plots, and the Shapiro-Wilk test (Shapiro and Wilk, 1965). Data that did not meet parametric assumptions were $\log_{10}$ transformed (Zar, 2010). Linear regressions were used to determine the relationship significance between specific variables and un-paired, two-sample t-tests adjusted for homogeneity of variance assumptions were used to determine significant differences among seasons (Zar, 2010). The Wilcoxon approach was used when data did not conform to the required parametric assumptions (Zar, 2010).

General linear models (GLM) inclusive of season, fork-length, whole-weight, age, somatic condition, $\delta^{13}C$, % carbon, $\delta^{15}N$ and % nitrogen were used to determine the best model to describe dorsal muscle % lipid values, caloric densities, and THg concentrations. Pearson correlation analysis (**see Appendix Tables 3.1 – 3.3**) and/or linear regression were used to establish the significance of variables expected to correlate with dorsal muscle % lipid values, caloric densities, and THg concentrations, with only significant variables being retained for use in GLM models. Significant two-way interactions among variables were similarly assessed, with significant interactions retained for use in GLM models. To reduce statistical issues associated with multicollinearity (Zar 2010), possible explanatory variables that were highly correlated ($r^2 >$ 0.70) or known to have biological redundancy (e.g. fork-length and whole-weight) were not included in the same model. To predict seasonal dorsal muscle % lipid values, caloric densities,

or THg concentrations models that included all possible combinations of the feasible set of significant explanatory variables and two-way interactions, as determined above, were considered.

Model selection was performed using the Akaike Information Criteria (*AIC*) adjusted for small sample sizes (*AICc*). The model with the lowest *AICc* score was considered the most accurate, except in circumstances where *AICc* values differed by less than two (Burnham and Anderson, 2002). Detailed description of the computation of the analytical metrics associated with the *AICc* methodology used here can be found in Burnham and Anderson (2002).

Results

In total, 200 anadromous Arctic charr were obtained from the August 2016 sampling in the marine environment and 118 from the post-winter sampling in spring 2017. Of those, $n = 40$ fish from the summer and post-winter season were sub-sampled for lipid analysis and $n = 30$ were retained from each sampling season for bomb calorimetry. For THg analysis $n = 49$ dorsal muscle samples from Deception Bay captured Arctic charr and $n = 55$ post-winter fish were used. Samples from the post-winter season came almost equally from lakes Duquet and Françoys-Malherbe (**Table 2.2**). Testing with δ^{34}S stable isotope analyses indicated $n = 4$ fish in the lipid and THg testing subset and $n = 3$ in the calorimetry testing subset were non-anadromous and these were excluded from further consideration. Regressions of fork-length and age against THg concentrations in summer or post-winter sampled fish were either non-significant (summer fork-length vs. THg concentrations: $r^2 = 0.03$, $p = 0.2460$; post-winter age vs. THg concentrations: $r^2 = 0.01$, $p = 0.4058$) or yielded regressions that poorly explained variation in THg concentrations (post-winter fork-length vs. THg concentrations: $r^2 = 0.09$, $p = 0.0335$; summer age vs. THg concentrations: $r^2 = 0.20$, $p = 0.0014$) and displayed significant

heteroscedasticity indicative of their statistical inadequacy. As such there was no compelling statistical evidence for length or age standardization of the THg concentrations data and raw results were used in all subsequent statistical analyses.

Seasonal Variation in Biological Variables and Stable Isotope Values

Means ± standard deviations and ranges for biological variables and stable isotope values for all summer sampled ($n = 61$) and post-winter captured ($n = 59$) Arctic charr can be found in **Table 2.1**. Biological variables descriptive of possible over-wintering anorexia including somatic condition ($Z_{(1,121)} = 4.36$, $p < 0.0001$) and % nitrogen ($Z_{(1,121)} = 6.80$, $p < 0.0001$) were significantly reduced in post-winter sampled Arctic charr, while whole-weight exhibited no significant seasonal variation ($t_{(1,121)} = 1.39$, $p = 0.1664$). Additionally, fork-length ($t_{(1,121)} = 0.20$, $p = 0.8380$), age ($t_{(1,118)} = 0.40$, $p = 0.6915$), % carbon ($Z_{(1,121)} = -1.11$, $p = 0.2658$), and $\delta^{15}N$ values ($t_{(1,121)} = -1.76$, $p = 0.0811$) of captured fish did not vary seasonally, while $\delta^{13}C$ was significantly more depleted in post-winter sampled Arctic charr ($Z_{(1,121)} = -5.85$, $p < 0.0001$). No evidence of short term winter feeding was determined via examination of the upper gastrointestinal tract.

Lipid Content and Caloric Density

Means ± standard deviations and ranges for % lipid values and caloric densities can be found in **Table 2.2** and significant seasonal variation existed for lipid content ($t_{(1,74)} = -6.49$, $p < 0.0001$) and caloric density ($t_{(1,55)} = -11.70$, $p < 0.0001$). Lipid content explained 28% of the variation in caloric density of Arctic charr during the post-winter fishery ($r^2 = 0.28$, $p = 0.0049$), but values were not significantly correlated in Arctic charr captured returning from the marine environment ($r^2 = 0.09$, $p = 0.1178$).

Relationships between % lipid values and caloric densities and studied correlates can be seen in **Fig. 2.2** through to **Fig. 2.5**. While % lipid values of late summer migrants significantly declined with increased offshore feeding ($r^2 = 0.12$, $p = 0.0296$) and % nitrogen values ($r^2 = 0.14$, $p = 0.0169$), but no significant relationships existed with fork-length ($r^2 = 0.00$, $p = 0.9747$), whole-weight ($r^2 = 0.00$, $p = 0.8035$), age ($r^2 = 0.00$, $p = 0.8633$), somatic condition ($r^2 = 0.01$, $p = 0.6556$), % carbon ($r^2 = 0.03$, $p = 0.2651$), or $\delta^{15}N$ values ($r^2 = 0.00$, $p = 0.8857$). Relationships with % lipid values and the studied variables of interest in post-winter sampled Arctic charr followed similar trends and were not significantly related to fork-length ($r^2 = 0.00$, $p = 0.9925$), whole-weight ($r^2 = 0.00$, $p = 0.8301$), age ($r^2 = 0.02$, $p = 0.4496$), somatic condition ($r^2 = 0.01$, $p = 0.5739$), $\delta^{15}N$ values ($r^2 = 0.02$, $p = 0.4196$), but decreased with % nitrogen ($r^2 = 0.12$, $p = 0.0347$). However, in this circumstance % lipid values were not significantly related to $\delta^{13}C$ values ($r^2 = 0.04$, $p = 0.2496$) and significantly increased with greater % carbon ($r^2 = 0.11$, $p = 0.0478$),

Caloric densities of late summer sampled Arctic charr were not significantly related to any of the variables of interest (whole-weight ($r^2 = 0.12$, $p = 0.0557$), fish age ($r^2 = 0.01$, $p = 0.5270$), somatic condition ($r^2 = 0.04$, $p = 0.2650$), stable isotope values ($\delta^{13}C$ ($r^2 = 0.03$, $p = 0.3842$); $\delta^{15}N$ ($r^2 = 0.13$, $p = 0.0537$)), % carbon ($r^2 = 0.05$, $p = 0.2415$), or % nitrogen ($r^2 = 0.04$, $p = 0.2659$)), except for fork-length ($r^2 = 0.16$, $p = 0.0308$). Caloric densities determined from the dorsal muscle of post-winter sampled Arctic charr were not significantly related to fork-length ($r^2 = 0.12$, $p = 0.0827$), whole-weight ($r^2 = 0.12$, $p = 0.0743$), fish age ($r^2 = 0.11$, $p = 0.0907$), somatic condition ($r^2 = 0.03$, $p = 0.3697$), or stable isotope values ($\delta^{13}C$ ($r^2 = 0.09$, $p = 0.1289$); $\delta^{15}N$ ($r^2 = 0.04$, $p = 0.2920$)), but values did significantly increase with % carbon ($r^2 = 0.30$, $p = 0.0030$) and decrease with % nitrogen ($r^2 = 0.43$, $p = 0.0002$).

THg

Mean THg concentrations ± standard deviations are reported in **Table 2.2** and contrary to what was hypothesized, THg concentrations of summer captured Arctic charr were significantly greater than those obtained from post-winter fish ($t_{(1,98)}$ = 2.59, p = 0.0109). Relationships between THg concentrations and tested variables (fork-length, whole-weight, age, somatic condition, $\delta^{13}C$, % carbon, $\delta^{15}N$, and % nitrogen) in both summer and post-winter sampled Arctic charr are visualized in **Fig. 2.6** and **Fig. 2.7**. THg concentrations of late summer migrants had no significant relationship with whole-weight (r^2 = 0.02, p = 0.3277), somatic condition, (r^2 = 0.02, p = 0.2959), $\delta^{15}N$ values (r^2 = 0.00, p = 0.7542), or % nitrogen (r^2 = 0.00, p = 0.7048), but did significantly decline with % carbon (r^2 = 0.19, p = 0.0017), and increase with offshore feeding (r^2 = 0.23, p = 0.0004). THg concentrations of post-winter sampled Arctic charr significantly increased with whole-weight (r^2 = 0.14, p = 0.0059) and $\delta^{15}N$ values (r^2 = 0.09, p = 0.0306), but had no significant relationship with any other variables of interest (somatic condition, (r^2 = 0.04, p = 0.1655); $\delta^{13}C$ values (r^2 = 0.05, p = 0.0990); % carbon (r^2 = 0.01, p = 0.5977); or % nitrogen (r^2 = 0.01, p = 0.4803)).

Relationships between THg concentrations, % lipid values, and caloric densities are visualized in **Fig. 2.8**. THg concentrations significantly declined with increasing lipid content in late summer captured Arctic charr (r^2 = 0.20, p = 0.0176), but were unrelated to % lipid values in post-winter sampled individuals (r^2 = 0.11, p = 0.0982). Additionally, THg concentrations were not significantly related to dorsal muscle caloric densities in either season (r^2 = 0.05, p = 0.3484 and r^2 = 0.00, p = 0.8168; summer and post-winter captured fish, respectively).

General Linear Models

Models best explaining variation in % lipid values, caloric densities and THg concentrations are reported in **Table 2.3**. *AICc* model selection established that % lipid values were best described by the model inclusive of season, % carbon, and % nitrogen, while variation in caloric densities were similarly supported by 3 models: (1) season, age, condition, % carbon, and % nitrogen; (2) season, fork-length, condition % carbon, and % nitrogen; and (3) season, whole-weight, condition, % carbon, and % nitrogen. The models best describing THg concentrations was inclusive of whole-weight, condition, and $\delta^{13}C$.

Discussion

Somatic condition and dorsal muscle % nitrogen declined in post-winter captured fish as hypothesized, yet no significant seasonal variation existed for whole-weight measurements. Additionally, seasonal variation existed for lipid content and caloric density, but contrary to what was hypothesized, values determined from Arctic charr collected during the post-winter sampling were significantly greater than those determined from fish returning from the marine environment. Percent lipid values and caloric densities were correlated in the tissue of post-winter sampled Arctic charr, but were not significantly related in late summer migrants. Additionally, significant relationships between % lipid values and caloric densities existed between some, but not all of the studied variables of interest. Seasonal variation existed for THg concentrations and was contrary to what was expected, declining in post-winter sampled Arctic charr. THg concentrations were significantly related to some, but not all, of the tested variables and were unrelated to % lipid values and caloric densities, except in late summer sampled Arctic charr where concentrations significantly declined with increasing lipid content. Models best supporting the data from the previously stated analyses better explained variation in data when

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inclusive of multiple parameters. The model that best described % lipid values was inclusive of season, % carbon, and % nitrogen, while caloric density data were similarly supported by three models also often inclusive of these predictor variables. Whole-weight, somatic condition, and $\delta^{13}C$ were determined to best describe the THg concentration data.

Seasonal Variation in Biological Variables and Stable Isotope Values

Although mean weights did not differ between seasonal sampling, mean K values and % nitrogen values of post-winter collected Arctic charr were determined to be significantly less than those of returning marine migrants. Similar significant seasonal differences in somatic condition have been reported for resident lacustrine Arctic charr (Klemetsen *et al.* 2003b; Amundsen and Knudsen, 2009), although the end of winter condition of non-reproductive individuals captured near Kangiqsualujjuaq, Nunavik, Québec, has been reported to consistently exceed 1.0 (Boivin and Power, 1990). Thus, variation in seasonal differences is apparent among populations and likely among years. Declines in condition appear linked to reduced seasonal feeding reflected in the seasonal differences of % nitrogen in the muscle tissue. Declines in % nitrogen have been reported in resident lacustrine Arctic charr after prolonged periods of fasting (Power *et al.* 2009). Reductions in % nitrogen have also been demonstrated in other species (Elliot 1976; Guerin-Ancy; 1976; van Weerd *et al.* 1995) and are associated with continuous losses of nitrogenous compounds (Elliot 1976; Guerin-Ancy; 1976; Steele and Daniel, 1978; Hobson *et al.* 1993) which are substantive when compared to continuously fed fish (van Weerd *et al.* 1995). The observed absence of short term feeding by post-winter captured Arctic charr, established through an analysis of the upper gastrointestinal tract, in conjunction with noted declines in % nitrogen and somatic condition are indicative of prolonged periods of fasting

exceeding several months (Hesslein *et al.* 1993; Power *et al.* 2009) in the post-winter sampled Deception River Arctic charr.

Lipid Content and Caloric Density

While elevated post-winter % lipid values and caloric densities are suggestive of diet subsidization by anadromous Arctic charr, something that has previously been inferred through observation of winter feeding behaviour (Boivin 1987) in another area in the Nunavik region and with examination of winter movement activities of in Labrador, Canada (Mulder *et al.* 2018), winter condition selective mortality can also produce patterns in the data, which are more consistent with the findings presented here. Condition selective mortality, as described in the literature, acts through a range of phenotypic and genotypic variables to remove individuals from a population with consequences for evolution and population demographics (Gagliano, *et al.* 2007; Ronget *et al.* 2017). Sources of condition dependent mortality often include starvation, thermal stress, predation, pathogens, failure to transition between ontogenetic life stages, and the interactions between the multiple factors (Woodhead 1964ab; Holt and Holt, 1983; Adams *et al.* 1985; Miranda and Hubbard, 1994ab; Billerbeck *et al.* 1997; Tort *et al.* 1998; Searcy and Sponaugle, 2001; Gagliano, *et al.* 2007; Ronget *et al.* 2017). For an especially cold-water adapted species such as Arctic charr, starvation would appear to be the mechanism of most interest.

Starvation or reduced feeding is a consistent driver of over-wintering and selective mortality and one that has been implied for different life stages of several fish species, including Arctic charr (Post and Evans, 1989; Shuter and Post, 1990; Hurst and Conover, 1998; Biro *et al.* 2004; Byström *et al.* 2006). Fish size often has considerable influence, as smaller fish with higher metabolic demands and lower lipid and protein reserves relative to larger conspecifics

deplete these critical reserves at an escalated rate resulting in more rapid starvation and subsequent mortality (Oliver *et al.* 1979; Henderson *et al.* 1988; Shuter and Post, 1990; Thompson *et al.* 1991; Smith and Griffith, 1994). For example, studies of condition selective mortality among age-0 walleye pollock (*Theragra chalcogramma*) showed that while lipid stores and body condition were rapidly reduced by starvation, survivors had significantly higher lipid content than mortalities, with values often exceeding those of pre-starvation fish (Sogard and Olla, 2000). Additionally, Searcy and Sponaugle (2001) examined mortality as a function of early life history traits (size-at-age and growth rates) at critical periods in the Bluehead wrasse (*Thalassoma bifasciatum*) and the Slippery dick (*Halichoeres bivittatus*) and similarly noted that better conditioned fish survived. The effect of condition selective mortality, therefore, will be to shift the mean of the trait distribution in ways that could yield no apparent effect of over-wintering on lipid reserves, or as here, apparent improvement as a result of the systematic removal of poorer conditioned individuals.

The life history of Arctic charr further argue for the influence of condition selective mortality. Arctic charr are a long lived fish species (Johnson 1983; Johnson 1989; Power *et al.* 2008) and the prevalence of condition dependent mortality has been associated with increased life span (Chen and Maklakov, 2012). Arctic charr are also fall spawning and body lipids have been reported to decrease by 30 – 80% after spawning and over-wintering (Dutil 1986; Jørgensen, *et al.* 1997; Jobling *et al.* 1998) with post-spawners being much more depleted when compared to non-reproductive individuals (Dutil 1986). Spawning has previously documented implications for over-winter mortality, e.g. largemouth bass, *Micropterus salmoides* (Post *et al.* 1998) and if condition-dependent mortality was influencing the Deception River population, it would be expected to increase the mortality of spawned fish with resulting low body reserves in

comparison to non-spawned fish. This would have the associated effect of increasing mean %

lipids and yielding seasonal differences in % lipid and caloric content in years when a high

proportion of fish spawn.

THg

Over-wintering anorexia prompted by a cessation of feeding by anadromous Arctic charr

during the winter months and the resulting ramifications of seasonal lipid and protein loss on

THg concentrations (Cizdziel et al., 2002, Cizdziel *et al.* 2003; Kahilainen *et al.* 2016; Keva *et*

al. 2017) was hypothesized. Observed seasonal differences in THg concentrations were contrary

to expectations and similarly may have resulted from the consequences of condition selective

mortality. For example, condition selective mortality acting to remove poorly conditioned, lower

lipid content individuals may have acted to increase lipid content, which itself is often negatively

correlated with THg concentrations (Wiener *et al.* 2002; Post *et al.* 2007).

General Linear Models

Models for explaining % lipid values, caloric densities, and THg concentrations were

generally better supported when multiple variables were used to explain the data. Consistent

across all three models that best describe caloric density data were the predictor variables season,

condition, % carbon, and % nitrogen. Season and condition have known implications for body

reserves in fish (Hoar 1939; Pinder and Eales, 1969; Naevdal *et al.* 1981; Herbinger and Friars,

1991; Dutil 1986; Thompson *et al.* 1991; Jørgensen, *et al.* 1997; Todd *et al.* 2008) and carbon

and nitrogen stable isotope values have previously demonstrated association with body reserves

and reduced feeding (Post *et al.* 2007; Power *et al.* 2009). As with % lipid values, the inclusion

of these variables in models best describing caloric densities would be consistent with previous

research detailing seasonal feeding and its implications for somatic condition and body reserve

depletion in Arctic charr (Jobling 1994; Sæther *et al.* 1996; Klemetsen *et al.* 2003b; Rikardsen *et al.* 2003; Amundsen and Knudsen, 2009). Additionally, the inclusion of variables that have associations with reduced feeding in models that best support % lipid and caloric data further support the hypothesis that condition selective mortality is exerting an influence on this population of Arctic charr, as starvation and reduced feeding is a common driver of condition selective mortality (Oliver *et al.* 1979; Henderson *et al.* 1988; Post and Evens, 1989; Shuter and Post, 1990; Hurst and Conover, 1998; Sogard and Olla, 2000; Searcy and Sponaugle, 2001; Biro *et al.* 2004; Byström *et al.* 2006).

The inclusion of somatic condition and δ^{13}C in the model that best describes concentration data would accord with previous research that has detailed relationships between these tested variables and metals (Eastwood and Couture, 2002; Power *et al.* 2002; Ikemoto *et al.* 2008a,b; Dittman and Driscoll, 2009; Swanson and Kidd, 2010; Goutte *et al.* 2015). Additionally, δ^{13}C's presence in the model emphasizes the impact of diet and feeding habits on metal concentrations, which has been suggested by numerous previous studies (Kidd *et al.* 1995; Hall *et al.* 1997; Power *et al.* 2002; Ikemoto *et al.* 2008a,b; Muir *et al.* 2005; van der Velden *et al.* 2013a; Goutte *et al.* 2015).

Conclusions

This research is believed to be the first demonstrating higher lipid content and caloric density of Arctic charr during the winter months, a period that has been previously associated with significant reductions in body reserves for this species. Condition selective mortality, as opposed to winter diet subsidization, was determined to be a more plausible influence on the observed results, as somatic condition and % nitrogen were significantly reduced in post-winter sampled Arctic charr and this suggests prolonged periods of fasting coincident with known

seasonal feeding behaviour of this species. Observed THg concentrations were contrary to what was expected, as well as to previously reported seasonal variation of this element in fish tissues, which further supports the influence of condition selective mortality. Relationships with studied variables of interest and % lipid values, caloric densities, and THg concentrations were seasonally dependent and not as consistent as hypothesized. However, multi-predictor variable models better described variation in data from all three analyses and results coincide with known associations between season, somatic condition, and feeding with body reserves, as well as with the influence of somatic condition and feeding behaviour on metal concentrations. Our unique findings suggest that future research should further evaluate seasonal influences on this population of Arctic charr as well as consider the implications of condition selective mortality on mature fish, especially in extreme northern environments like the Arctic.

Table 2.1
Summary data for Arctic charr collected during both sampling periods for % lipid analysis, bomb calorimetry, and THg analysis. Means ± standard deviations and ranges are given for fork-lengths, whole-weights, ages, somatic condition, $\delta^{13}C$ values, % carbon, $\delta^{15}N$ values, and % nitrogen of Arctic charr captured during each sampling season (summer 2016 and post-winter 2017). Significant seasonal variation is denoted with * ($p < 0.05$), ** ($p < 0.001$), and *** ($p < 0.0001$).

Season of Capture	Fork-length (mm)	Whole-weight(g)	Age (Years)	Condition (K)	$\delta^{13}C$ (‰)	% Carbon	$\delta^{15}N$ (‰)	% Nitrogen
Summer 2016	460.87 ± 132.08 143.00; 689.00	1272.70 ± 856.13 20.00; 3300.00	9.17 ± 2.82 3; 15	1.05 ± 0.29*** 0.57; 2.38	-19.44 ± 1.07*** -22.97; -16.82	47.37 ± 2.80 35.72; 52.19	12.94 ± 1.29 8.12; 15.35	14.12 ± 0.79*** 11.22; 15.73
Post-Winter 2017	456.07 ± 127.69 220.98; 698.50	1064.33 ± 803.46 99.79; 3229.58	8.97 ± 2.81 5; 20	0.91 ± 0.12 0.68; 1.46	-20.52 ± 0.96 -22.75; -16.89	48.36 ± 2.60 44.03; 57.51	13.30 ± 0.97 11.23; 15.22	12.92 ± 1.06 8.60; 14.64

Table 2.2
Means ± standard deviations and ranges of dorsal muscle % lipids, caloric densities, and THg concentrations of Arctic charr captured in Deception Bay in the summer of 2016 and during the post-winter sampling period in spring 2017. * ($p < 0.05$), ** ($p < 0.001$), and *** ($p < 0.0001$) indicate significant seasonal variation.

Location of Capture	Sample Size	Lipids (%)	Sample Size	Caloric Density (cal·g^{-1})	Sample Size	THg (mg·kg^{-1})
Summer 2016	40	4.08 ± 2.00 2.15; 11.76	30	1327.60 ± 51.56 1180.79; 1409.76	49	0.12 ± 0.05* 0.06; 0.26
Post-Winter 2017	36	8.34 ± 4.85*** 2.66; 27.98	27	1545.75 ± 88.46*** 1371.79; 1723.81	51	0.09 ± 0.05 0.05; 0.35

Table 2.3

Ranking of the models that best described variation in % lipid values (top) caloric densities (cal·g^{-1}) (middle) and THg concentrations (mg·kg^{-1}) (bottom) from anadromous Deception River Arctic charr determined through *AICc* model selection. The model including variables* season, % carbon, and % nitrogen best described % lipid values, while caloric density data were best supported by 3 models inclusive of: (1) season, age, condition, % carbon, and % nitrogen; (2) season, fork-length, condition % carbon, and % nitrogen; and (3) season, whole-weight, condition, % carbon, and % nitrogen. THg concentrations were best supported by the model inclusive of whole-weight, condition, and δ^{13}C.

Model	*K*	*RSS*	*AICc*	*Δ$_i$*	*e^i*	*w$_i$*	*ER$_i$*
Season, % Carbon, % Nitrogen	3	2.32	-38.78	0	1	0.62	1
Season, % Nitrogen	2	2.42	-37.79	0.99	0.61	0.38	1.63
Season, Age, Condition, % Carbon, % Nitrogen	5	0.01	-296.32	0	1	0.42	1
Season, Fork-Length, Condition, % Carbon, % Nitrogen	5	0.01	-296.20	0.12	0.94	0.39	1.06
Season, Whole-Weight, Condition, % Carbon, % Nitrogen	5	0.01	-294.69	1.64	0.44	0.19	2.27
Whole-Weight, Condition, δ^{13}C	3	2.40	-78.34	0	1	0.47	1
Whole-Weight, Condition, δ^{13}C, δ^{15}N	4	2.37	-77.73	0.61	0.74	0.35	1.36
Season, Whole-Weight, Condition, δ^{13}C	4	2.39	-76.49	1.85	0.40	0.19	2.52

* General linear models were inclusive of the following variables: season (summer 2016 and post-winter 2017), fork-length (mm), whole-weight (g), age (years), somatic condition (K), δ^{13}C (‰), % carbon, δ^{15}N (‰), % nitrogen, and significant two-way interactions. Explanatory variables that were highly correlated, or known to have biological redundancy (e.g. fork-length and whole-weight) were not included in the same model.
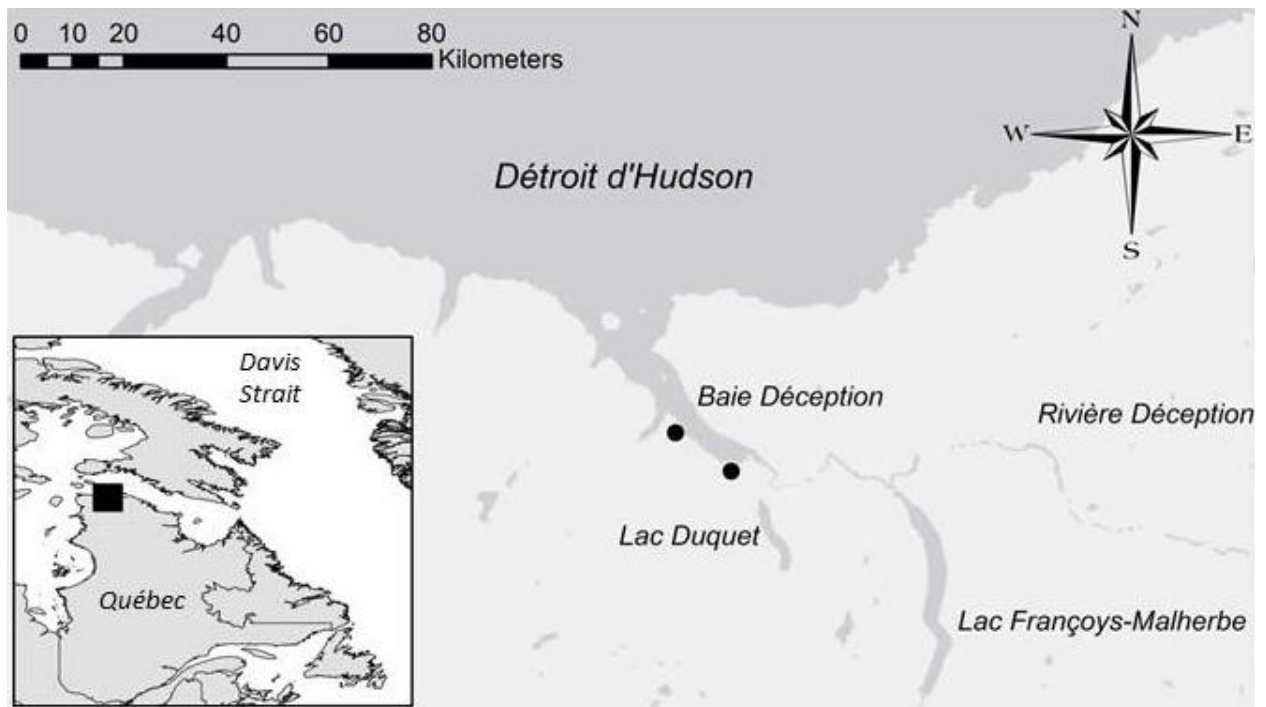
Fig. 2.1. Map of the Deception Bay, the Deception River, and the two over-wintering lakes, Lake Duquet and Lake Françoys-Malherbe, from which Arctic charr were sampled for this study. Black circles represent mining operations present in the area, while the black square represents the sampling locations in relation to the province of Québec in eastern Canada.
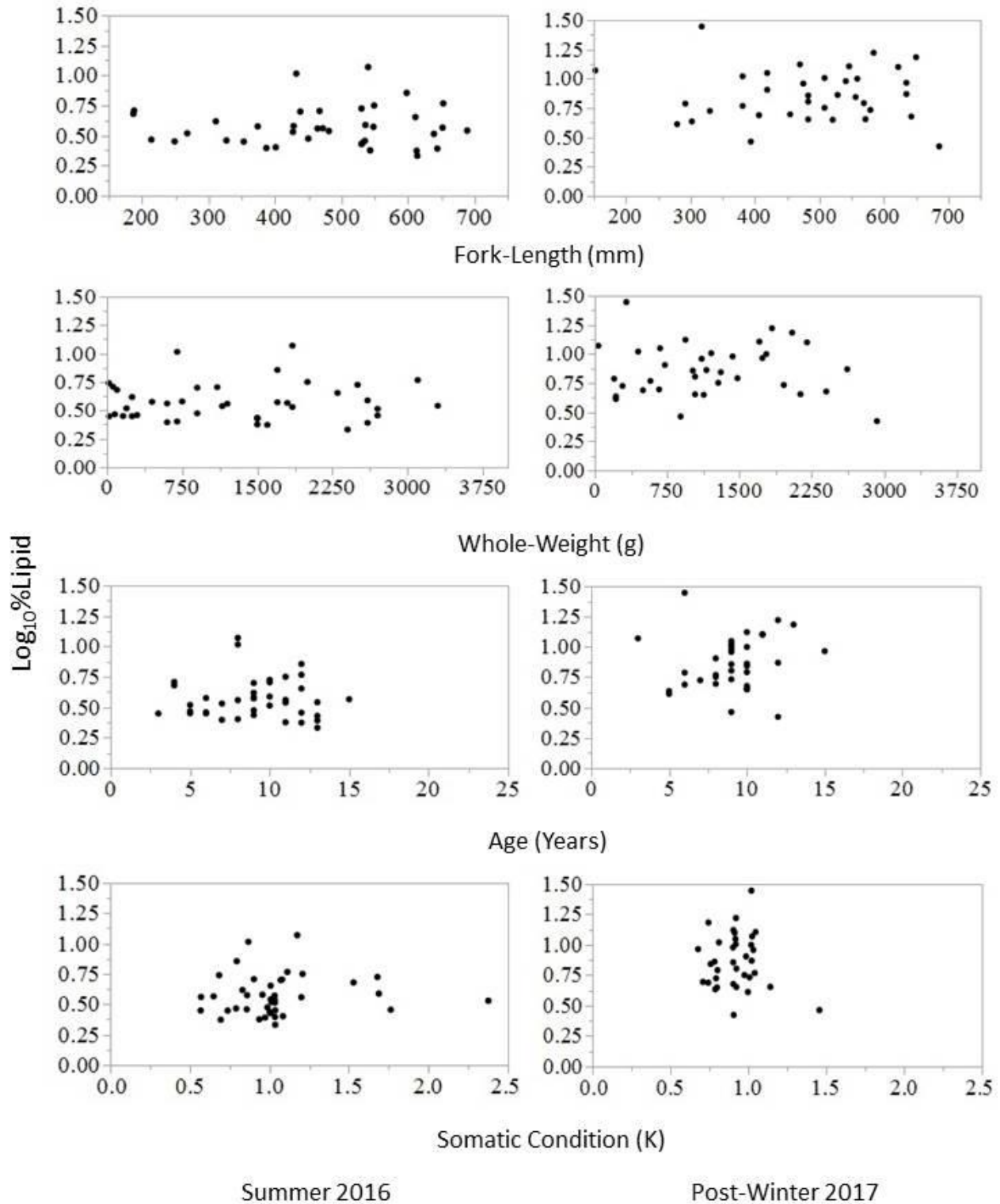
Fig. 2.2. Relationships between summer sampled (left) and post-winter collected (right) dorsal muscle % lipid values and fork-length, whole-weight, fish age, and somatic condition.
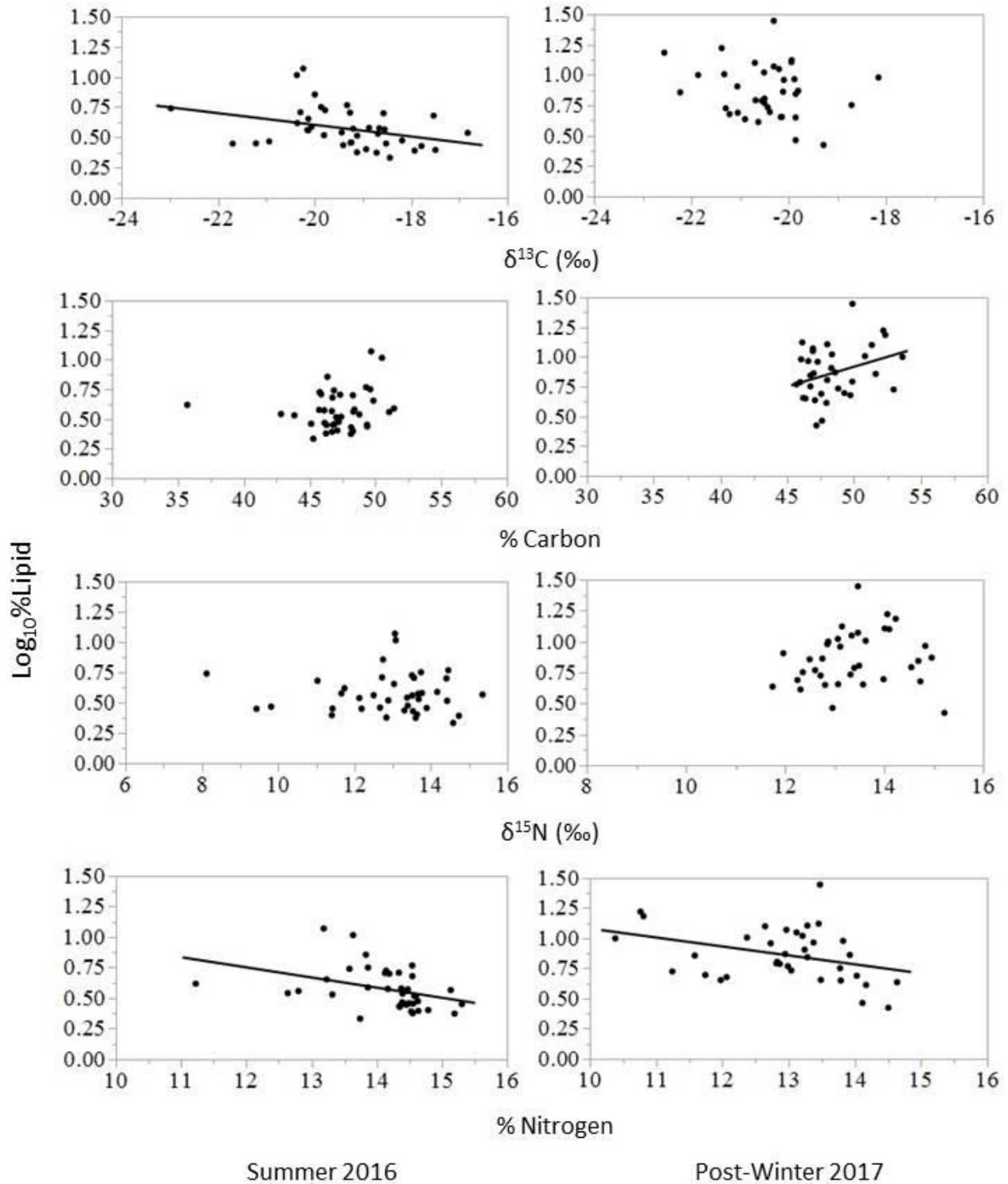
Fig. 2.3. Relationships between % lipid values determined from dorsal muscle tissue sampled from anadromous Deception River Arctic charr captured in the marine environment during the summer of 2016 (left), as well as in the post-winter season (right) and stable isotopes (δ^{13}C, % carbon, δ^{15}N, and % nitrogen).

Fig. 2.4. Relationships between summer captured (left) and post-winter sampled (right) dorsal muscle caloric densities and fork-length, whole-weight, fish age, and somatic condition.
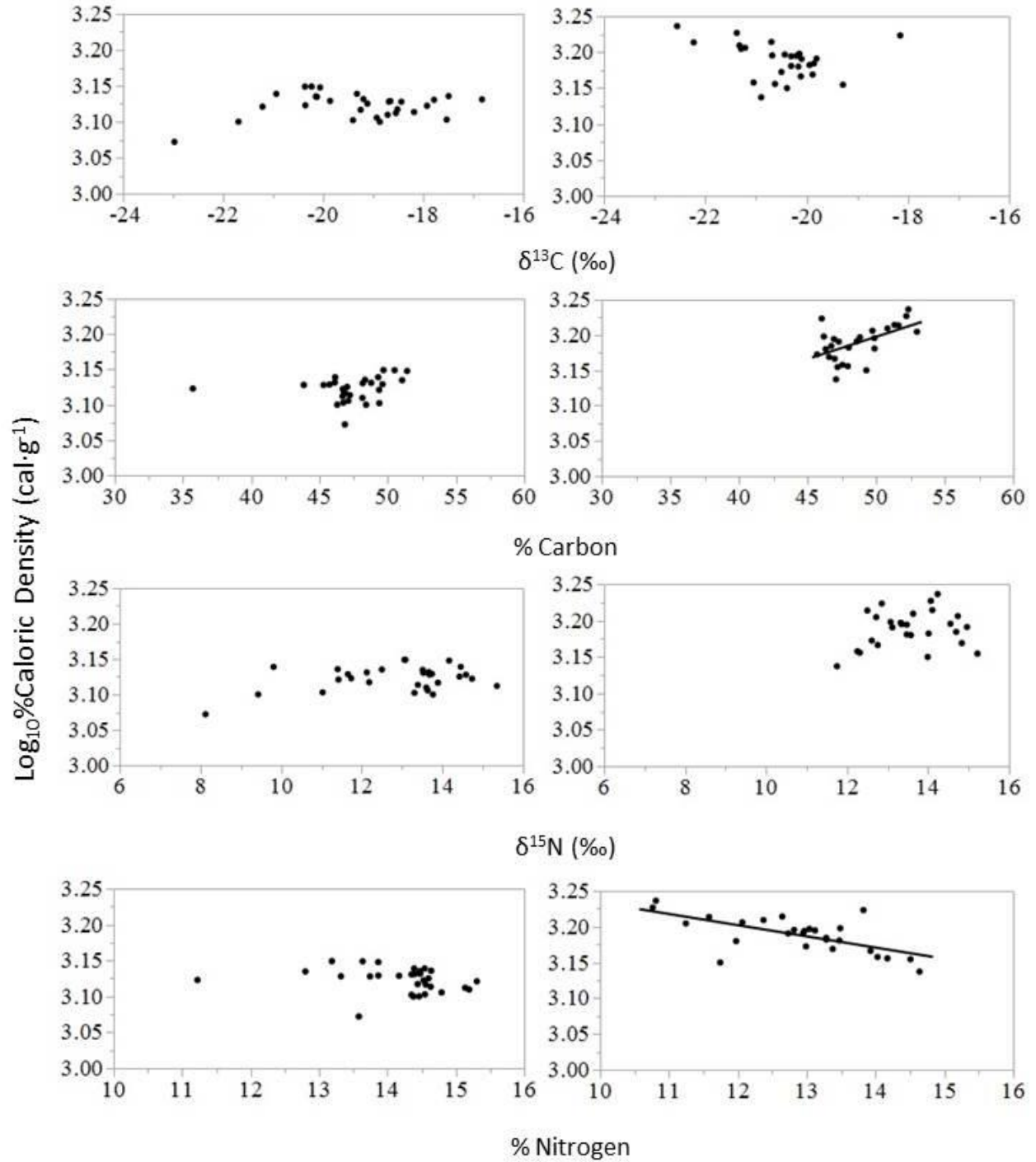
Fig. 2.5. Relationships between caloric densities determined from dorsal muscle tissue sampled from anadromous Deception River Arctic charr captured in the marine environment during the summer of 2016 (left), as well as in the post-winter season (right) and stable isotopes (δ^{13}C, % carbon, δ^{15}N, and % nitrogen).

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Fig. 2.6. Relationships between summer captured (left) and post-winter sampled (right) dorsal muscle THg concentrations and fork-length, whole-weight, fish age, and somatic condition.

Fig. 2.7. Relationships between THg concentrations determined from dorsal muscle tissue sampled from anadromous Deception River Arctic charr captured in the marine environment during the summer of 2016 (left), as well as in the post-winter season (right) and stable isotopes ($\delta^{13}C$, % carbon, $\delta^{15}N$, and % nitrogen).
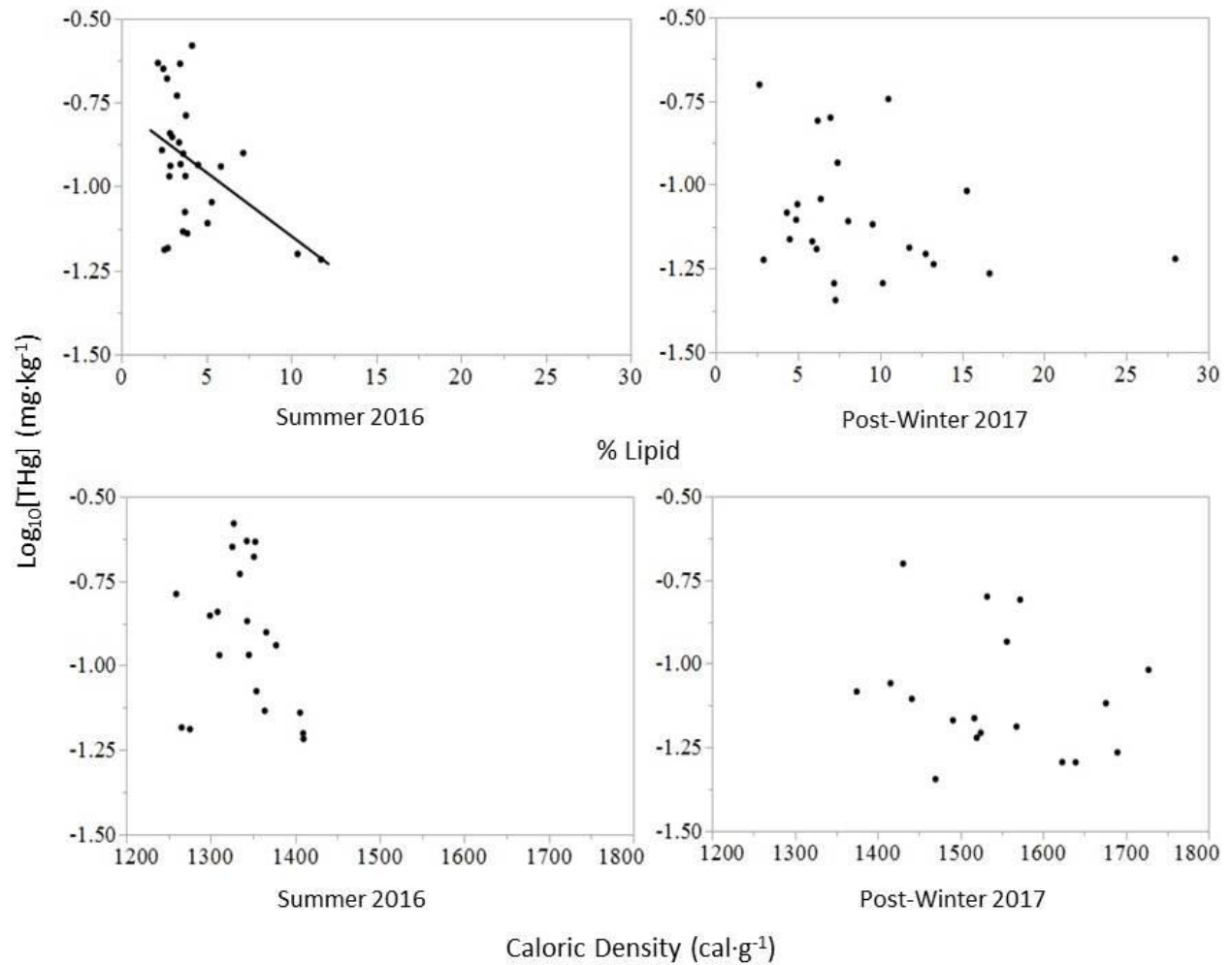
Fig. 2.8. Relationships between THg concentrations, % lipid values, and caloric densities for late summer captured (left) and post-winter collected Arctic charr (right).

Chapter 3: A seasonal comparison of metal concentrations in the tissues of Arctic charr (*Salvelinus alpinus*) in Northern Québec, Canada

Introduction

Uptake and handling of metals into tissues by fish can depend on the variability and interaction of abiotic factors, e.g. temperature, pH, alkalinity (Laurén and McDonald, 1986; Spry and Weiner, 1991; Köck *et al.* 1996) and organism biology and physiology, e.g., feeding, age, somatic condition, and growth (Murphey *et al.* 1978; Weiner and Giesy, 1979; Ney and Van Hasssel, 1983; Sörenson 1991; Campbell 1994; Kidwell *et al.* 1995; Greenfield *et al.* 2001; Power *et al.* 2002; Farkas *et al.* 2003). Additionally, metal dependent biomagnification in the food web can occur (Ikemoto *et al.* 2008a,b; Jara-Marini *et al.* 2009) and seasonal variation and elevation of metals in fish tissue have been reported (Köck *et al.* 1996; Cizdziel *et al.*, 2002; Eastwood and Couture, 2002; Cizdziel *et al.* 2003; Kahilainent *et al.* 2016; Keva *et al.* 2017). However, despite the dynamic processes associated with trace metal concentrations in fish tissues, ecotoxicological research exploring metals contamination of northern fishes such as Arctic charr (*Salevlinus alpinus*, L.) has been poorly represented in the literature beyond examination of mercury (Hg) concentrations (e. g. Köck *et al.* 1996; Dallinger *et al.* 1997; Allen-Gil *et al.* 2003; Muir *et al.* 2005; Gantner *et al.* 2009; Gantner *et al.* 2012).

Arctic charr are valued for their significant dietary contribution and cultural importance to northern peoples, such as the Inuit, throughout their circumpolar distribution (Kuhnlein and Receveur 2007; Condon *et al.* 1994). While, Hg is a stressor of specific concern to northern peoples due to its neurologically toxic health effects (Mergler *et al.* 2007) and ability to bioaccumulate in aquatic food webs, particularly in highly valued predatory fish (Kidd *et al.* 1995; Muir *et al.* 2005; Power *et al.* 2002; Evans *et al.* 2005; Lockhart *et al.* 2005; Gantner *et al.*

2010; van der Velden *et al.* 2013a), other non-essential and essential metals at high

concentrations can also have negative implications for human (Lu *et al.* 2005; Uriu-Adams and

Keen, 2005; Godt *et al.* 2006; Sanders *et al.* 2009; Smith and Steinmaus, 2009; Plum *et al.* 2010)

and fish health (Henry and Atchison, 1979; Sörensen 1991; Jones *et al.* 2001; Eastwood and

Couture, 2002; Couture and Kumar, 2003; Ghosh *et al.* 2006; Osman *et al.* 2007; Mishra and

Mohanty, 2008). Given the importance and ubiquity of Arctic charr in the diet of northern

Indigenous peoples (Kuhnlein and Receveur, 2007; Huet *et al.* 2012), study and quantification of

metals concentrations will increase understanding of accumulation patterns of essential and non-

essential metals in fish such as Arctic charr, provide insight into factors that may influence

accumulation levels, and aid in determining the potential for human exposure risks. For example,

for anadromous Arctic charr which migrate seasonally between freshwater and marine

environments for summer feeding (Dutil 1986; Jonsson *et al.* 1988; Rikardsen *et al.* 2003; Power

et al. 2008), differing water chemistry environments suggest that many of the parameters

associated with trace metal uptake may vary seasonally. In many parts of the north where there

are seasonal winter fisheries for Arctic charr (e.g., Boivin and Power, 1990), the potential for

seasonal variations in metal contamination similarly implies differential seasonal exposure risks

for humans.

Coupled with contaminant analysis, stable isotope analysis can assist with investigating

patterns related to trace metals in aquatic food webs (Atwell *et al.* 1998; Croteau *et al.* 2005

Ikemoto *et al.* 2008a,b). With stable isotope analyses, the relative abundance of carbon ($^{13}C/^{12}C$)

and nitrogen ($^{15}N/^{14}N$) stable isotopes allow inferences to be made about fish habitat use

(Murdoch and Power 2013b), geographic distribution (Campana *et al.* 2000), ontogenetic life

history traits (Grey 2001) and feeding relationships (Kling *et al.* 1992; Vander Zanden *et al.*

1998; Bearhop *et al.* 1999). Unlike stomach content analysis, which only documents relatively recent feeding, stable isotope analyses describe predator prey trophic interactions over longer periods of time (Fry and Sherr 1984; Peterson and Fry 1987), typically months in northern fishes (Hesslein et al 1993). As nitrogen stable isotope values are consistently incremented with trophic transfer (DeNiro and Epstein, 1981; Minagawa and Wada, 1984), the values can be used to indicate food web position (Cabana and Rasmussen, 1994; Post 2002) and can be correlated with metal concentrations to estimate biomagnification rates (Kidd *et al.* 1995; Atwell *et al.* 1998; van der Velden 2013a). In contrast, carbon stable isotope values remain relatively constant during trophic transfer (DeNiro and Epstein, 1981; Fry and Sherr, 1984; Vander Zanden and Rasmussen, 2001), but can provide insight into feeding location or habitat use (Hecky and Hesslein, 1995; Power et al., 2002). Together with trace metal analysis, stable isotopes can be used to infer relationships between Arctic charr tissue metal concentrations, food web position, feeding strategies, and habitat use.

Here we analyzed dorsal muscle and liver tissue samples collected from anadromous Arctic charr in the Deception River system of Nunavik, Québec, Canada for metal concentrations and combined the data with co-measured stable isotope ratios to describe relationships between observed metal concentrations and patterns of bioaccumulation. Specifically, collected data were used to test the hypotheses that: (i) concentrations of essential (copper (Cu) and zinc (Zn)) and non-essential metals (arsenic (As), cadmium (Cd), chromium (Cr), nickel (Ni), and lead (Pb)) in dorsal muscle and liver tissues of anadromous Arctic charr would differ significantly by tissue type, with concentration values determined from liver tissue being greater than in dorsal muscle samples (Roméo *et al.* 1999; Andres *et al.*2000; Canli and Atli, 2003; Agah *et al.* 2009); (ii) concentrations would vary seasonally and be elevated in samples collected during the winter

months (Köck *et al.* 1996; Cizdziel *et al*., 2002; Cizdziel *et al.* 2003; Kahilainent *et al.* 2016; Keva *et al.* 2017); (iii) concentrations would be positively correlated with fork-length and age (Cizdziel *et al*., 2002; Power *et al.* 2002; Trudel and Rasmussen, 2006), but decline as somatic condition increases (Dittman and Driscoll, 2009; Swanson and Kidd, 2010); and, (iv) concentrations would be positively correlated with trophic position (Power *et al.* 2002; Muir *et al.* 2005; van der Velden *et al.* 2013a), but negatively correlated with the carbon stable isotope gradient (Power *et al.* 2002). In addition, we aimed to determine whether metal concentrations could be better described by multi-predictor variable statistical models inclusive of combinations of the above tested variables and their interactions. Thus data were used to test the hypotheses: (v) that models of variations in the concentrations of essential metals (Cu and Zn) are better descriptors of the data when including information on trophic position or feeding strategies as represented by $\delta^{15}N$ and $\delta^{13}C$, and season as a result of the uptake processes associated with these metals (Shears and Fletcher, 1983; Handy 1996; Hardy *et al.* 1987; Glover and Hostrand, 2002; Kamunde *et al.* 2002a,b; Bury *et al.* 2003) and the dominance of seasonal summer feeding by anadromous Arctic charr; and, (vi) that similar models of variations in non-essential metals (As, Cd, Cr, Ni, and Pb) that are not under homeostatic control would be best described by models inclusive of biological descriptors of fork-length and/or age and trophic position, as represented by $\delta^{15}N$ (Cizdziel *et al*., 2002; Power *et al.* 2002; Muir *et al.* 2005; Trudel and Rasmussen, 2006; van der Velden *et al.* 2013a), as well as season, (Köck *et al.* 1996; Cizdziel *et al*., 2002; Cizdziel *et al.* 2003; Kahilainent *et al.* 2016; Keva *et al.* 2017) as these variables are known to significantly influence measured metal concentrations in fish tissue (Weiner *et al.* 2002; Kahilainent *et al.* 2016).

Methods

Study Area

The Deception River and tributaries (**Fig. 3.1**) span an area of 3870 km^2 between latitudes 61°31'26" N and 62°11'01" W and are located approximately 60km east of Salluit, Nunavik, Québec. The river flows into Deception Bay on the south side of the Hudson Strait, a deep and wide channel that connects Hudson Bay and the Foxe Basin with the Labrador Sea and the Davis Strait (Drinkwater 1986). The growing season in the region is less than 120 days per year and average daily temperatures range from -25.6ºC in February, to 10.5ºC in August (Environment Canada 2011a,b). In addition to traditional hunting and fishing activities, the area is impacted by two nickel and copper mining projects: the Raglan Mine and Canadian Royalties Inc., and was also the historic site for the now shuttered Asbestos Hill Mine (Purtiniq). Mine personnel are present year round and a 95 km road, that follows the Deception River and its tributaries closely for most of its length, connects Raglan's main mine site with additional camps and a harbour on Deception Bay. Arctic charr spawn and overwinter in the Deception River headwater lakes Duquet (Inuit name: Tasialujjuaq) 62°03'18 N, 74°31'51 W and Françoys-Malherbe (Inuit name: Pangaligiak) 62°00'06 N, 74°15'25 W from October to June, connected, respectively, to Deception Bay by 2.5 and 15km stretches of river. There is a commercial fishing permit active for both lakes, and a Raglan sport fishing permit is active for Lake Françoys-Malherbe.

Sample Collection

Summer sampled anadromous Arctic charr were captured via experimental gill net (25 – 150 mm mesh X 120 m) from eight locations in Deception Bay and the mouth of the Deception River in August of 2016 as fish were migrating upstream. A second post-winter sample

collection occurred at Lake Françoys-Malherbe and in Lake Duquet in May 2017, approximately a month prior to ice break up (Canadian Ice Service, 2018). Post-winter samples were collected via jigging lines throughout the lakes by Nunavik Research Centre (NRC) staff in collaboration with the Elder's Spring Fishing Event hosted by Qaqqalik Landholding Corporation and supported by Raglan Mine.

In the laboratory, all captured Arctic charr were weighed ($\pm$ 1 g) and measured for fork-length ($\pm$ 1 mm) and the measurements were used to calculate Fulton's condition factor ($K = 10^5 * W/L^3$) after confirming isometric growth (Ricker, 1975). Isometric growth was determined by the slope of standardized weight-length regression (Deception Bay sampling – 3.12, post-winter sampling – 3. 03) (Ricker, 1975), which did not differ significantly from 3 (Deception Bay, t-test, $p = 0.4569$, post-winter sampling, t-test, $p = 0.2546$). A sample of dorsal muscle tissue (≈ 10 g) was removed from above the lateral line, posterior to the dorsal fin on the left side of each Arctic charr (van der Velden $et\ al.$ 2013a) and immediately frozen for subsequent analyses. A random sub-sample from each season ($n = 32$ for summer and $n = 35$ for post-winter sampled fish) were chosen for trace-metal analysis. Sampled tissues were placed in acid washed (15% HNO_3) Eppendorf polypropylene tubes that had been rinsed seven times in ultrapure water before use to minimize accidental metal contamination. Anadromy of the post-winter Arctic charr was confirmed with $\delta^{34}S$ stable isotope analysis (Doucett $et\ al.$ 1999). Fish ages were determined by NRC staff by submersing the otolith in water and examining it with reflected light under a dissecting microscope (Chilton and Beamish 1982).

Stable Isotope Analysis

Stable isotope analyses were performed at the Environmental Isotope Laboratory at the University of Waterloo (Waterloo, Ontario, Canada) with a Delta Plus Continuous Flow Stable

Isotope Ratio Mass Spectrometer (Thermo Finnigan, Bremen, Germany) coupled to a Carlo Erba

Elemental Analyzer (CHNS-O EA1108, Carlo Erba, Milan, Italy) following methods described

in van der Velden *et al.* (2013a). Dorsal muscle tissue was dried at 50°C for 48 h and then

pulverized into a homogenate powder with a mortar and pestle before being weighed to 0.275 –

0.300 mg (UMX2, Mettler-Toledo GmbH, Greifensee, Switzerland) and simultaneously

analyzed for stable carbon and nitrogen stable isotopes (δ^{13}C, δ^{15}N). All measurements were

expressed using standard delta notation (δ) as:

$$\delta = \left[\frac{R_{sample} - R_{standard}}{R_{standard}}\right] x \; 1000$$

Where *R* is the measured ratio of the abundance of the heavy to the light isotope in the sample or

the standard. International reference standards used included Vienna Peedee Belemnite carbonate

rock (Craig 1957) for δ^{13}C analyses and nitrogen gas in the atmosphere (Mariotti 1983) for δ^{15}N

analyses. Machine analytical precision for δ^{13}C and δ^{15}N, respectively, was determined to be ±

0.2‰ and ± 0.3‰ and was established by repeat analyses of internal laboratory working

standards (IAEA-N_1 + N_2, IAEA-CH_3 + CH_6) cross calibrated to International Atomic Energy

Agency (IAEA) standards: CH_6 for δ^{13}C and N_1 and N_2 for δ^{15}N. Internal standards were placed

at the beginning, middle and end of every run of samples to control for analytical drift.

Repeatability was assessed by repeat analysis of 1 in 10 samples. Reported δ^{13}C values were not

normalized for lipid content as the C:N ratios were consistently below the 4.0 threshold above

which extraction is required (Logan *et al.* 2008; Sanderson *et al.* 2009; Jardine *et al.* 2011)

Trace Metal Analysis

Trace metal analyses were performed at the Institut Nationale de la Recherche

Scientifique – Centre Eau, Terre, Environnement (INRS – ETE) in Québec City, Québec,

Canada. After lyophilisation for 72 hours (FTS Systems TMM, Kinetics Thermal Systems,

Longueil, QC, Canada), freeze-dried samples were weighed to 0.100-0.150 g ± 0.1 mg (XS205

DualRange Analytical Balance, Mettler Toledo, Mississauga, ON, Canada) to determine dry

weight (dw). Tissue was then digested in 1 ml nitric acid (70%, v/v, Optima grade, Fisher

Scientific, Whitby, ON, Canada) for 3 days at room temperature before being heated at 60°C for

2 hours. After samples had cooled, 0.5 ml hydrogen peroxide (30%, v/v, Optima grade, Fisher

Scientific, Whitby, ON, Canada) was added and the sample was again heated at 60°C for 2

hours. The final digestion volume of 1 mL/mg of sample was reached through dilution with

ultrapure water. Concentrations of As, Cd, Cr, Cu, Ni, Pb, and Zn were then quantified using

inductively coupled plasma mass spectrometry (ICP-MS) (Model x-7, Thermo Elemental,

Winsford, England, UK). Results are represented in dry weight.

Certified reference materials from the National Research Council of Canada (NRCC)

TORT-3 (Lobster hepatopancreas, National Research Council of Canada, NRCC, Halifax, NS,

Canada), DOLT-4 (Dogfish liver, National Research Council of Canada, NRCC, Halifax, NS,

Canada), and blanks were subjected to the same digestion procedure and analyzed concurrently.

Mean percent recoveries ± standard deviations of TORT-3 analyzed in conjunction with muscle

and liver tissue of Deception Bay Arctic charr captured during the summer of 2016 were within

the certified ranges for As (104% ± 10%, $n = 2$), Cd (96% ± 10%, $n = 2$), Cu (88% ± 8%, $n = 2$),

Ni (86% ± 8%, $n = 2$), Pb (90% ± 6%, $n = 2$) and Zn (94% ± 9%, $n = 2$). Mean percent

recoveries ± standard deviations of DOLT-4 were as follows: for As (97% ± 5%, $n = 3$), Cd

(110% ± 5%, $n = 3$), Cu (111% ± 10%, $n = 3$), Pb (84% ± 1%, $n = 3$) and Zn (113% ± 5%, $n =$

3). Recovery of Cr was below the certified ranges for TORT-3 and DOLT-4 (53% ± 3%, n=2

and N/A n=3, respectively) and Ni was below the certified range for DOLT-4 (63% ± 8%, $n = 2$).

Mean percent recoveries ± standard deviations of TORT-3 analyzed in conjunction with muscle

and liver tissue collected during the post-winter sampling period in May 2017 were within the

certified ranges for As (108% ± 3%, $n = 3$), Cd (100% ± 3%, $n = 3$), Cu (91% ± 3%, $n = 3$), Ni

(83% ± 2%, $n = 3$), Pb (100% ± 4%, $n = 3$) and Zn (107% ± 3%, $n = 3$). DOLT-4 mean percent

recoveries ± standard deviations were within ranges for As (92% ± 1%, $n = 3$), Cd (109% ± 2%,

$n = 3$), Cu (107% ± 2%, $n = 3$), Pb (111% ± 3%, $n = 3$) and Zn (119% ± 2%, $n = 3$) as well.

Recovery of Cr was below certified ranges for TORT-3 and DOLT-4 (57% ± 3% $n = 3$ and 59±

5%, $n = 3$, respectively) and Ni was below the certified range for DOLT-4 (48% ± 8%, $n = 3$).

Recoveries below certified ranges (Ni and Cr) suggest that presented mean concentrations ±

standard deviations may not be an accurate representation of the true tissue concentrations for the

specified elements. However, the obtained recovery rates should have no additional influence on

the interpretation of relationships between measured concentrations and additional collected

data.

Statistical Analysis

Type I statistical error was set to $\alpha = 0.05$ and JMP software (v. 13.0.0, SAS Institute,

CA) was used to perform all statistical analyses. Compliance of data to the assumptions of

normality and homoscedasticity was determined through assessment of residual diagnostic

histograms, visual assessment of Q-Q plots, and with use of the Shapiro-Wilk W test (Shapiro

and Wilk, 1965). All data that did not meet parametric assumptions were $\log_{10}$ transformed (Zar,

2010). Student's t-tests or the Mann-Whitney U tests were used to determine significant

differences between tissue types and seasons (Zar, 2010). Linear regressions were estimated to

determine the relationship significance between metal concentration data and fork-length, age,

somatic condition, $\delta^{13}C$, and $\delta^{15}N$ in for dorsal muscle and liver tissue data separated by season

of collection. Model residuals were examined to ensure conformance with regression

assumptions and outliers that may have unduly influenced regression results were assessed using Cook's Distance statistic (Cook 1977) and subsequently removed. Additionally, general linear model (GLM) methods were used to construct statistical models required for determining the importance of trophic, feeding, biological, and seasonal factors for explaining variation in the concentrations of essential metals. GLM methods were also used for determining the importance of biological variables for explaining variation in the concentrations of the non-essential metals.

Correlations between measured dorsal muscle and liver metal concentrations and factors hypothesized to significantly co-vary with them were assessed using Pearson correlation analysis (**see Appendix Tables 3.1 – 3.7**) and/or linear regression, with significant correlations and interactions (e.g. length vs condition) included as candidate explanatory variables in multi-predictor variable GLM models used to describe the overall variation in metals concentrations. Model selection was performed using the Akaike Information Criteria (AIC) adjusted for small sample sizes (*AICc*), with models including all combinations of potential predictor variables as assessed above and a null model considered. The model with the lowest *AICc* score was considered the most accurate (Burnham and Anderson, 2002). Where multiple models had *AICc* values differing by less than two, model averaging was used following methods outlined in Lukacs *et al.* (2009) to reduce biases that may be introduced when using data to select a single "best" model from a large set of models that can imply different predictor values (Lukacs *et al.* 2009). With the creation of the composite model, any parameter with a relative importance weighted <0.5 and inclusive of 0 in its 95% upper and lower confidence interval, was dropped from the resulting averaged model. Computational details for the additional statistics associated with the *AIC* methodology and model averaging can be found in Burnham and Anderson (2002), Lukacs *et al.* (2009) and Symonds and Moussalli (2011), respectively.

Results

Organotropism and Seasonal Variations

A total of 32 Arctic charr were randomly sampled for matched dorsal muscle and liver samples from the Deception Bay summer fishery and 35 similarly matched samples were obtained from the post-winter fishery for metal concentrations analyses with ICP-MS. Samples from the post-winter season came almost equally from lakes Duquet ($n = 18$) and Françoys-Malherbe ($n = 17$). Stable isotope $\delta^{34}S$ analysis indicated $n = 6$ fish from the subset were non-anadromous ($n = 4$ from Lake Duquet and $n = 2$ from Françoys-Malherbe) and these were excluded from further consideration.

Summary data (fork-length, age, somatic condition, $\delta^{13}C$ and $\delta^{15}N$ values for the anadromous Arctic charr on which trace metal analyses were performed are given in **Table 3.1**. Fork-length ($t_{(1,59)} = -1.15$, $p = 0.2537$), age ($t_{(1,57)} = -0.81$, $p = 0.4191$), and $\delta^{15}N$ values ($t_{(1,59)} = 0.6$, $p = 0.5530$) exhibited no significant seasonal variation, while somatic condition ($Z_{(1,59)} = -4.33$, $p < 0.0001$) and $\delta^{13}C$ ($t_{(1,59)} = -4.80$, $p < 0.0001$) values were significantly greater in Arctic charr captured in the marine environment.

Mean metal concentrations and ranges (essential and non-essential) for dorsal muscle and liver tissue collected from Arctic charr captured during the summer sampling campaign in Deception Bay and the post-wintering period are reported in **Table 3.2**. Measured liver concentrations were significantly greater than dorsal muscle concentrations for Cd ($t_{(1,120)} = 22.47$, $p < 0.0001$), Cu ($t_{(1,120)} = 31.82$, $p < 0.0001$), Ni ($t_{(1,120)} = 6.44$, $p < 0.0001$) and Zn ($t_{(1,119)} = 30.19$, $p < 0.0001$) but not for As ($t = 0.55$, $p = 0.5817$), Cr ($t_{(1,118)} = -1.87$, $p = 0.0638$), or Pb ($t_{(1,119)} = 0.55$, $p = 0.5814$.

All analyzed metals exhibited seasonal variation, but results were often tissue dependent. Cr and Pb concentrations were both significantly greater in dorsal muscle (Cr: $t_{(1,58)} = 11.46$, $p < 0.0001$; Pb: $t_{(1,58)} = 2.58$, $p = 0.0124$) and liver tissue (Cr: $t_{(1,58)} = 10.69$, $p < 0.0001$; Pb: $t_{(1,59)} = 4.90$, $p < 0.0001$) collected from post-winter Arctic charr. As and Cu concentrations did not vary significantly by season in dorsal muscle samples (As: $t_{(1,59)} = 0.17$, $p = 0.8665$; Cu: $t_{(1,59)} = -1.04$, $p = 0.3045$). Concentrations of the same metals did differ seasonally in liver, with As being higher in summer sampled fish ($t_{(1,59)} = -3.04$, $p = 0.0035$) and Cu being higher in post-winter captured Arctic charr ($t_{(1,59)} = 3.28$, $p = 0.0017$). Ni and Zn liver concentrations displayed no significant seasonal variation (Ni: $t_{(1,59)} = -1.08$, $p = 0.2841$; Zn: $t_{(1,58)} = 2.07$, $p = 0.0428$), whereas dorsal muscle concentrations for the same metals were significantly greater in post-winter Arctic charr (Ni: $t_{(1,59)} = 5.37$, $p < 0.0001$; Zn: $t_{(1,58)} = 2.07$, $p = 0.0428$). Both dorsal muscle and liver Cd concentrations exhibited significant seasonal variation, with dorsal muscle Cd concentrations ($t_{(1,59)} = -8.14$, $p < 0.0001$) being higher in summer sampled fish and liver Cd concentrations higher in post-winter collected fish ($t_{(1,59)} = 4.42$, $p < 0.0001$).

Relationships with Biological Variables and Stable Isotope Values

Relationships between dorsal muscle and liver concentrations of As, Cd, Cr, Cu, Ni, Pb, and Zn and fork-length, age, somatic condition, δ^{13}C, and δ^{15}N are plotted in **Fig. 3.2 – 3.11** and were season and tissue specific. Summer dorsal muscle As concentrations were not significantly related to any of the tested variables. In contrast, winter As concentrations were significantly positively correlated with all tested variables except somatic condition and δ^{13}C. Liver As concentrations, in addition to dorsal muscle and liver Cd concentrations were not significantly related to any of the tested variables in either summer or post-winter sampled Arctic charr.

Dorsal muscle Cr concentrations determined from late summer migrants significantly declined as trophic position increased, but no additional significant relationships existed.

Dorsal muscle Cu concentrations in both seasons were not significantly related to fork-length, age, K values, δ^{13}C, or δ^{15}N. However, Cu concentrations in summer and the post-winter liver samples significantly increased with δ^{13}C. Liver Cu and Ni concentrations significantly declined as somatic condition increased. For Ni there were no other significant relationships. Summer dorsal muscle and liver Pb concentrations were not significantly related to any of the investigated variables, while Pb concentrations in post-winter sampled fish significantly declined as δ^{13}C increased. No additional significant relationships between Pb concentrations and tested variables were determined for post-winter dorsal muscle or liver samples.

Summer Zn concentrations were not significantly related to fork-length, age, somatic condition, δ^{13}C, or trophic position. Summer liver Zn concentrations significantly negatively correlated with fork-length, somatic condition, and trophic position. Post-winter Zn concentrations in the dorsal muscle and liver significantly declined with fork-length and trophic position, but had no significant relationship with somatic condition, or δ^{13}C. Dorsal muscle Zn concentrations were significantly inversely correlated with fish age, whereas liver concentrations showed no significant relationship.

Essential Metals (Cu, Zn)

The relative importance of individual parameters for explaining variation in dorsal muscle and liver concentrations of essential metals in Deception River Arctic charr are reported in **Table 3.3**. While no single parameter dominated in all sets, the relative importance of season, fork-length, and δ^{13}C was high when summed across all *AICc* determined models for describing variation in the data (see **Appendix Tables 3.8** and **3.9**). *AICc* analysis indicated no single model

"best" described the data for either Cu or Zn, with multiple plausible models yielding *AICc*

values within 2 of the "best" model. Composite models based on model averaging of parameters

across all plausible models are reported in **Table 3.4** and **Table 3.5**. Model averaging resulted in

parameter estimate confidence limits that included zero in many instances, suggesting that the

associated parameters were not important in explaining variation in the observed data. No

composite model could be determined for Cu dorsal muscle concentrations given the *AICc*

equivalence of the estimated single parameter models.

Non-Essential Metals (As, Cd, Cr, Ni, and Pb)

The relative importance of individual parameters for explaining variation in dorsal

muscle and liver concentrations of non-essential metals in Deception River Arctic charr can be

seen **Table 3.3**. As seen with essential metals, no single parameter dominated in all data sets.

However, the relative importance of season and somatic condition was high when summed

across all models that best described variation in the data, which were determined through *AICc*

model selection and were ranked as the most important variable, respectively, in seven of ten and

six of ten of the estimated non-essential metal models. *AICc* analysis indicated no single model

"best" described the data for any of the considered non-essential metals, with multiple models

plausible models yielding *AICc* values within 2 of the "best" model (see **Appendix Tables 3.10

– 3.14**). Composite models based on model averaging of parameters across all plausible models

are reported in **Table 3.4** and **Table 3.5**. As with the essential metals, model averaging of non-

essential metals resulted in parameter confidence limits that included zero in many instances.

Discussion

Higher liver than dorsal muscle metal concentrations were observed for some (Cd Cu, Ni,

Zn), but not all (As, Cr, Pb) metals. All analyzed metals exhibited seasonal variation, although

results were often tissue dependent. Significant correlations with fork-length, age, somatic condition and trophic descriptors ($\delta^{13}C$, $\delta^{15}N$) existed for some, but not all of the considered metals. Models of essential and non-essential metal concentrations were often inclusive of some of the hypothesized descriptor variables, but better explained variation in concentrations when multiple parameters were included. Across all considered metals and tissue types, season, somatic condition, and $\delta^{13}C$ dominated as the variables of greatest relative importance. Fork-length also appeared as a variable of high relative importance for essential metals, and age and $\delta^{15}N$ tended to be of greater relative importance to the non-essential metals. The majority of composite models for describing elemental tissue concentrations were often inclusive of these previously parameters.

Organotropism

Metal organotropism was observed with Cd, Cu, Ni, and Zn accumulation with total liver metal concentrations being significantly greater than concentrations determined from dorsal muscle tissue. Elements As, Cr, and Pb did not behave as predicted and exhibited no significant variation in concentrations among the analyzed tissue types. The organotropic pattern of preferential Cd, Cu, Ni, and Zn liver accumulation has been observed with other fish species across several different families, e.g. Clupedaie, Caragidae, Percidae, Scombridae, and Serranidae (Roméo *et al.* 1999; Andres *et al.* 2000; Canli and Atli, 2003; Fernandes *et al.* 2007; Agah *et al.* 2009), as the liver is one of the main sites for metal storage and detoxification in fish. Previous studies have established that metal concentrations in the liver are often elevated in relation to muscle tissue concentrations (Roméo *et al.* 1999; Fernandes *et al.* 2007; Pannetier *et al.* 2015*)*, as a result of a targeting of metabolically active tissues by heavy metals (Langston, 1990; Serra *et al.* 1993; Roesijadi and Robinson, 1994; Canli *et al.* 1998). However, some

exceptions to the general pattern have been noted and may be the consequence of species-specific physiology, feeding behaviour, and/or habitat use (Phillips, 1977; Camusso *et al.* 1995; Canli *et al.* 1997; Suñer *et al.* 1999; Canli and Atli, 2003; Wagner and Bowman, 2003; Squadrone *et al.* 2013; Pannetier *et al.* 2015), the preferential induction of metal binding proteins to certain elements over others (Tulasi, *et al.* 1992; Allen 1994; Roesijadi and Robinson 1994), or elemental elimination rates (Kalay and Canli, 1999). Differences in lipid solubility of the specified metal and/or exposure duration and concentration bioavailability (Ray *et al.* 1984; Wiener *et al.* 1984; Spry and Wood, 1989; Barak and Mason 1990a,b; Harrison and Klaverkamp, 1990; Sharif *et al.* 1993; Cossa *et al.* 2011) may also have contributed to the observed variation in organotropism.

Measured As, Cr, and Pb concentrations exhibited no significant variation between analyzed elemental dorsal muscle and liver concentrations. The lack of significant differences for Pb accords with observations reported for marine fishes such as Skipjacks, *Katsuwonus pelamis*, Swordfish, *Xiphias gladius*, and Yellowfin tunas, *Thunnus albacares* (Kojadinovic *et al.*2007) and has been hypothesized to be associated with Pb accumulation and distribution channels given the affinity for Pb uptake in mucosal membranes (gills/fins/skin/intestines) as opposed to muscle or liver tissues (Somero *et al.* 1977; Varanasi and Gmur, 1978; Sörenson 1991). Previous studies have also documented lower liver Pb accumulation when compared to other non-essential metals (Tulasi *et al.* 1992; Allen, 1992; Roesijadi and Robinson 1994). Organotropism of As and Cr appears to vary by species (Phillips, 1977; Camusso *et al.* 1995; Canli *et al.* 1997; Canli and Kalay, 1998; Suñer *et al.* 1999; Canli and Atli, 2003; Wagner and Bowman, 2003; Yilmaz *et al.* 2010; Squadrone *et al.* 2013; Pannetier *et al.* 2015). For example, higher hepatic Cr concentrations have been reported for the broad striped anchovy, *Anchoa hepsetus* (Canli and

Atli, 2003) and the European catfish, *Silurus glanis* (Squadrone *et al.* 2013), while higher muscle

concentrations observed in the Vietnamese catfish, *Clarias fucus* (Wagner and Bowman, 2003).

Additionally, no significant variation between muscle and liver tissue As concentrations has been

documented in American, *Anguilla rostrata*, and European eels, *Anguilla anguilla* (Pannetier *et al.* 2015). Differences among species suggest that observed tissue concentrations may be related

to exposure duration, elemental kinetics, and/or the environmental bioavailability (Spry and

Wood, 1989; Sharif *et al.* 1993; Cossa *et al.* 2011), as these predictors have been previously

associated with species specific variation of trace metal concentrations.

Seasonal Variation

The significantly greater post-winter tissue metal concentrations observed in this research

are consistent with data reported for other trace metals (e.g. Hg) and fish species (e.g. European

whitefish (*Coregonus lavaretus*)) (Köck *et al.* 1996; Cizdziel et al., 2002, Cizdziel *et al.* 2003;

Kahilainent *et al.* 2016; Keva *et al.* 2017) and may result from the distinct patterns of seasonal

feeding behavior in Arctic charr (Dutil 1986; Jonsson *et al.* 1988; Rikardsen *et al.* 2003; Power

et al. 2008), as regulatory processes associated with several of the analyzed metals are greatly

influenced by diet (Murphey *et al.* 1978; Weiner and Giesy, 1979; Shears and Fletcher, 1983;

Handy 1996; Hardy *et al.* 1987; Sörenson 1991; Glover and Hostrand, 2002; Kamunde *et al.*

2002a,b; Bury *et al.* 2003). Both feeding and metabolism increase in the summer, the latter as a

result of increased water temperatures and food intake (Jobling 1981; Yang *et al.* 2000; Van

Leeuwan *et al.* 2012) and both of these variables have implications for trace metal accumulation

(Douben 1989; Köck *et al.* 1996; Yang *et al.* 2000; Nichols and Playle, 2004). Seasonal feeding

and metabolic changes will increase metal uptake and subsequent depuration rates (Heath 1987;

Niimi 1987; Douben 1990; Yang *et al.* 2000; Nichols and Playle, 2004; Van Leeuwan *et al.*

2012), with the balance likely to favour depuration given the low concentration environments in which Arctic charr feed in the summer. For example metal concentrations in marine environments are typically lower in comparison to freshwater counterparts (Somero *et al.* 1977; Stagg and Shuttleworth, 1982; Grosell *et al.* 2007; Vicente-Martorell *et al.* 2008), implying that metals uptake through feeding or across the gill via respiration will be lower in marine than freshwater environments (Birdsong and Avault, 1971; Somero *et al.* 1977; Sörenson 1991; Blackmore and Wang, 2003; Zhang and Wang, 2007; Loro *et al.* 2012). Thus summer occupancy of marine environments favours metabolically driven elimination of previously accumulated metals whereas winter occupancy of freshwater environments favours accumulation as a result of habitat-driven exposure and reduced metabolic-driven depuration.

In addition to the reduced metabolically driven depuration of trace metals during the ice-covered period (Jobling 1981; Heath 1987; Niimi 1987; Douben 1990; Yang *et al.* 2000; Nichols and Playle, 2004; Van Leeuwen *et al.* 2012), winter reductions in body reserves and documented declines in somatic condition (Dutil 1986, Jørgensen, *et al.* 1997; Klemetsen *et al.* 2003b; Amundsen and Knudsen, 2009) could have significant implications for over-wintering metal concentrations. The starvation – concentration phenomenon has been reported for Hg concentrations after seasonal protein and lipid loss (Cizdziel et al., 2002, Cizdziel *et al.* 2003) and condenses Hg in remaining tissues (Kahilainent *et al.* 2016) resulting in higher concentrations during the ice-covered period (Keva *et al.* 2017). As winter for anadromous Arctic charr is characterized by lipid and protein losses (Dutil 1986, Jørgensen, *et al.* 1997) and somatic condition reductions, as seen here and elsewhere (e.g. Klemetsen *et al.* 2003b; Amundsen and Knudsen, 2009), it is hypothesized that declines in Arctic charr body reserves during the ice-covered period associated with the starvation – concentration phenomenon

similarly condense trace metal concentrations in the remaining tissues to produce the observed seasonal variation and elevation of concentrations in post-winter sampled tissues.

Notable exceptions to the pattern of seasonal winter increases were liver As and dorsal muscle Cd concentrations, found to be highest in summer. As bioavailability is greater in the marine environment (Cullen and Reimer, 1989; Seyler and Martin, 1991) and an association between As concentrations and the influence of the marine environment has been previously demonstrated in the American eel and the European eel in both Canada and France (Pannetier *et al.* 2015). Thus, annual migrations and subsequent marine residency are sufficient to explain elevated summer As concentrations. In contrast, observed variation in Cd concentrations are more likely related to exposure time, uptake dynamics, and Cd distribution channels. For example, increased summer water temperatures have been associated with elevated Cd uptake in fish (Douben 1989; Köck *et al.* 1996), while Cd liver concentrations appear to be dictated by exposure time (Mount and Stephen, 1967; Eisler 1974; Cearley and Coleman, 1974; Benoit *et al.* 1976; Varanasi and Markey, 1978; Sörenson 1991; Odžak and Zvonaric, 1995; Dang and Wang, 2009) or organ uptake dynamics. For example, early after both aqueous and dietary uptake, greater concentrations of Cd can be found in tissues, such as the gills, scales, and muscle (Mount and Stephen, 1967; Eisler 1974; Varanasi and Markey, 1978; Sörenson 1991; Odžak and Zvonaric, 1995), but prolonged exposure results in significantly greater concentrations in liver and kidney tissue (Cearley and Coleman, 1974; Benoit *et al.* 1976; Sörenson 1991; Odžak and Zvonaric, 1995; Dang and Wang, 2009).

Relationships with Biological Variables and Stable Isotope Values

Observed relationships between As and fork-length and age may be explained by the associations between As and marine environmental influences (Cullen and Reimer, 1989; Seyler

and Martin, 1991; Pannetier *et al.* 2015) with larger/older fish having experienced greater exposure to increased As bioavailability through their accumulated annual migrations to the marine environment. Decreases in Zn with fish length likely depend on the association between Zn and metabolism (Matthiessen and Bradfield, 1977; Zhang and Wang, 2007). The dilution effect with age mirrors results reported for other fish species e.g. Chinook salmon, *Oncorhynchus tshawytscha*, Rainbow trout, *Oncorhynchus mykiss,* and White sucker, *Catostomus commersonii* (Goodman 1951; Chapman 1978; Ney and Van Hessel, 1983; De Wet *et al.* 1994) and has been attributed to age-dependent decreases in daily ration (Marmulla and Rösch, 1990).

Several significant inverse relationships existed between tissue concentrations and K values, as seen here, have been reported for several other fish species, e.g. Arctic charr, European eel, and Yellow perch, *Perca flavescens* (Eastwood and Couture, 2002; Giguère *et al.* 2004; Maes *et al.* 2005; Dittman and Driscoll, 2009; Swanson and Kidd, 2010). The negative relationships between trace metal concentrations and somatic condition may be attributed to the dilution effect of lipids (Eisler 1987; Wiener *et al.* 2002; Farkas *et al.* 2003; Swanson and Kidd, 2010; Kahilainen *et al.* 2016), as lipid content and K values have been previously associated, (Hoar 1939; Pinder and Eales, 1969; Naevdal *et al.* 1981; Herbinger and Friars, 1991; Dutil 1986; Thompson *et al.* 1991; Todd *et al.* 2008).

Measured Pb concentrations were inversely related to $\delta^{13}C$, while Cu behaved in a manner opposite to what was predicted. Relationships between Pb and $\delta^{13}C$ would infer that increased feeding in marine influenced environments promotes reduced Pb accumulation (Peterson and Fry 1987; Schaffner and Swart 1991; Hobson *et al.* 1997), and is likely associated with reported significant differences between metal concentrations in freshwater vs. marine prey

items (Evans *et al.* 2005). Previously documented relationships between Cu and δ^{13}C vary

(Barwick and Maher, 2003; Campbell *et al.* 2005; Hao *et al.* 2013; Nfon *et al.* 2009; Tu *et al.*

2012; Zhao *et al.*2013; Borrell *et al.* 2016) and appear independent of species, habitat use, and/or

feeding (Bradley and Morris, 1986; Kress *et al.* 1999; Pouil *et al.* 2017). Thus, species-specific

homeostatic regulation may have a greater influence on accumulation of Cu than environment.

While As was influenced by trophic position as predicted, Zn and Cr exhibited biodiminution.

Biodiminution has been observed previously with other aquatic organisms and fish (Kraemer *et*

al. 2012; Borrell *et al.* 2016; Bungala *et al.* 2017) and has been to attributed to food web

simplicity for Zn (Cardwell *et al.* 2013) with generally no biomagnification of this element

occurring when food chains consist of only primary producers, macroinvertebrate consumers,

and fish. Considering the aquatic habitats and communities in which Arctic charr reside and feed

are relatively simple (Christoffersen *et al.* 2008), this may suggest that the observed

biodiminution of Zn is the result of food web interactions. The trend for Cr may be the result of

poor accumulation of this element from the environment (Bungala *et al.* 2017) in conjunction

with elemental half-life and storage properties that can prompt concentration reductions during

food web trophic transfers (Nordberg 1998; Rabinowitz 1991; Campbell et al., 2005).

The lack of consistent single variable relationships between metal concentrations and

considered fish biological descriptors, e.g., length or age, suggests that these variables are not the

best descriptors of elemental concentrations in anadromous Arctic charr. Rather concentration

data were better described when season, somatic condition, or trophic descriptors (δ^{13}C, and

δ^{15}N) were included in predictive models. Thus, for Arctic charr it appears that seasonally and

physiologically dependent integrative processes have the greatest influence on trace metal

concentrations in this species as has been documented in previous literature (Murphey *et al.*

1978; Weiner and Giesy, 1979; Shears and Fletcher, 1983; Handy 1996; Hardy *et al.* 1987; Sörenson 1991; Glover and Hostrand, 2002; Kamunde *et al.* 2002a,b; Bury *et al.* 2003). It is where ($\delta^{13}C$), when (season), and how successfully (K) an individual feeds that are important for determining among-individual trace metal concentration variations.

Conclusions

This research has provided one of the first studies of the biological and trophic factors thought to be significant for explaining variations in trace metals concentrations in anadromous Arctic charr. Observed organotropism was generally consistent with previous literature observations, while seasonal differences in concentrations appear to be linked to seasonally regulated metabolic depuration and elimination processes in association with habitat driven exposure and winter fasting induced condensation of metal tissue concentrations. Relationships with fork-length, age, and somatic condition, as well as stable isotope values were dependent on the element of interest as well as the analyzed tissue and provided no consistency in terms of explanatory power as hypothesized. Predictive models of concentration data were best described when multiple variables were included. Multi-predictor variable models of tissue concentration data improved abilities to explain variations in the data and were often best supported when season, somatic condition, and trophic descriptors were included in the model. Results highlight the influence of these variables on the uptake and handling of trace metals in Arctic charr and suggest that seasonally and physiologically dependent integrative processes have the largest influence on trace metal concentrations in anadromous Arctic charr.

Table 3.1

Summary data for anadromous Arctic charr captured during both collection periods (summer 2016 and post-winter 2017). Means ± standard deviations and ranges are given for fork-lengths, condition values, ages, and dorsal muscle stable isotopes ($\delta^{13}C$ and $\delta^{15}N$). Significant seasonal variation is denoted with * ($p < 0.05$), ** ($p < 0.001$), and *** ($p < 0.0001$).

Season	N	Fork-length (mm)	Age (Years)	Condition (K)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Summer 2016	30	487.29 ± 87.43	9.50 ± 2.39	1.05 ± 0.02***	-19.48 ± 0.89***	13.05 ± 0.83
		311.00; 653.00	5; 15	0.57; 1.69	-21.64; -17.39	10.76; 15.00
Post-Winter 2017	29	452.56 ± 139.59	8.97 ± 2.65	0.90 ± 0.10	-20.70 ± 1.11	13.22 ± 1.13
		220.98; 698.50	4; 16	0.51; 1.02	-22.89; -16.85	10.94; 15.04

Table 3.2

Means ± standard deviations and ranges dorsal muscle (top) and liver (bottom) concentrations (dry weight) of As, Cd, Cr, Cu, Ni, Pb, and Zn from anadromous Arctic charr captured during both capture seasons (summer 2016 and post-winter 2017). * ($p < 0.05$), ** ($p < 0.001$), and *** ($p < 0.0001$) are representative of significant seasonal variation.

Season	As (mg·kg⁻¹)	Cd (mg·kg⁻¹)	Cr (mg·kg⁻¹)	Cu (mg·kg⁻¹)	Ni (mg·kg⁻¹)	Pb (mg·kg⁻¹)	Zn (mg·kg⁻¹)
Summer 2016	1.93 ± 0.60	0.03 ± 0.03***	0.26 ± 0.06	1.79 ± 0.48	0.09 ± 0.06	0.05 ± 0.07	22.77 ± 4.40
	0.83; 3.34	0.00; 0.16	0.21; 0.55	1.09; 3.72	0.02; 0.35	0.00; 0.28	16.67; 39.76
Post-Winter 2017	1.96 ± 0.76	0.01 ± 0.01	0.46 ± 0.11***	1.71 ± 0.72	0.15 ± 0.07***	0.05 ± 0.03*	28.12 ± 13.96*
	0.09; 3.02	0.00; 0.04	0.36; 0.84	1.00; 4.48	0.08; 0.35	0.02; 0.17	15.87; 85.63
Summer 2016	2.3 ± 0.75*	0.52 ± 0.41	0.26 ± 0.04	21.26 ± 64.70	0.23 ± 0.14	0.03 ± 0.02	115.68 ± 28.00
	1.22; 3.83	0.17; 2.01	0.20; 0.38	6.10; 343.75	0.05; 0.71	0.01; 0.12	70.02; 172.90
Post-Winter 2017	1.68 ± 0.91	1.00 ± 0.76***	0.37 ± 0.05***	72.22 ± 42.65*	0.19 ± 0.06	0.05 ± 0.02***	119.14 ± 33.94
	0.08; 3.63	0.30; 4.24	0.30; 0.51	25.39; 203.99	0.08; 0.41	0.03; 0.10	48.15; 190.14

Table 3.3
The relative importance of individual parameters and interaction terms included in the models determined through *AICc* model selection that best described anadromous Deception River Arctic charr dorsal muscle and liver concentrations of essential (Cu and Zn) (left) and non-essential metals (As, Cd, Cr, Ni, and Pb) (right). The parameters with the greatest relative importance to elemental tissue concentrations are bolded.

	Cu (mg·kg^{-1})		Zn (mg·kg^{-1})		As (mg·kg^{-1})		Cd (mg·kg^{-1})		Cr (mg·kg^{-1})		Ni (mg·kg^{-1})		Pb (mg·kg^{-1})	
	Dorsal Muscle	Liver	Dorsal Muscle	Liver	Dorsal Muscle	Liver	Dorsal Muscle	Liver	Dorsal Muscle	Liver	Dorsal Muscle	Liver	Dorsal Muscle	Liver
Season	**0.48**	**0.99**	0.15	0.24	0.89	**1.00**	**1.00**	0.73	**1.00**	**1.00**	**1.00**	**1.00**	0.28	**1.00**
Fork-Length	0.11	0.31	**0.99**	**0.99**	0.18	-	0.36	0.63	-	-	0.28	-	-	-
Age	-	-	-	-	0.54	**1.00**	0.18	0.37	-	-	0.18	**1.00**	**1.00**	-
Somatic Condition	0.25	0.51	0.69	**0.99**	**1.00**	0.09	**1.00**	**1.00**	-	0.86	0.12	**1.00**	**1.00**	**1.00**
δ^{13}C	0.21	**0.99**	0.67	**0.99**	**1.00**	0.63	-	-	**1.00**	0.43	-	-	**1.00**	0.16
δ^{15}N	0.23	0.68	-	0.75	0.83	0.52	**1.00**	**1.00**	0.32	0.27	0.26	-	**1.00**	0.22
Season*Condition	-	0.51	0.15	-	0.64	-	-	-	-	0.13	-	0.35	-	0.22
Season*δ^{13}C	0.09	**0.99**	-	-	0.24	-	-	-	-	-	-	-	-	-
Fork-Length*δ^{15}N	-	-	-	0.51	-	-	-	0.63	-	-	-	-	-	-
Age*δ^{15}N	-	-	-	-	-	0.20	-	0.37	-	-	-	-	**1.00**	-
Condition*δ^{15}N	-	-	-	-	0.67	-	**1.00**	0.54	-	-	-	-	**1.00**	0.22

Table 3.4

Summary of the composite models (parameter and interaction term estimates $(\widetilde{\overline{B}})$, unconditional standard errors $(\hat{s}e(\widetilde{\overline{B}}))$, and upper (UCI) and lower (LCI) 95% confidence intervals), determined through model averaging, that best describe dorsal muscle concentrations of essential (Cu and Zn) and non-essential metals (As, Cd, Cr, Cu, Ni, and Pb).

Element	Parameter	$\widetilde{\overline{B}}$	$\hat{s}e(\widetilde{\overline{B}})$	UCI	LCI
Cu (mg·kg^{-1})	Intercept	0.300	0.168	0.637	-0.037
	Season	-0.009	0.014	0.019	-0.036
	Fork-Length	7.889 X 10^{-7}	1.353 X 10^{-5}	2.790 X 10^{-5}	-2.600 X 10^{-5}
	Condition	-0.019	0.043	0.067	-0.106
	δ^{13}C	0.001	0.004	0.009	-0.007
	δ^{15}N	-0.003	0.007	0.011	-0.017
	Season*δ^{13}C	-0.002	0.005	0.007	-0.012
Zn (mg·kg^{-1})	Intercept	1.374	0.380	2.134	0.614
	Season	0.001	0.004	0.008	-0.006
	Fork-Length	-4.704 X 10^{-3}	1.212 X 10^{-3}	-2.300 X 10^{-3}	-7.100 X 10^{-3}
	Condition	-0.118	0.111	0.104	-0.340
	δ^{13}C	-0.017	0.015	-0.016	-0.017
	Season*Condition	-0.073	0.087	0.102	-0.248
As (mg·kg^{-1})	Intercept	-5.384	2.170	-1.041	-9.727
	Season	-0.127	0.157	0.187	-0.441
	Fork-Length	-3.332 X 10^{-3}	5.875 X 10^{-3}	1.509 X 10^{-2}	-8.400 X 10^{-3}
	Age	0.026	0.037	0.101	-0.049
	Condition	0.253	0.921	2.095	-1.589
	δ^{13}C	-0.226	0.081	-0.065	-0.388
	δ^{15}N	0.172	0.127	0.426	-0.082
	Season*Condition	1.106	1.045	3.198	-0.985
	Season*δ^{13}C	1.028	2.7.459	10.486	-10.486
	Condition*δ^{15}N	-0.742	0.652	2.104	-1.126
Cd (mg·kg^{-1})	Intercept	-1.185	0.749	0.314	-2.685
	Season	-0.302	0.041	-0.221	-0.384
	Fork-Length	-2.168 X 10^{-3}	3.494 X 10^{-3}	9.160 X 10^{-3}	-4.800 X 10^{-3}

	Age	-3.952×10^{-3}	1.814×10^{-3}	7.705×10^{-2}	-6.910×10^{-2}
	Condition	-0.207	0.242	0.278	-0.692
	$\delta^{15}N$	-0.030	0.054	0.077	-0.137
	Condition*$\delta^{15}N$	0.537	0.188	0.914	0.160
Cr (mg·kg^{-1})	Intercept	-0.861	0.242	-0.376	-1.345
	Season	0.108	0.012	0.132	0.084
	$\delta^{13}C$	-0.022	0.010	-0.001	-0.043
	$\delta^{15}N$	-0.003	-0.006	0.010	-0.016
Ni (mg·kg^{-1})	Intercept	-1.381	1.684	1.987	-4.750
	Season	0.149	0.149	0.446	-0.149
	Fork-Length	3.160×10^{-3}	5.767×10^{-3}	1.470×10^{-2}	-8.400×10^{-3}
	Age	7.027×10^{-3}	1.402×10^{-2}	3.509×10^{-2}	-2.100×10^{-2}
	Condition	-0.011	0.024	0.037	-0.060
	$\delta^{15}N$	-0.011	0.022	0.032	-0.054
Pb (mg·kg^{-1})	Intercept	-3.996	1.217	-1.562	-6.431
	Season	0.015	0.032	0.079	-0.048
	Age	-0.011	0.018	0.038	-0.060
	Condition	-0.565	0.305	0.046	-1.177
	$\delta^{13}C$	-0.164	0.048	-0.068	-0.259
	$\delta^{15}N$	-8.725×10^{-5}	0.063	0.126	-0.127
	Age*$\delta^{15}N$	-0.043	0.020	-0.002	-0.083
	Condition*$\delta^{15}N$	-0.562	0.255	-0.052	-1.072

Table 3.5

Summary of the composite models (parameter and interaction term estimates ($\widetilde{\overline{B}}$), unconditional standard errors ($\hat{s}e(\widetilde{\overline{B}})$), and upper (UCI) and lower (LCI) 95% confidence intervals), determined through model averaging, that best describe liver concentrations of essential (Cu and Zn) and non-essential metals (As, Cd, Cr, Cu, Ni, and Pb).

Element	Parameter	$\widetilde{\overline{B}}$	$\hat{s}e(\widetilde{\overline{B}})$	UCI	LCI
Cu (mg·kg^{-1})	Intercept	5.821	0.973	7.768	3.875
	Season	0.237	0.046	0.328	0.146
	Fork-Length	1.281×10^{-3}	6.083×10^{-2}	1.204×10^{-2}	-1.230×10^{-2}
	Condition	0.097	0.214	0.524	-0.331
	$\delta^{13}C$	0.164	0.035	0.235	0.094
	$\delta^{15}N$	-0.067	0.053	0.040	-0.173
	Season*Condition	0.289	0.340	0.970	-0.392
	Season*$\delta^{13}C$	-0.082	0.035	-0.012	-0.151
Zn (mg·kg^{-1})	Intercept	3.424	0.339	4.101	2.745
	Season	-0.003	0.007	0.011	-0.017
	Fork-Length	-3.753×10^{-3}	1.449×10^{-3}	-8.600×10^{-5}	-6.700×10^{-3}
	Condition	-0.250	0.085	-0.079	-0.421
	$\delta^{13}C$	0.039	0.013	0.065	0.013
	$\delta^{15}N$	-0.013	0.017	0.022	-0.047
	Fork-Length*$\delta^{15}N$	1.074×10^{-3}	1.300×10^{-3}	3.670×10^{-3}	-1.500×10^{-3}
As (mg·kg^{-1})	Intercept	-1.272	3.011	4.753	-7.296
	Season	-0.429	0.133	-0.163	-0.695
	Age	-0.054	0.054	0.055	-0.163
	Condition	0.052	0.129	0.309	-0.206
	$\delta^{13}C$	-0.122	0.128	0.133	-0.377
	$\delta^{15}N$	0.097	0.130	0.357	-0.164
	Age*$\delta^{15}N$	0.011	0.021	0.053	-0.032
Cd (mg·kg^{-1})	Intercept	0.571	0.433	1.438	-0.295
	Season	0.051	0.045	0.140	-0.039
	Fork-Length	-8.789×10^{-5}	2.444×10^{-3}	4.010×10^{-3}	-5.800×10^{-3}
	Age	0.011	0.015	0.040	-0.019

	Condition	-0.809	0.215	-0.380	-1.239
	$\delta^{15}N$	-0.010	0.049	0.088	-0.108
	Fork-Length*$\delta^{15}N$	5.423×10^{-3}	4.521×10^{-3}	1.477×10^{-2}	-3.600×10^{-3}
	Age*$\delta^{15}N$	0.011	0.015	0.041	-0.020
	Condition*$\delta^{15}N$	0.173	0.191	0.556	-0.210
Cr (mg·kg^{-1})	Intercept	-0.289	0.321	0.353	-0.930
	Season	0.068	0.009	0.086	0.050
	Condition	-0.075	0.056	0.037	-0.186
	$\delta^{13}C$	-0.001	0.005	0.009	-0.011
	$\delta^{15}N$	0.002	0.004	0.011	-0.007
	Season*Condition	-0.006	0.015	0.023	-0.035
Ni (mg·kg^{-1})	Intercept	-0.335	0.181	0.027	-0.670
	Season	-0.073	0.026	-0.021	-0.125
	Age	0.008	0.009	0.026	-0.010
	Condition	-0.458	0.170	-0.117	-0.798
	Season*Condition	0.069	0.123	0.315	-0.177
Pb (mg·kg^{-1})	Intercept	-1.019	0.340	-0.339	-1.699
	Season	0.120	0.037	0.194	0.046
	Condition	-0.471	0.231	-0.009	-0.932
	$\delta^{13}C$	-0.004	0.009	0.014	-0.021
	$\delta^{15}N$	-0.003	0.011	0.018	-0.024
	Season*Condition	0.058	0.117	0.292	-0.176
	Condition*$\delta^{15}N$	-0.068	0.118	0.168	-0.304
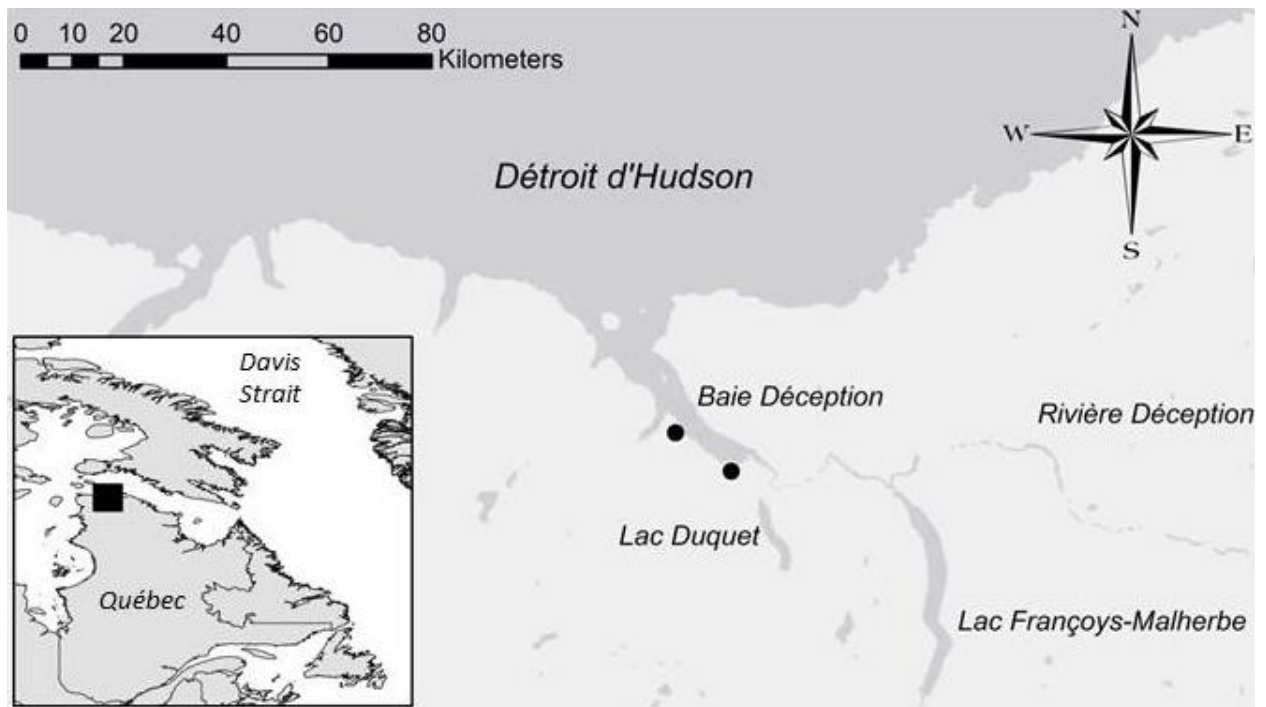
Fig. 3.1. Map of the Deception River system, including the three main sampling areas: Deception Bay, and Lakes Duquet and Françoys-Malherbe. Black circles represent current mining operations present in the area, while the black square visible on the map in the lower left hand corner represents the sampling locations in relation to the Province of Québec.
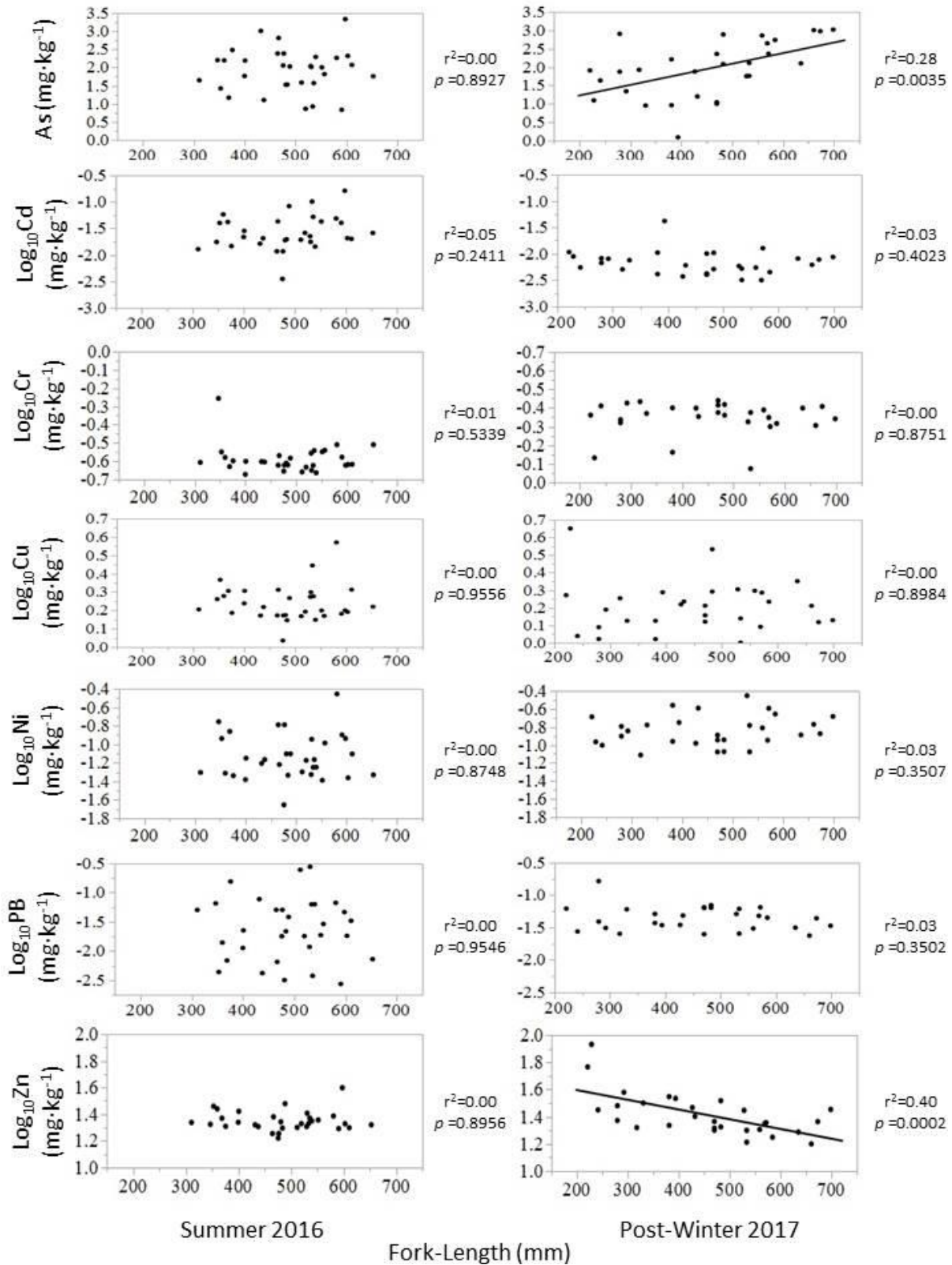
Fig. 3.2. Dorsal muscle As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations of anadromous Deception River Arctic charr captured in the marine environment during the summer and during the post-winter sampling periods in relation to fork-length measurements.
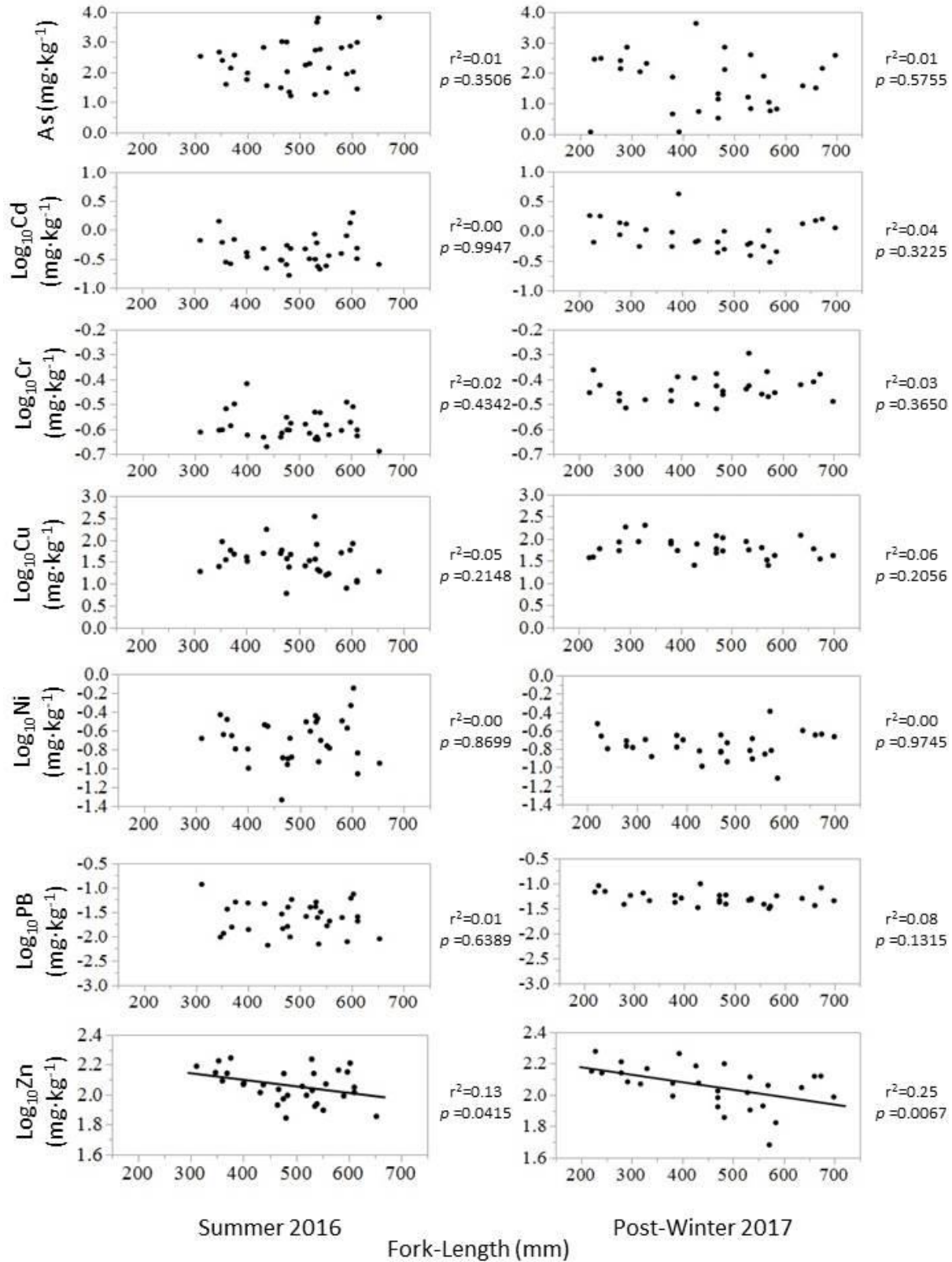
Fig. 3.3. Liver As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations of anadromous Deception River Arctic charr captured in the marine environment during the summer and during the post-winter sampling periods in relation to fork-length measurements.
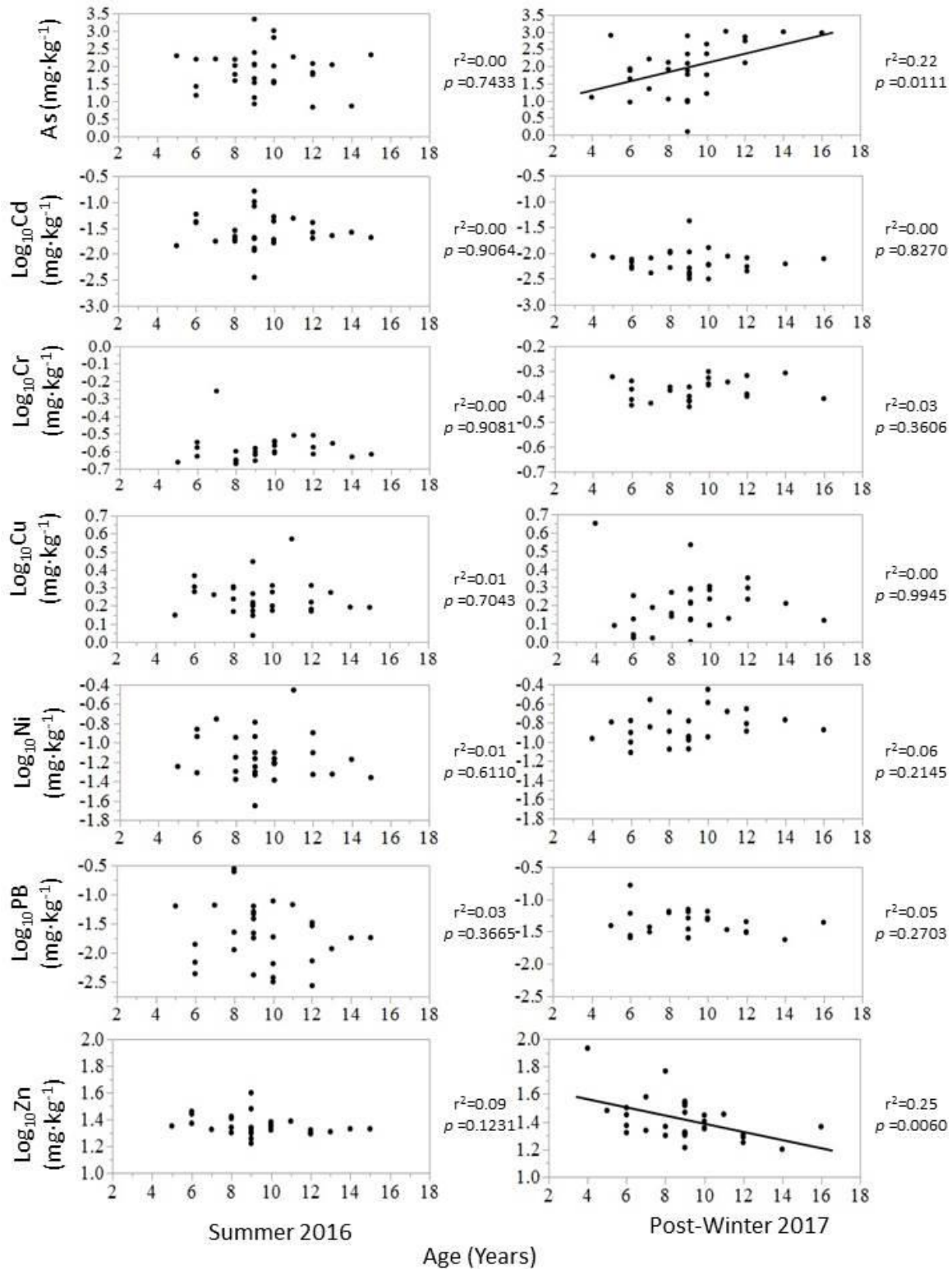
Fig. 3.4. Dorsal muscle As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations of anadromous Deception River Arctic charr captured in the marine environment during the summer and during the post-winter sampling periods in relation to age.
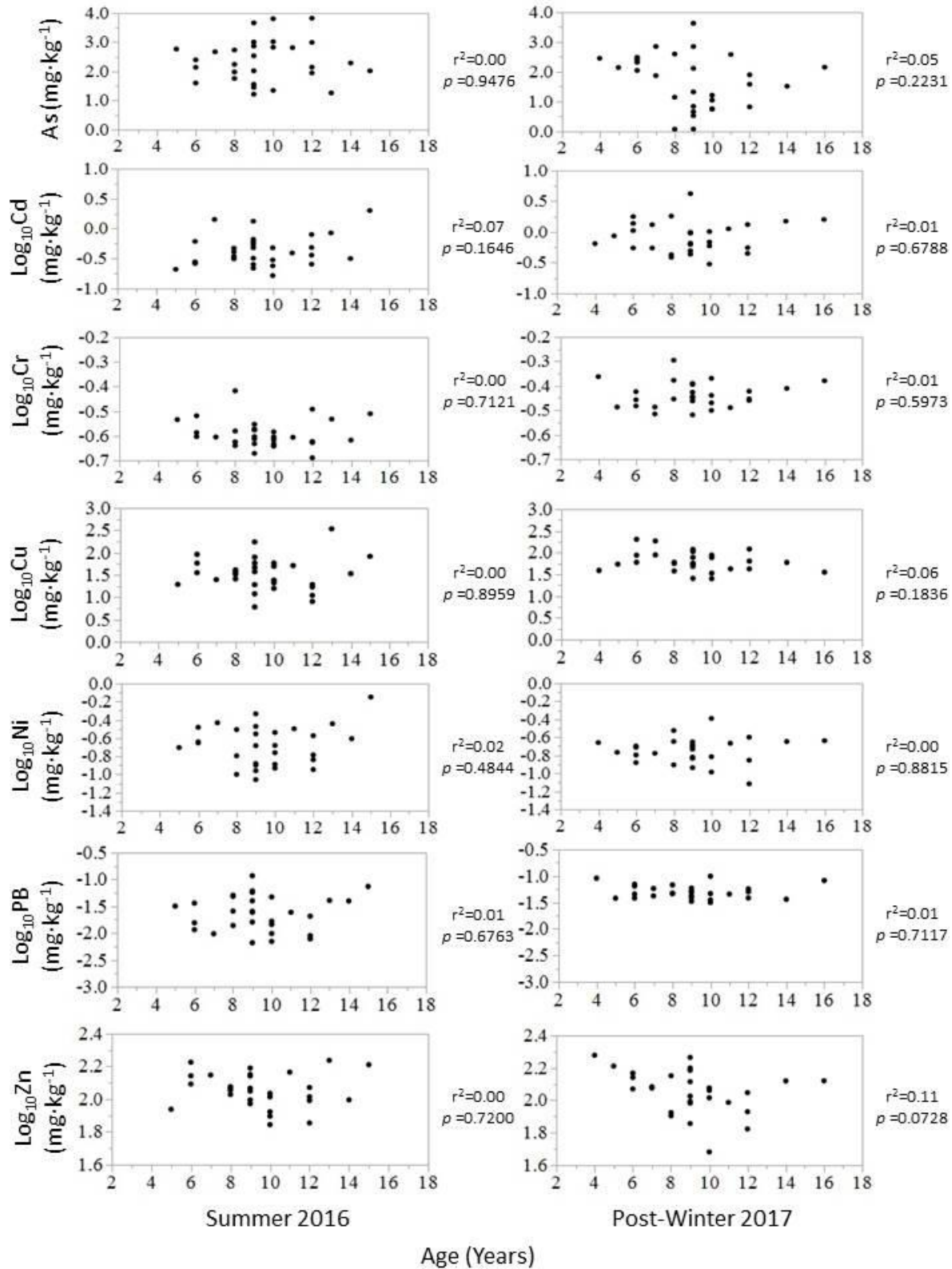
Fig. 3.5. Liver As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations of anadromous Deception River Arctic charr captured in the marine environment during the summer and during the post-winter sampling periods in relation to age.
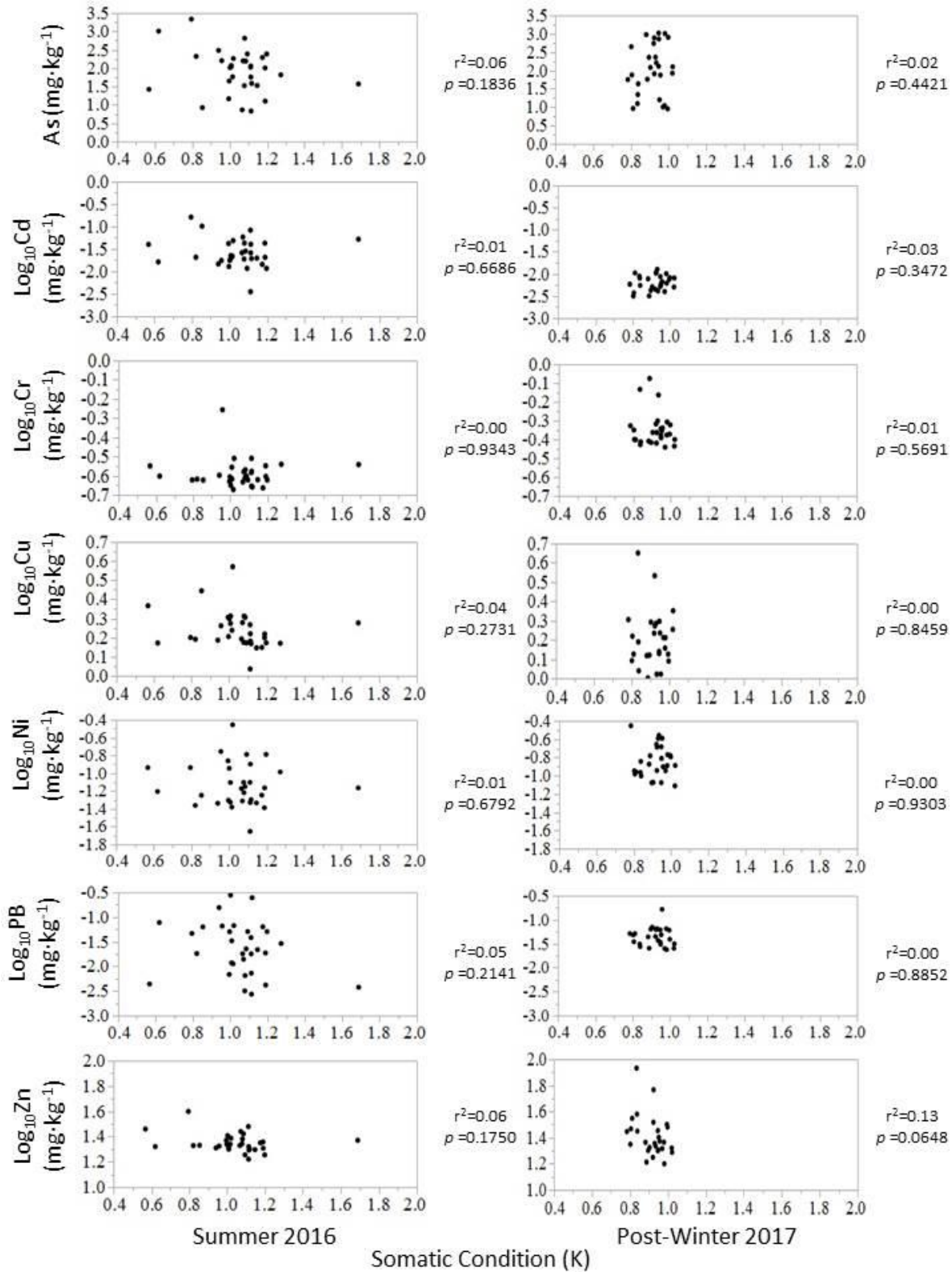
Fig. 3.6. Dorsal muscle As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations of anadromous Deception River Arctic charr captured in the marine environment during the summer and during the post-winter sampling periods in relation to somatic condition.
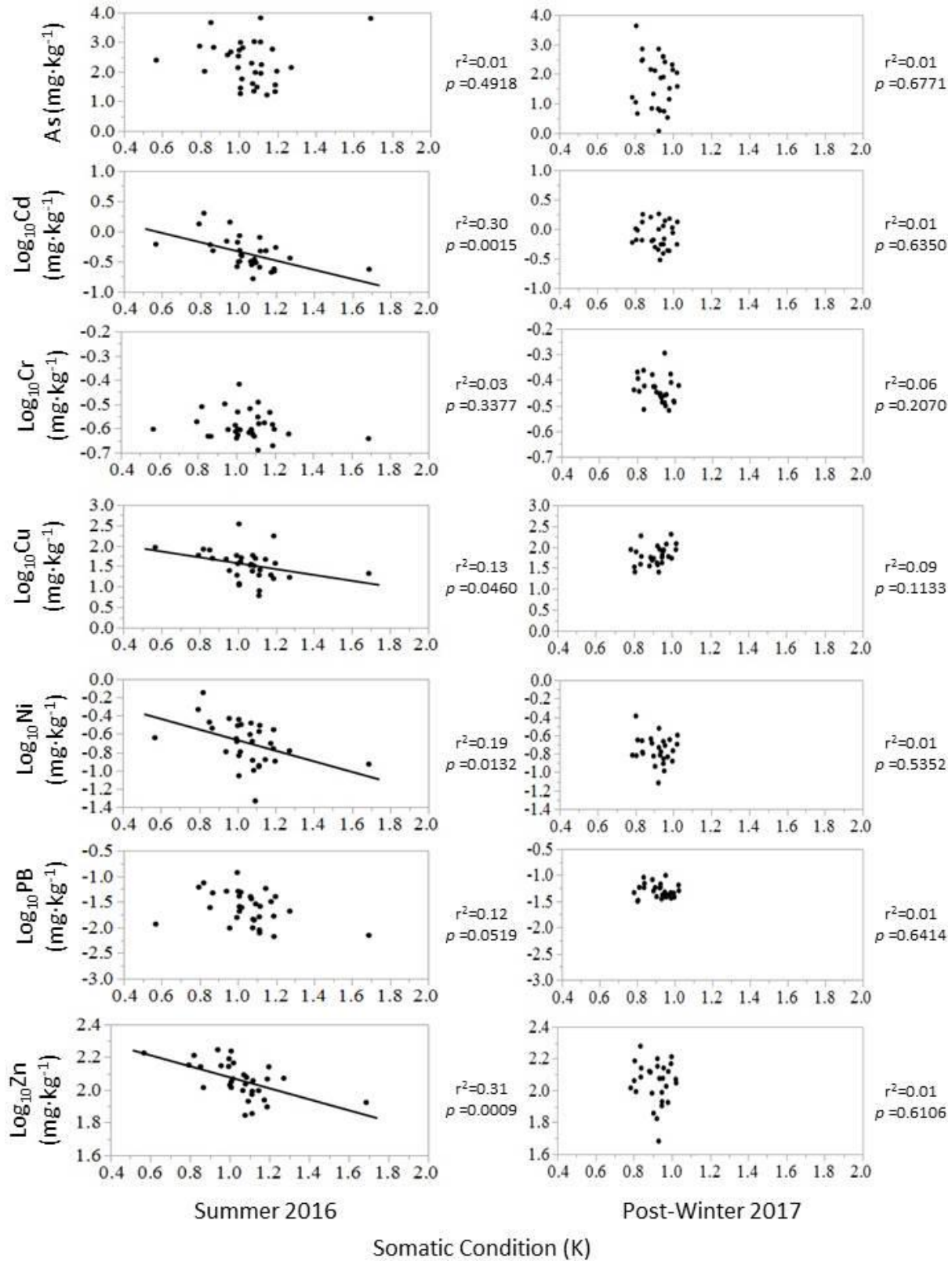
Fig. 3.7. Liver As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations of anadromous Deception River Arctic charr captured in the marine environment during the summer and during the post-winter sampling periods in relation to somatic condition.
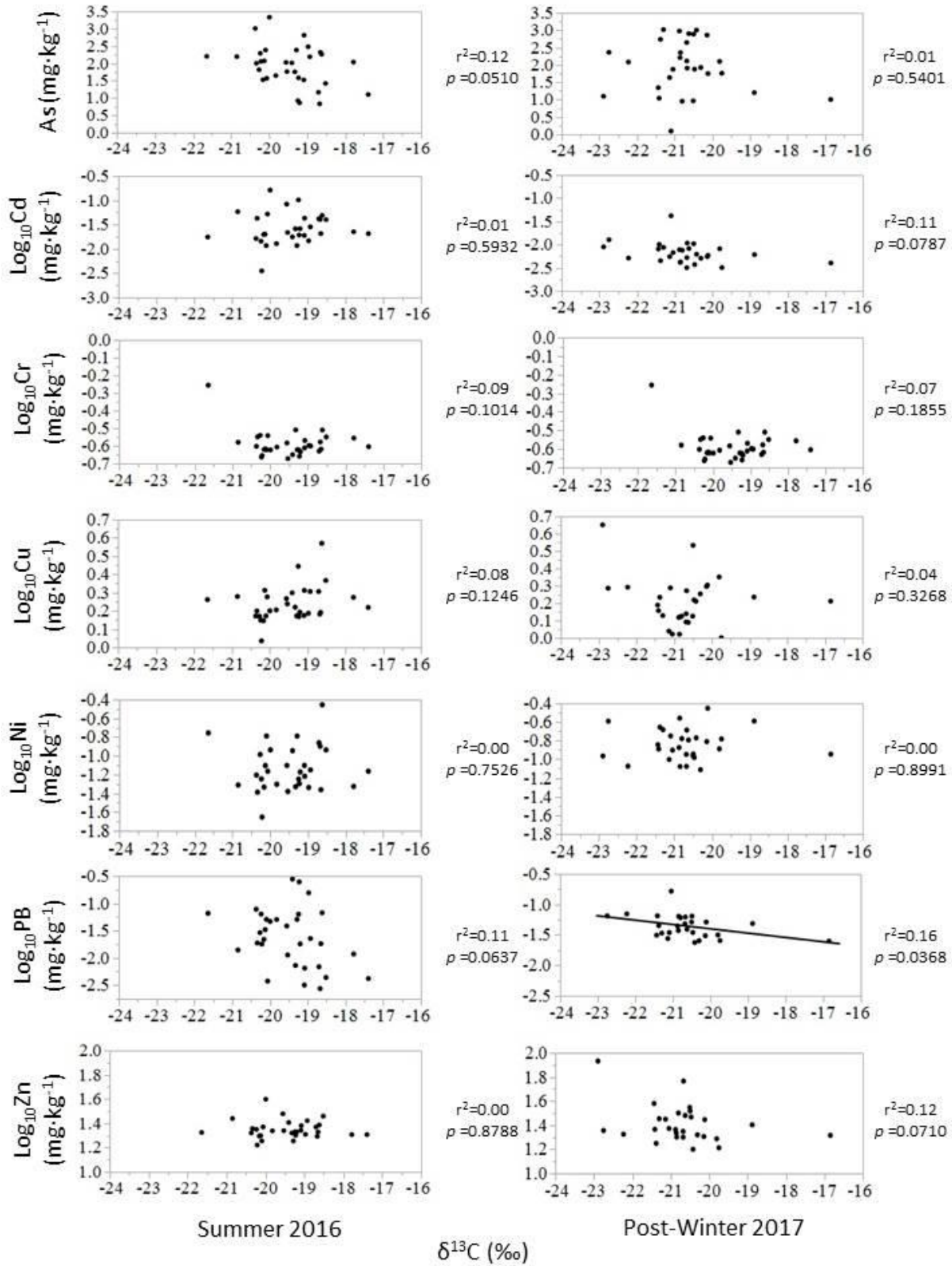
Fig. 3.8. Dorsal muscle As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations of anadromous Deception River Arctic charr captured in the marine environment during the summer and during the post-winter sampling periods in relation to $\delta^{13}C$.
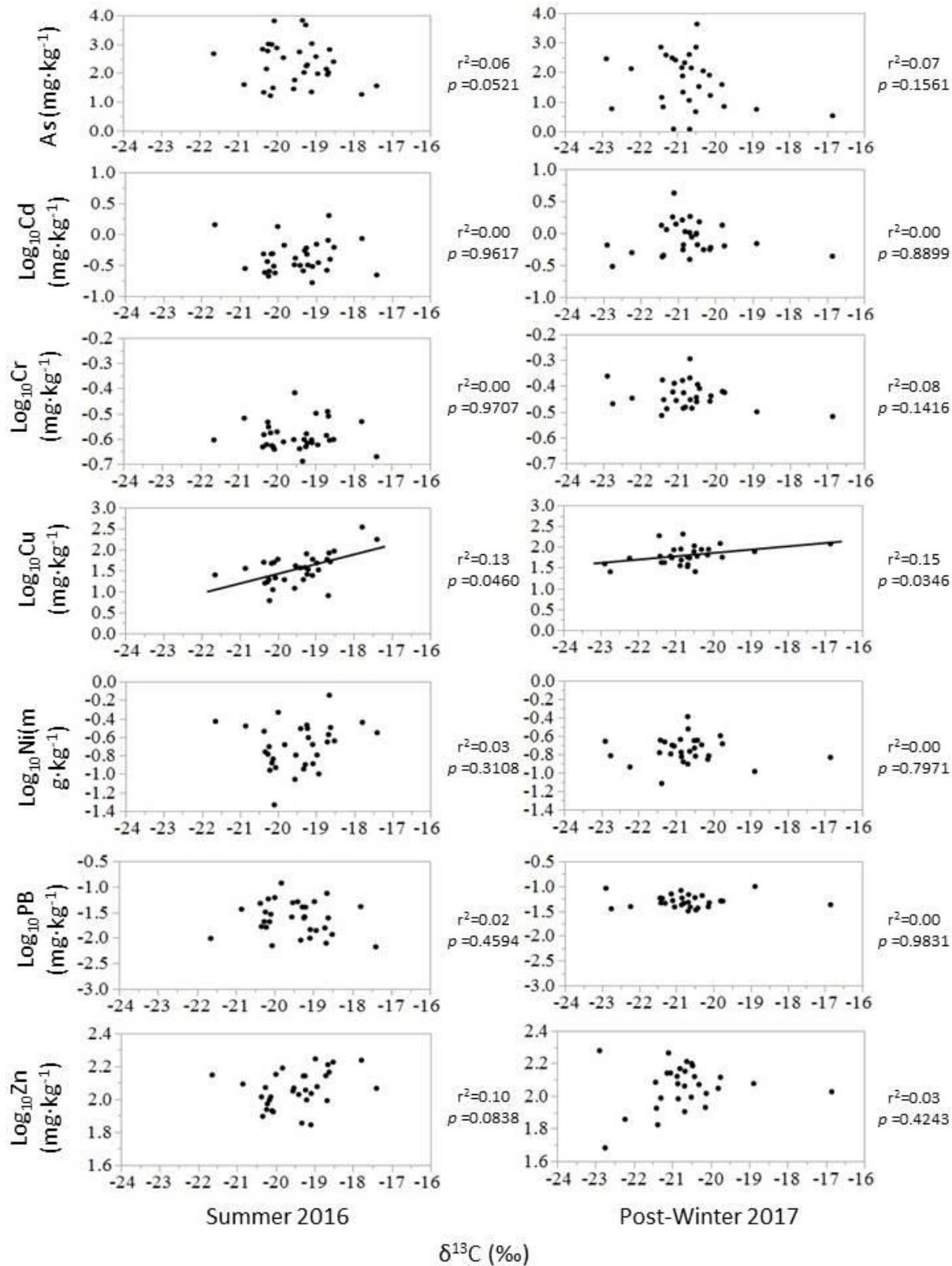
Fig. 3.9. Liver As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations of anadromous Deception River Arctic charr captured in the marine environment during the summer and during the post-winter sampling periods in relation to $\delta^{13}C$.

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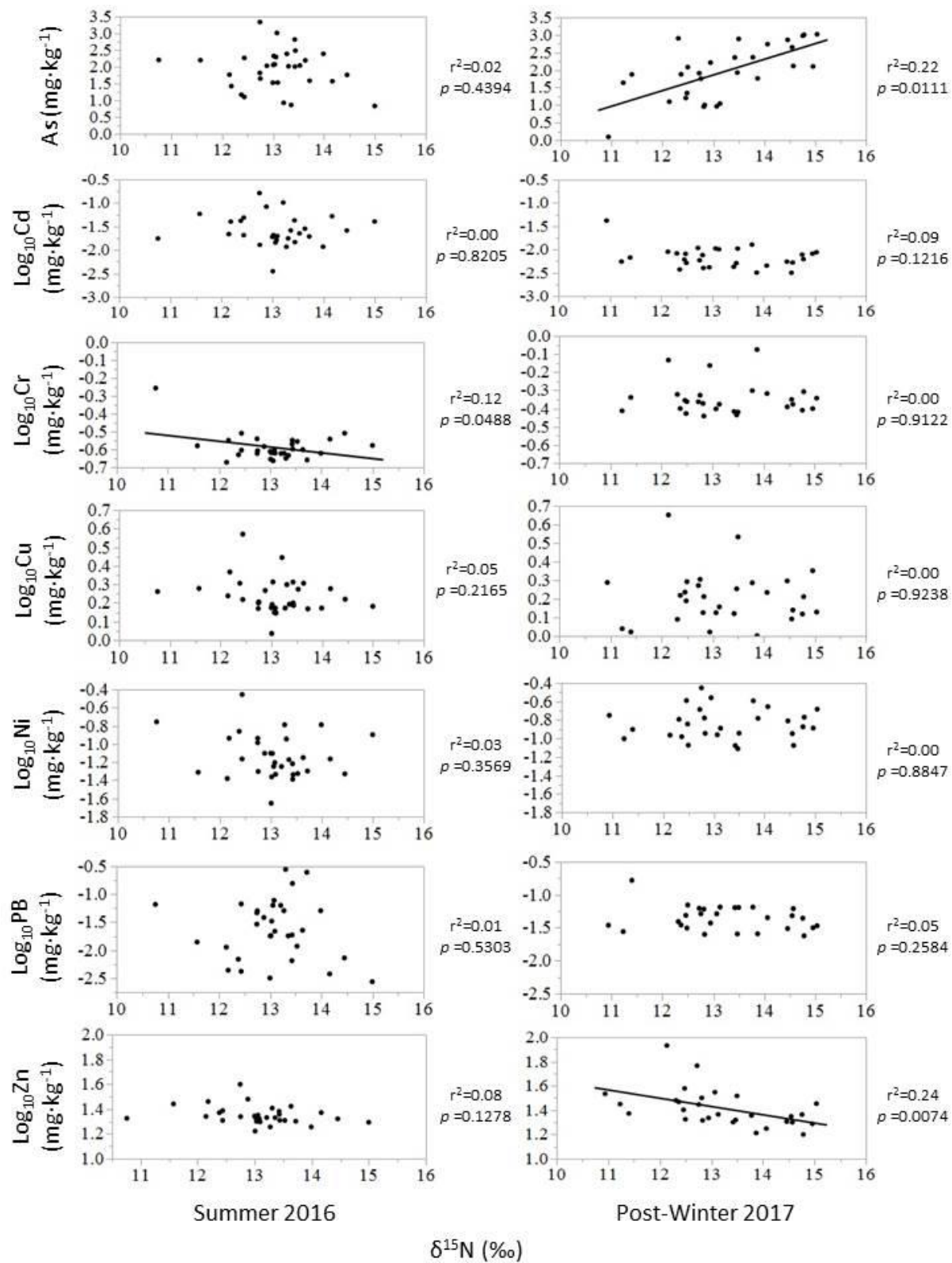
Fig. 3.10. Dorsal muscle As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations of anadromous Deception River Arctic charr captured in the marine environment during the summer and during the post-winter sampling periods in relation to $\delta^{15}N$.
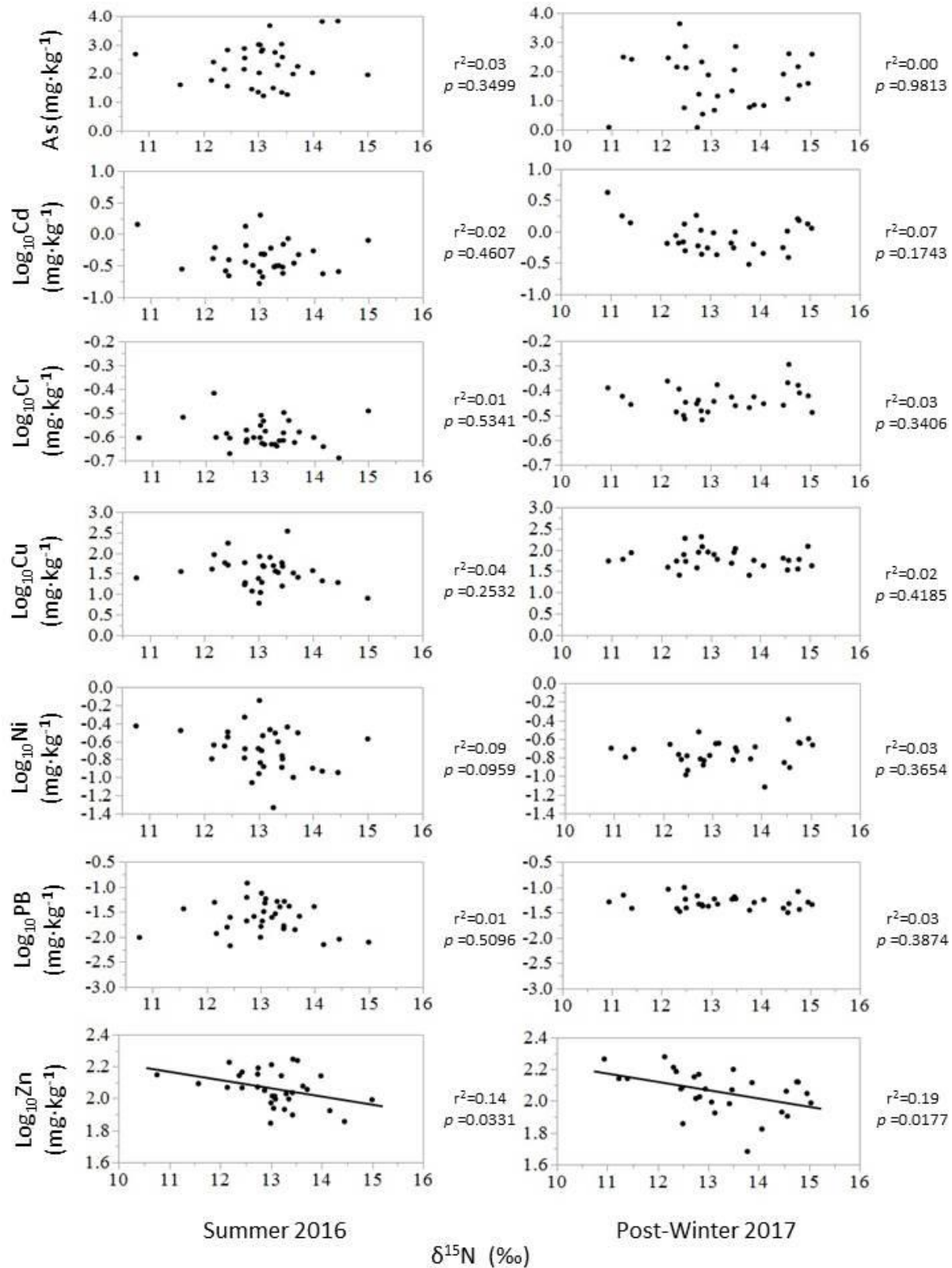
Fig. 3.11. Liver As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations of anadromous Deception River Arctic charr captured in the marine environment during the summer and during the post-winter sampling periods in relation to $\delta^{15}N$.

Chapter 4: Conclusions and Future Directions

Summary of Findings

Chapter 2 examined the impact of the over-wintering period on condition measures and THg concentrations in anadromous Deception River Arctic charr. While somatic condition and % nitrogen values were indicative of prolonged periods of fasting consistent with previous literature detailing the over-winter period for anadromous Arctic charr (Jøgensen *et al.* 1997; Jobling *et al.* 1998; Amundsen and Knudsen, 2009; Power *et al.* 2009), seasonal variation in lipid content and caloric density were contrary to what was hypothesized and were significantly greater in the dorsal muscle tissue of post-wintering Arctic charr. Although the elevated post-winter % lipid values and caloric densities might be indicative of winter diet subsidization, previously inferred in scientific literature for anadromous Arctic charr (Boivin 1987; Mulder *et al.* 2018), the observed absence of short term feeding, i.e. empty stomachs upper gastrointestinal tracts, and depletion of % nitrogen values were indicative of prolonged periods of non-feeding (Hesslein et al 1993; Power *et al.* 2009). Considered together, data suggested condition selective mortality operating over the winter period. Condition selective mortality has been linked theoretically with longer life spans, as seen in Arctic charr (Johnson 1983; Johnson 1989; Power *et al.* 2008; Chen and Maklakov, 2012), and is closely associated with starvation and other stressful periods with teleost fish (Oliver *et al.* 1979; Healy 1982; Henderson *et al.* 1988; Shuter and Post, 1990; Thompson *et al.* 1991; Smith and Griffith, 1994; Sogard and Olla, 2000; Searcy and Sponaugle, 2001). The removal of lower condition individuals from the population via condition selective mortality would shift both lipid trait and caloric density distributions, likely increasing mean values, and may as a result, subsequently influence population demographics (Chen and Maklakov, 2012).

Seasonal variation in THg concentrations was contrary to expectations, being significantly greater in tissue collected from Arctic charr sampled during the summer in the marine environment. Observed results, however, would accord with those expected if condition selective mortality was operating in the population, shifting the post-winter distribution of sampled THg concentrations to reflect the increase in % lipid values and caloric densities that would result from the mortality of poorer conditioned fish (Wiener *et al.* 2002; Post *et al.* 2007).

Season, condition, and stable isotope values (% carbon and % nitrogen) were the best descriptors of variation in % lipid content and caloric densities, which coincides with the known associations between season, somatic condition, and stable isotope values and body reserves, while THg concentrations were best described by models that included whole-weight, somatic condition, and $\delta^{13}C$ as explanatory variables. Thus, variables associated with diet and fish condition appear to exert the greatest influence on the bioaccumulation of THg concentrations in the Deception River Arctic charr population (Power *et al.* 2002; Ikemoto *et al.* 2008a,b; Dittman and Driscoll, 2009; Swanson and Kidd, 2010; Goutte *et al.* 2015).

Chapter 3 examined the implications of biological descriptors (fork-length, age, and somatic condition) and factors associated with feeding on trace metal concentrations in anadromous Arctic charr. Season dominated as a relatively important variable for explaining variation in both essential and non-essential metals. Fork-length and $\delta^{13}C$ were also of importance for determining variations in essential metals, with somatic condition, age, and $\delta^{15}N$ contributed significantly to understanding variations in the non-essential metals. Observed organotropism was generally consistent with previous literature (Roméo *et al.* 1999; Andres *et al.*2000; Canli and Atli, 2003; Fernandes *et al.* 2007; Agah *et al.* 2009), while seasonal variation appeared to be linked to metabolism, metal depuration and elimination, environmental

influences, seasonal reductions in body reserves and subsequent condensation of concentrations in remaining tissues (Somero *et al.* 1977; Jobling 1981; Heath 1987; Niimi 1987; Douben 1990; Yang *et al.* 2000; Cizdziel et al., 2002, Cizdziel *et al.* 2003; Klemetsen *et al.* 2003b; Nichols and Playle, 2004; Grosell *et al.* 2007; Vicente-Martorell *et al.* 2008; Van Leeuwan *et al.* 2012; Kahilainent *et al.* 2016; Keva *et al.* 2017). Results highlight the importance and influence of dietary linked factors for the uptake and handling of trace metals in the studied tissues of Arctic charr and suggest that dynamic and integrative processes that are seasonally and physiologically dependent have the greatest influence on trace metal concentrations in anadromous Arctic charr.

Study Significance

Given the observed declines in the somatic condition of anadromous Deception Bay Arctic charr and the cultural and economic importance of this species to the local communities, this research examined variables linked with implications for fish condition in an effort to address potential causes. While, further investigation into relationships between somatic condition declines of anadromous Deception Bay Arctic charr and 2016 and 2017 collected data was discontinued as a result of historically small sample sizes and non-standardized sampling times or methods, this MSc. research has improved the overall available scientific database for Nunavik Arctic charr populations. Additionally, this research has contributed to the limited research detailing the over-wintering period for anadromous Arctic charr, the metals research focused on this species, and an understanding of seasonal implications for trace metal accumulation.

Despite having cultural, dietary, and economic importance (Condon 1994; Lawn and Harvey, 2004; Kuhnlein and Receveur, 2007; Sharma 2010; AMAP 2011; Huet *et al.* 2012), research on Arctic charr in Deception Bay is limited, dated, and summer specific. (Batterman

and Cook 1981; Locke 1999; Locke 2001; Locke 2002). The lack of available data is representative of a larger regional trend, as most scientific studies of Arctic charr in Nunavik has focused on lacustrine Arctic charr. Only a few studies have assessed anadromous populations in the region (e.g., Boivin and Power, 1990; Murdoch and Power 2013a,b; van der Velden *et al.* 2013b) and only one directly examined issues related to over-wintering (Boivin and Power, 1990). The limited availability of winter research detailing anadromous Arctic char is a trend that extends beyond the Nunavik region to include the circumpolar distribution of this species, as over-wintering anadromous Arctic charr have been poorly described in the literature beyond cessation of feeding during the ice-covered period and resulting reduced condition (e. g. Sprules 1952; Moore and Moore, 1974; Dutil 1986; Boivin and Power, 1990; Jørgensen, *et al.* 1997; Rikardsen *et al.* 2003). In addressing knowledge gaps associated with available regional and population specific data, Chapter 2 also addressed the limited scientific literature detailing the implications of the over-wintering period for anadromous Arctic charr. The observed results are believed to be the first detailing higher lipid content and caloric density of Arctic charr captured during the winter months, a period that has been previously associated with significant reductions in body reserves (Dutil 1986, Jørgensen, *et al.* 1997). THg concentrations were also correspondingly reduced in post-winter sampled Arctic charr and results were contrary to previous reported seasonal observations of this element in fish tissues (Cizdziel *et al*., 2002; Cizdziel *et al.* 2003; Kahilainent *et al.* 2016; Keva *et al.* 2017). The implications of this sub-optimal period on fish condition measures and THg concentrations in anadromous Deception Bay Arctic charr may suggest a population specific condition selective mortality phenomenon or may infer broader regional or circumpolar trends. However, more research is needed before the observed results can be extrapolated.

Most previous metals related research on Arctic charr has focused on mercury concentrations (Muir *et al.* 2005; Gantner *et al.* 2010; Swanson and Kidd, 2010; Swanson *et al.* 2011; Gantner *et al.* 2012; van der Velden *et al.* 2013a,b), despite the negative implications other essential and non-essential metals have at high concentrations for human (Lu *et al.* 2005; Uriu-Adams and Keen, 2005; Godt *et al.* 2006; Sanders *et al.* 2009; Smith and Steinmaus, 2009; Plum *et al.* 2010) and fish health (Henry and Atchison, 1979; Sörensen 1991; Jones *et al.* 2001; Couture and Kumar, 2003; Ghosh *et al.* 2006; Osman *et al.* 2007; Mishra and Mohanty, 2008). Research has generally neglected seasonal variation in metal concentrations despite seasonal variation being reported for a number of other species (e.g. European whitefish (*Coregonus lavaretus*), Yellow perch (*Perca flavescens*) and elements (e.g. cadmium, copper, mercury, nickel, lead, and zinc) (Köck *et al.* 1996; Kahilainen *et al.* 2016; Keva *et al.* 2017). Chapter 3 helped fill this gap by examining seasonal variations of essential (Cu and Zn) and non-essential metals (As, Cd, Cr, Ni, and Pb) in Arctic charr. The chapter documented organotropism, and generally higher concentrations in tissues sampled from the post-winter period. Seasonal variation appeared to be linked to metabolism, metal depuration and elimination, seasonal subsequent condensation of concentrations in remaining tissues after over-wintering losses of body reserves, and distinct seasonal environmental influences (Somero *et al.* 1977; Jobling 1981; Heath 1987; Niimi 1987; Douben 1990; Yang *et al.* 2000; Cizdziel et al., 2002, Cizdziel *et al.* 2003; Klemetsen *et al.* 2003b; Nichols and Playle, 2004; Grosell *et al.* 2007; Vicente-Martorell *et al.* 2008; Van Leeuwan *et al.* 2012; Kahilainent *et al.* 2016; Keva *et al.* 2017). Additionally, results from this chapter highlighted the influence of season, condition, and diet on trace metal concentrations in this species and suggest dynamic and integrative processes that are seasonally

and physiologically dependent have the greatest influence on trace metal concentrations in anadromous Arctic charr.

Future Work

While this research has elucidated links between season, somatic condition, and dietary variables for Deception Bay Arctic charr, further work is necessary to address additional possible causes of declines in fish condition and better understand the effects of condition selective mortality for both seasonal variation in measured tissue concentrations and Arctic charr population dynamics.

Results obtained in chapter 2 suggest a condition selective mortality effect exerting an influence on the observed % lipid values, caloric densities, and THg concentrations. The phenomenon has been established as an operative during critical life stages in a number of teleost fish (Oliver *et al.* 1979; Healy 1982; Henderson *et al.* 1988; Shuter and Post, 1990; Thompson *et al.* 1991; Smith and Griffith, 1994; Sogard and Olla, 2000; Searcy and Sponaugle, 2001). As winter is a stressful time for anadromous Arctic charr, it could be implied that condition selective mortality may be influencing over-wintering population demographics by supporting the survival of fish with greater lipid and body reserves. This would have the associated effect of increasing mean % lipids and caloric densities during post-winter sampling and would yield the observed seasonal variation in THg, despite significant reductions in somatic condition and % nitrogen values that indicate prolonged periods of fasting. As most research documenting condition selective mortality has focused on juvenile life stages, future research must consider the implications of the phenomenon on mature fish, particularly in extreme environments such as the Arctic. Additionally, further work is necessary to determine whether condition selective mortality has any implications for the observed declines in somatic condition.

Chapter 3 documented consistently higher elemental concentrations in tissues collected from post-winter sampled Arctic charr, which could be attributed to the influence of seasonal feeding behaviours and subsequent metabolism, metal depuration and elimination, and over-winter condensation of metal concentrations, as well as seasonal environmental influences (Somero *et al.* 1977; Jobling 1981; Heath 1987; Niimi 1987; Douben 1990; Yang *et al.* 2000; Cizdziel et al., 2002, Cizdziel *et al.* 2003; Klemetsen *et al.* 2003b; Nichols and Playle, 2004; Grosell *et al.* 2007; Vicente-Martorell *et al.* 2008; Van Leeuwan *et al.* 2012; Kahilainent *et al.* 2016; Keva *et al.* 2017). It was also determined that statistical models better described As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations when incorporating multiple predictors, including: season, somatic condition, and carbon and nitrogen stable isotope values. This suggests that dynamic and integrative processes that are seasonally linked have the greatest influence on trace metal concentrations in anadromous Arctic charr and future metals related research should further consider these variables when evaluating elemental accumulation in Arctic charr and other northern fish species. The inclusion of somatic condition as a predictor with generally high relative importance in models best supporting metals concentration data would also suggest linkages between somatic condition and trace metals. This is compelling evidence to further evaluate the influence of trace metals on somatic condition declines in this population of anadromous Arctic charr. As Arctic charr are a sentinel species for evaluating the impacts of a changing climate and spatial and temporal metal contaminant trends (Reist *et al.* 2006; Douglas et al., 2011), and are culturally and economically are essential to northern communities, further understanding of what influences Arctic charr tissue metal concentrations will assist in future preservation and management of this species, ensuring its continued success and cultural and economic contribution to northern circumpolar communities.

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Appendix

Table 2.1

Correlation coefficients for variables used to assess the significance of factors for explaining % lipid values determined from the dorsal muscle tissue of anadromous Deception River Arctic charr. The upper value represents the Pearson correlation coefficient while the lower is the associated *p* value. Significant correlations are bolded and underlined.

	% Lipid	Season	Fork-Length (mm)	Whole-Weight (g)	Age (Years)	Somatic Condition (K)	$\delta^{13}C$ (‰)	% Carbon	$\delta^{15}N$ (‰)	% Nitrogen
% Lipid	1.0000	**0.6025**	0.0631	-0.0292	0.0360	-0.1304	**-0.4653**	**0.3418**	0.1485	**-0.5772**
	-	**<0.0001**	0.5879	0.8026	0.7592	0.2614	**<0.0001**	**0.0025**	0.2004	**<0.0001**
Season		1.0000	0.1024	-0.0531	-0.0036	**-0.2349**	**-0.4615**	**0.2467**	0.1936	**-0.5617**
		-	0.3785	0.6490	0.9756	**0.0412**	**<0.0001**	**0.0317**	0.0938	**<0.0001**
Fork-Length (mm)			1.0000	**0.8922**	**0.9020**	0.0327	0.1946	0.2072	**0.7299**	-0.1556
			-	**<0.0001**	**<0.0001**	0.7790	0.0921	0.0725	**<0.0001**	0.1795
Whole-Weight (g)				1.0000	**0.7755**	**0.3241**	0.1808	0.1357	**0.6484**	-0.0846
				-	**<0.0001**	**0.0043**	0.1181	0.2424	**<0.0001**	0.4676
Age (Years)					1.0000	-0.0456	0.1787	0.0890	**0.6691**	-0.1325
					-	0.6979	0.1250	0.4478	**<0.0001**	0.2571
Somatic Condition (K)						1.0000	**0.2614**	-0.0466	0.1434	0.0983
						-	**0.0226**	0.6895	0.2166	0.3980
$\delta^{13}C$ (‰)							1.0000	**-0.3302**	**0.2413**	**0.5844**
							-	**0.0036**	**0.0358**	**<0.0001**
% Carbon								1.0000	0.1989	**-0.2732**
								-	0.0849	**0.0169**
$\delta^{15}N$ (‰)									1.0000	-0.1433
									-	0.2169
% Nitrogen										1.0000
										-

Table 2.2

Correlation coefficients for terms used to assess the significance of factors for explaining dorsal muscle caloric densities of sampled anadromous Deception River Arctic charr. The upper value represents the Pearson correlation coefficient while the lower is the associated *p* value. Significant correlations are bolded and underlined.

	Caloric Density (cal·g^{-1})	Season	Fork-Length (mm)	Whole-Weight (g)	Age (Years)	Somatic Condition (K)	δ^{13}C (‰)	% Carbon	δ^{15}N (‰)	% Nitrogen
Caloric Density (cal·g^{-1})	1.0000	**0.8446**	**0.3178**	0.1948	0.1408	-0.1320	**-0.4151**	**0.3840**	**0.3572**	**-0.7057**
	-	**<0.0001**	**0.0160**	0.1465	0.3005	0.3277	**0.0013**	**0.0032**	**0.0064**	**<0.0001**
Season		1.0000	0.1543	0.0160	0.0209	-0.2546	**-0.4666**	0.2282	**0.2613**	**-0.5834**
		-	0.2517	0.9057	0.8785	0.0560	**0.0003**	0.0878	**0.0496**	**<0.0001**
Fork-Length (mm)			1.0000	**0.8890**	**0.8917**	0.0147	0.2149	0.2385	**0.8234**	-0.1029
			-	**<0.0001**	**<0.0001**	0.9133	0.1084	0.0739	**<0.0001**	0.4462
Whole-Weight (g)				1.0000	**0.7601**	**0.2192**	0.2018	0.1841	**0.7363**	-0.0200
				-	**<0.0001**	**0.0155**	0.1323	0.1705	**<0.0001**	0.8823
Age (Years)					1.0000	-0.0832	0.1972	0.0966	**0.7429**	-0.0941
					-	0.5419	0.1453	0.4787	**<0.0001**	0.4905
Somatic Condition (K)						1.0000	**0.2834**	-0.0583	0.1387	0.0883
						-	**0.0327**	0.6667	0.3035	0.5139
δ^{13}C (‰)							1.0000	**-0.2993**	0.2381	**0.5666**
							-	**0.0237**	0.0745	**<0.0001**
% Carbon								1.0000	0.2250	-0.2075
								-	0.0924	0.1215
δ^{15}N (‰)									1.0000	-0.1646
									-	0.2212
% Nitrogen										1.0000
										-

Table 2.3

Correlation coefficients for variables used to assess the significance of factors for explaining dorsal muscle THg concentrations of anadromous Deception River Arctic. The upper value represents the Pearson correlation coefficient while the lower is representative of the associated *p* value. Significant correlations are bolded and underlined.

	THg (mg·kg⁻¹)	Season	Fork-Length (mm)	Whole-Weight (g)	Age (Years)	Somatic Condition (K)	$\delta^{13}C$ (‰)	% Carbon	$\delta^{15}N$ (‰)	% Nitrogen
THg (mg·kg⁻¹)	1.0000	**-0.2535**	**0.2790**	**0.3090**	**0.2800**	-0.0443	**0.4176**	**-0.2915**	0.1636	0.1954
	-	**0.0109**	**0.0049**	**0.0018**	**0.0052**	0.6612	**<0.0001**	**0.0033**	0.1038	0.0514
Season		1.0000	-0.1827	**-0.2240**	-0.1529	**-0.3587**	**-0.5452**	0.1657	0.0846	**-0.5004**
		-	0.0689	**0.0251**	0.1327	**0.0002**	**<0.0001**	0.0995	0.4026	**<0.0001**
Fork-Length (mm)			1.0000	**0.9155**	**0.8044**	0.1228	0.1890	**0.3505**	**0.7132**	-0.1512
			-	**<0.0001**	**<0.0001**	0.2236	0.0597	**0.0003**	**<0.0001**	0.1332
Whole-Weight (g)				1.0000	**0.7258**	**0.3619**	0.1705	**0.2724**	**0.6943**	-0.1039
				-	**<0.0001**	**0.0002**	0.0898	**0.0061**	**<0.0001**	0.3038
Age (Years)					1.0000	0.0555	0.1425	**0.3118**	**0.5425**	**-0.2513**
					-	0.5876	0.1616	**0.0018**	**<0.0001**	**0.0126**
Somatic Condition (K)						1.0000	**0.2224**	0.0132	0.1754	0.1295
						-	**0.0262**	0.8959	0.0810	0.1990
$\delta^{13}C$ (‰)							1.0000	**-0.3226**	0.1346	**0.5971**
							-	**0.0011**	0.1817	**<0.0001**
% Carbon								1.0000	**0.3575**	**-0.2335**
								-	**0.0003**	**0.0194**
$\delta^{15}N$ (‰)									1.0000	**-0.1971**
									-	**0.0494**
% Nitrogen										1.0000
										-

Table 3.1

Correlation coefficients for variables used to assess the significance of factors for explaining Cu concentrations in dorsal muscle (top) and liver (bottom) tissue collected from anadromous Deception River Arctic charr in both the marine environment (summer 2016) and the during the post-winter season (spring 2017). The upper value represents the Pearson correlation coefficient while the lower is the associated p value. Significant correlations are bolded and underlined.

	Cu (mg·kg⁻¹)	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Cu (mg·kg⁻¹)	1.0000	-0.1337	0.0007	-0.0127	-0.0714	0.0582	-0.1000
	-	0.3045	0.9593	0.9242	0.5845	0.6559	0.4433
Season		1.0000	-0.1484	0.1072	**-0.4243**	**-0.5302**	0.0774
		-	0.2537	0.4191	**0.0007**	**<0.0001**	0.5531
Fork-Length (mm)			1.0000	**0.7697**	0.2055	0.1805	**0.7024**
			-	**<0.0001**	0.1120	0.1638	**<0.0001**
Age (Years)				1.0000	0.0871	0.2521	**0.5666**
				-	0.5118	0.0541	**<0.0001**
Somatic Condition (K)					1.0000	0.2260	**0.2796**
					-	0.0799	**0.0291**
$\delta^{13}C$ (‰)						1.0000	0.1142
						-	0.3806
$\delta^{15}N$ (‰)							1.0000
							-

	Cu (mg·kg⁻¹)	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Cu (mg·kg⁻¹)	1.0000	**0.3928**	**-0.2553**	-0.1160	**-0.3538**	0.1478	-0.1262
	-	**0.0017**	**0.0470**	0.3816	**0.0052**	0.2557	0.3325
Season		1.0000	-0.1484	0.1072	**-0.4243**	**-0.5302**	0.0774
		-	0.2537	0.4191	**0.0007**	**<0.0001**	0.5531
Fork-Length (mm)			1.0000	**0.7697**	0.2055	0.1805	**0.7024**
			-	**<0.0001**	0.1120	0.1638	**<0.0001**
Age (Years)				1.0000	0.0871	0.2521	**0.5666**
				-	0.5118	0.0541	**<0.0001**
Somatic Condition (K)					1.0000	0.2260	**0.2796**
					-	0.0799	**0.0291**
$\delta^{13}C$ (‰)						1.0000	0.1142
						-	0.3806
$\delta^{15}N$ (‰)							1.0000
							-

Table 3.2

Correlation coefficients for variables used to assess the significance of factors for explaining Zn concentrations in both dorsal muscle (top) and liver (bottom) tissue collected from anadromous Deception River Arctic charr captured during summer 2016 in the marine environment, as well as the post-winter season (spring 2017). The upper value represents the Pearson correlation coefficient while the lower is the associated p value. Significant correlations are bolded and underlined.

	Zn (mg·kg⁻¹)	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	δ¹³C (‰)	δ¹⁵N (‰)
Zn (mg·kg⁻¹)	1.0000 -	**0.2624** **0.0428**	**-0.4959** **<0.0001**	**-0.4261** **0.0009**	**-0.3158** **0.0140**	**-0.3402** **0.0078**	**-0.3893** **0.0021**
Season		1.0000 -	-0.1484 0.2537	0.1072 0.4191	**-0.4243** **0.0007**	**-0.5302** **<0.0001**	0.0774 0.5531
Fork-Length (mm)			1.0000 -	**0.7697** **<0.0001**	0.2055 0.1120	0.1805 0.1638	**0.7024** **<0.0001**
Age (Years)				1.0000 -	0.0871 0.5118	0.2521 0.0541	**0.5666** **<0.0001**
Somatic Condition (K)					1.0000 -	0.2260 0.0799	**0.2796** **0.0291**
δ¹³C (‰)						1.0000 -	0.1142 0.3806
δ¹⁵N (‰)							1.0000 -

	Zn (mg·kg⁻¹)	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	δ¹³C (‰)	δ¹⁵N (‰)
Zn (mg·kg⁻¹)	1.0000 -	-0.0140 0.9149	**-0.4336** **0.0005**	-0.2219 0.0912	**-0.3688** **0.0034**	0.1931 0.1360	**-0.4129** **0.0009**
Season		1.0000 -	-0.1484 0.2537	0.1072 0.4191	**-0.4243** **0.0007**	**-0.5302** **<0.0001**	0.0774 0.5531
Fork-Length (mm)			1.0000 -	**0.7697** **<0.0001**	0.2055 0.1120	0.1805 0.1638	**0.7024** **<0.0001**
Age (Years)				1.0000 -	0.0871 0.5118	0.2521 0.0541	**0.5666** **<0.0001**
Somatic Condition (K)					1.0000 -	0.2260 0.0799	**0.2796** **0.0291**
δ¹³C (‰)						1.0000 -	0.1142 0.3806
δ¹⁵N (‰)							1.0000 -

Table 3.3

Correlation coefficients for variables used to assess the significance of factors for explaining As concentrations in dorsal muscle (top) and liver (bottom) tissue collected from anadromous Deception River Arctic charr in both the marine environment (summer 2016) and the during the post-winter season (spring 2017). The upper value is the Pearson correlation coefficient while the lower is the associated p value. Significant correlations are bolded and underlined.

	As (mg·kg^{-1})	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	δ^{13}C (‰)	δ^{15}N (‰)
As (mg·kg^{-1})	1.0000	0.0220	**0.3399**	0.2354	0.0041	-0.1904	**0.3540**
	-	0.8665	**0.0074**	0.0726	0.9749	0.1416	**0.0051**
Season		1.0000	-0.1484	0.1072	**-0.4243**	**-0.5302**	0.0774
		-	0.2537	0.4191	**0.0007**	**<0.0001**	0.5531
Fork-Length (mm)			1.0000	**0.7697**	0.2055	0.1805	**0.7024**
			-	**<0.0001**	0.1120	0.1638	**<0.0001**
Age (Years)				1.0000	0.0871	0.2521	**0.5666**
				-	0.5118	0.0541	**<0.0001**
Somatic Condition (K)					1.0000	0.2260	**0.2796**
					-	0.0799	**0.0291**
δ^{13}C (‰)						1.0000	0.1142
						-	0.3806
δ^{15}N (‰)							1.0000
							-

	As (mg·kg^{-1})	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	δ^{13}C (‰)	δ^{15}N (‰)
As (mg·kg^{-1})	1.0000	**-0.3683**	0.0621	-0.0764	0.2419	0.0110	0.0293
	-	**0.0035**	0.6343	0.5654	0.0604	0.9329	0.8226
Season		1.0000	-0.1484	0.1072	**-0.4243**	**-0.5302**	0.0774
		-	0.2537	0.4191	**0.0007**	**<0.0001**	0.5531
Fork-Length (mm)			1.0000	**0.7697**	0.2055	0.1805	**0.7024**
			-	**<0.0001**	0.1120	0.1638	**<0.0001**
Age (Years)				1.0000	0.0871	0.2521	**0.5666**
				-	0.5118	0.0541	**<0.0001**
Somatic Condition (K)					1.0000	0.2260	**0.2796**
					-	0.0799	**0.0291**
δ^{13}C (‰)						1.0000	0.1142
						-	0.3806
δ^{15}N (‰)							1.0000
							-

Table 3.4
Correlation coefficients for terms used to assess the significance of factors for explaining Cd concentrations in dorsal muscle (top) and liver (bottom) tissue collected from anadromous Deception River Arctic charr in summer 2016 and post-winter season (spring 2017). The upper value is the Pearson correlation coefficient while the lower is the associated p value. Significant correlations are bolded and underlined.

	Cd (mg·kg^{-1})	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	δ^{13}C (‰)	δ^{15}N (‰)
Cd (mg·kg^{-1})	1.0000	**-0.7301**	0.1171	0.0467	0.1970	**0.3398**	-0.1561
	-	**<0.0001**	0.3730	0.7278	0.1314	**0.0079**	0.2336
Season		1.0000	-0.1484	0.1072	**-0.4243**	**-0.5302**	0.0774
		-	0.2537	0.4191	**0.0007**	**<0.0001**	0.5531
Fork-Length (mm)			1.0000	**0.7697**	0.2055	0.1805	**0.7024**
			-	**<0.0001**	0.1120	0.1638	**<0.0001**
Age (Years)				1.0000	0.0871	0.2521	**0.5666**
				-	0.5118	0.0541	**<0.0001**
Somatic Condition (K)					1.0000	0.2260	**0.2796**
					-	0.0799	**0.0291**
δ^{13}C (‰)						1.0000	0.1142
						-	0.3806
δ^{15}N (‰)							1.0000
							-

	Cd (mg·kg^{-1})	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	δ^{13}C (‰)	δ^{15}N (‰)
Cd (mg·kg^{-1})	1.0000	**0.4986**	-0.1728	0.0915	**-0.6066**	**-0.2718**	-0.1353
	-	**<0.0001**	0.1831	0.4908	**<0.0001**	**0.0341**	0.2986
Season		1.0000	-0.1484	0.1072	**-0.4243**	**-0.5302**	0.0774
		-	0.2537	0.4191	**0.0007**	**<0.0001**	0.5531
Fork-Length (mm)			1.0000	**0.7697**	0.2055	0.1805	**0.7024**
			-	**<0.0001**	0.1120	0.1638	**<0.0001**
Age (Years)				1.0000	0.0871	0.2521	**0.5666**
				-	0.5118	0.0541	**<0.0001**
Somatic Condition (K)					1.0000	0.2260	**0.2796**
					-	0.0799	**0.0291**
δ^{13}C (‰)						1.0000	0.1142
						-	0.3806
δ^{15}N (‰)							1.0000
							-

Table 3.5

Correlation coefficients for variables used to assess the significance of factors for explaining Cr concentrations in dorsal muscle (top) and liver (bottom) tissue collected from anadromous Deception River Arctic charr captured during summer 2016 in the marine environment, as well as the post-winter season (spring 2017). The upper value represents the Pearson correlation coefficient while the lower is the associated p value. Significant correlations are bolded and underlined.

	Cr (mg·kg⁻¹)	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Cr (mg·kg⁻¹)	1.0000	**0.3290**	-0.1491	-0.1181	**-0.3467**	**-0.5644**	0.0155
	-	**<0.0001**	0.2556	0.3732	**0.0067**	**<0.0001**	0.9063
Season		1.0000	-0.1484	0.1072	**-0.4243**	**-0.5302**	0.0774
		-	0.2537	0.4191	**0.0007**	**<0.0001**	0.5531
Fork-Length (mm)			1.0000	**0.7697**	0.2055	0.1805	**0.7024**
			-	**<0.0001**	0.1120	0.1638	**<0.0001**
Age (Years)				1.0000	0.0871	0.2521	**0.5666**
				-	0.5118	0.0541	**<0.0001**
Somatic Condition (K)					1.0000	0.2260	**0.2796**
					-	0.0799	**0.0291**
$\delta^{13}C$ (‰)						1.0000	0.1142
						-	0.3806
$\delta^{15}N$ (‰)							1.0000
							-

	Cr (mg·kg⁻¹)	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Cr (mg·kg⁻¹)	1.0000	**0.8144**	-0.0985	-0.0626	**-0.4839**	**-0.5010**	0.0843
	-	**<0.0001**	0.4541	0.6406	**<0.0001**	**<0.0001**	0.5217
Season		1.0000	-0.1484	0.1072	**-0.4243**	**-0.5302**	0.0774
		-	0.2537	0.4191	**0.0007**	**<0.0001**	0.5531
Fork-Length (mm)			1.0000	**0.7697**	0.2055	0.1805	**0.7024**
			-	**<0.0001**	0.1120	0.1638	**<0.0001**
Age (Years)				1.0000	0.0871	0.2521	**0.5666**
				-	0.5118	0.0541	**<0.0001**
Somatic Condition (K)					1.0000	0.2260	**0.2796**
					-	0.0799	**0.0291**
$\delta^{13}C$ (‰)						1.0000	0.1142
						-	0.3806
$\delta^{15}N$ (‰)							1.0000
							-

Table 3.6
Correlation coefficients for terms used to assess the significance of factors for explaining Ni concentrations in dorsal muscle (top) and liver (bottom) tissue collected from anadromous Deception River Arctic charr in both the marine environment (summer 2016) and the during the post-winter season (spring 2017). The upper value represents the Pearson correlation coefficient while the lower is representative of the associated p value. Significant correlations are bolded and underlined.

	Ni (mg·kg^{-1})	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	δ^{13}C (‰)	δ^{15}N (‰)
Ni (mg·kg^{-1})	1.0000	**0.5727**	-0.0069	-0.251	**-0.2970**	**-0.2750**	-0.0142
	-	**<0.0001**	0.9579	0.8502	**0.0201**	**0.0320**	0.9134
Season		1.0000	-0.1484	0.1072	**-0.4243**	**-0.5302**	0.0774
		-	0.2537	0.4191	**0.0007**	**<0.0001**	0.5531
Fork-Length (mm)			1.0000	**0.7697**	0.2055	0.1805	**0.7024**
			-	**<0.0001**	0.1120	0.1638	**<0.0001**
Age (Years)				1.0000	0.0871	0.2521	**0.5666**
				-	0.5118	0.0541	**<0.0001**
Somatic Condition (K)					1.0000	0.2260	**0.2796**
					-	0.0799	**0.0291**
δ^{13}C (‰)						1.0000	0.1142
						-	0.3806
δ^{15}N (‰)							1.0000
							-

	Ni (mg·kg^{-1})	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	δ^{13}C (‰)	δ^{15}N (‰)
Ni (mg·kg^{-1})	1.0000	-0.1394	0.0348	0.1068	**-0.2580**	0.1443	-0.0977
	-	0.2841	0.7901	0.4210	**0.0447**	0.2673	0.4538
Season		1.0000	-0.1484	0.1072	**-0.4243**	**-0.5302**	0.0774
		-	0.2537	0.4191	**0.0007**	**<0.0001**	0.5531
Fork-Length (mm)			1.0000	**0.7697**	0.2055	0.1805	**0.7024**
			-	**<0.0001**	0.1120	0.1638	**<0.0001**
Age (Years)				1.0000	0.0871	0.2521	**0.5666**
				-	0.5118	0.0541	**<0.0001**
Somatic Condition (K)					1.0000	0.2260	**0.2796**
					-	0.0799	**0.0291**
δ^{13}C (‰)						1.0000	0.1142
						-	0.3806
δ^{15}N (‰)							1.0000
							-

Table 3.7

Correlation coefficients for terms used to assess the significance of variables for explaining Pb concentrations in both dorsal muscle (top) and liver (bottom) tissue collected from anadromous Deception River Arctic charr in summer 2016 and post-winter season (spring 2017). The upper value represents the Pearson correlation coefficient while the lower is the associated p value. Significant correlations are bolded and underlined.

	Pb (mg·kg⁻¹)	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K)	δ¹³C (‰)	δ¹⁵N (‰)
Pb (mg·kg⁻¹)	1.0000 / -	**0.3210** / **0.0124**	-0.0879 / 0.5044	**-0.2815** / **0.0308**	**-0.2916** / **0.0238**	**-0.4109** / **0.0011**	-0.0827 / 0.5298
Season		1.0000 / -	-0.1484 / 0.2537	0.1072 / 0.4191	**-0.4243** / **0.0007**	**-0.5302** / **<0.0001**	0.0774 / 0.5531
Fork-Length (mm)			1.0000 / -	**0.7697** / **<0.0001**	0.2055 / 0.1120	0.1805 / 0.1638	**0.7024** / **<0.0001**
Age (Years)				1.0000 / -	0.0871 / 0.5118	0.2521 / 0.0541	**0.5666** / **<0.0001**
Somatic Condition (K)					1.0000 / -	0.2260 / 0.0799	**0.2796** / **0.0291**
δ¹³C (‰)						1.0000 / -	0.1142 / 0.3806
δ¹⁵N (‰)							1.0000 / -

	Pb (mg·kg⁻¹)	Season	Fork-Length (mm)	Age (Years)	Somatic Condition (K0	δ¹³C (‰)	δ¹⁵N (‰)
Pb (mg·kg⁻¹)	1.0000 / -	**0.5382** / **<0.0001**	-0.1948 / 0.1325	-0.0335 / 0.8014	**-0.4686** / **0.0001**	**-0.3440** / **0.0066**	-0.0548 / 0.6749
Season		1.0000 / -	-0.1484 / 0.2537	0.1072 / 0.4191	**-0.4243** / **0.0007**	**-0.5302** / **<0.0001**	0.0774 / 0.5531
Fork-Length (mm)			1.0000 / -	**0.7697** / **<0.0001**	0.2055 / 0.1120	0.1805 / 0.1638	**0.7024** / **<0.0001**
Age (Years)				1.0000 / -	0.0871 / 0.5118	0.2521 / 0.0541	**0.5666** / **<0.0001**
Somatic Condition (K)					1.0000 / -	0.2260 / 0.0799	**0.2796** / **0.0291**
δ¹³C (‰)						1.0000 / -	0.1142 / 0.3806
δ¹⁵N (‰)							1.0000 / -

Table 3.8
AICc model* selection summary for Cu concentrations (mg·kg^{-1}) in the dorsal muscle (top) and liver (bottom) tissue of anadromous Deception River Arctic charr.

Model	K	RSS	AICc	Δ_i	e^i	w_i	ER_i
Season	3	0.88	-79.28	0	1	0.19	1
δ^{15}N	3	0.88	-78.80	0.49	0.78	0.15	1.28
Condition	3	0.89	-78.50	0.79	0.67	0.13	1.48
δ^{13}C	3	0.90	-78.39	0.89	0.64	0.12	1.56
Season, Condition	4	0.86	-78.25	1.03	0.60	0.12	1.68
Fork-Length	3	0.89	-78.19	1.10	0.58	0.11	1.73
Season, δ^{13}C, Season*δ^{13}C	5	0.83	-77.72	1.56	0.46	0.09	2.19
Season, δ^{15}N	4	0.87	-77.49	1.79	0.41	0.08	2.45
Season, Condition, δ^{13}C, δ^{15}N, Season*Condition, Season*δ^{13}C	8	3.23	14.36	0	1	0.37	1
Season, δ^{15}N, δ^{13}C, Season*δ^{13}C	6	3.64	14.71	0.35	0.84	0.31	1.19
Season, Fork-Length, δ^{13}C, Season*δ^{13}C	6	3.71	15.90	1.54	0.46	0.17	2.16
Season, Fork-Length, Condition, δ^{13}C, Season*Condition, Season*δ^{13}C	8	3.43	16.36	2.00	0.37	0.14	2.71

* General linear models were inclusive of the following variables: season (summer 2016 and post-winter 2017), fork-length (mm), age (years), somatic condition (K), δ^{13}C (‰), and δ^{15}N (‰), and significant two-way interactions. Explanatory variables that were highly correlated, or known to have biological redundancy (e.g. fork-length and age) were not included in the same model.

Table 3.9

Ranking of the models* that best described dorsal muscle (top) and liver (bottom) Zn concentrations (mg·kg^{-1}) of anadromous Deception River Arctic charr determined through *AICc* model selection.

Model	K	RSS	$AICc$	Δ_i	e^i	w_i	ER_i
Fork-Length, Condition, δ^{13}C	5	0.61	-94.07	0	1	0.37	1
Fork-Length, δ^{13}C	4	0.64	93.67	0.40	0.82	0.30	1.22
Fork-Length, Condition	4	0.65	-92.54	1.53	0.46	0.17	2.15
Season, Fork-Length, Condition, Season*Condition	6	0.60	-92.32	1.75	0.41	0.15	2.39
Fork-Length, Condition, δ^{13}C, δ^{15}N, Fork-Length*δ^{15}N	7	0.50	-103.34	0	1	0.51	1
Season, Fork-Length, Condition, δ^{13}C	6	0.54	-101.92	1.42	0.49	0.24	2.04
Fork-Length, Condition, δ^{13}C , δ^{15}N	6	5.54	-101.91	1.44	0.49	0.24	2.05

* General linear models were inclusive of the following variables: season (summer 2016 and post-winter 2017), fork-length (mm), age (years), somatic condition (K), δ^{13}C (‰), and δ^{15}N (‰), and significant two-way interactions. Explanatory variables that were highly correlated, or known to have biological redundancy (e.g. fork-length and age) were not included in the same model.

Table 3.10

AICc model* ranking for As dorsal muscle (top) and liver (bottom) concentrations (mg·kg^{-1}) of anadromous Deception River Arctic charr.

Model	K	RSS	AICc	Δ_i	e^i	w_i	ER_i
Season, Age, Condition, δ^{13}C, δ^{15}N, Season*Condition, Condition*δ^{15}N	9	16.39	113.53	0	1	0.10	1
Season, Fork-Length, Condition, δ^{13}C, Season*Condition	7	17.70	113.76	0.23	0.89	0.09	1.12
Season, Age, Condition, δ^{13}C, Season*Condition	7	18.13	114.00	0.48	0.89	0.08	1.27
Season, Age, Condition, δ^{13}C, δ^{15}N, Season*Condition	8	17.33	114.04	0.51	0.77	0.08	1.29
Season, Condition, δ^{13}C, δ^{15}N, Condition*δ^{15}N	7	17.82	114.15	0.62	0.73	0.07	1.36
Season, Age, Condition, δ^{13}C, δ^{15}N, Condition*δ^{15}N	8	17.38	114.22	0.69	0.71	0.07	1.41
Age, Condition δ^{13}C, δ^{15}N, Condition*δ^{15}N	7	18.20	114.23	0.71	0.70	0.07	1.42
Season, Condition, δ^{13}C, δ^{15}N, Season*Condition, Condition*δ^{15}N	8	17.10	114.29	0.73	0.70	0.07	1.46
Season, Condition, δ^{13}C, δ^{15}N, Season*δ^{13}C, Condition*δ^{15}N	8	17.21	114.67	1.15	0.68	0.06	1.78
Season, Fork-Length, Condition, δ^{13}C, δ^{15}N, Season*Condition, Condition*δ^{15}N	9	16.46	114.73	1.20	0.56	0.05	1.83
Season, Age, Condition, δ^{13}C, δ^{15}N, Season*Condition, Season*δ^{13}C, Condition*δ^{15}N	10	15.93	114.73	1.25	0.55	0.05	1.87
Season, Age, Condition, δ^{13}C, δ^{15}N, Season*δ^{13}C, Condition*δ^{15}N	9	16.79	114.97	1.44	0.54	0.05	2.06
Season, Condition, δ^{13}C, δ^{15}N, Season*Condition, Season*δ^{13}C, Condition*δ^{15}N	9	16.59	115.20	1.67	0.48	0.04	2.31
Season, Age, Condition, δ^{13}C, δ^{15}N, Season*Condition, Season*δ^{13}C	9	03.86	115.20	1.67	0.43	0.04	2.31
Season, Fork-Length, Condition, δ^{13}C, δ^{15}N, Season*Condition	8	17.41	115.38	1.83	0.43	0.04	2.53
Condition, δ^{13}C, δ^{15}N, Condition*δ^{15}N	6	19.99	115.47	1.95	0.39	0.04	2.65
Season, Age, δ^{13}C	5	36.30	149.91	0	1	0.23	1
Season, Age, δ^{13}C, δ^{15}N	6	34.97	150.18	0.28	0.87	0.20	1.15

Season, Age	4	38.32	150.71	0.81	0.67	0.16	1.50
Season, Age, $\delta^{15}N$	5	37.19	151.34	1.43	0.49	0.11	2.04
Season, Age, $\delta^{13}C$, $\delta^{15}N$, Age*$\delta^{15}N$	7	34.24	151.53	1.62	0.45	0.11	2.25
Season, Age, $\delta^{15}N$, Age*$\delta^{15}N$	6	35.86	151.68	1.77	0.41	0.10	2.43
Season, Age, Condition, $\delta^{13}C$	6	35.90	151.74	1.83	0.40	0.09	2.50

* General linear models were inclusive of the following variables: season (summer 2016 and post-winter 2017), fork-length (mm), age (years), somatic condition (K), $\delta^{13}C$ (‰), and $\delta^{15}N$ (‰), and significant two-way interactions. Explanatory variables that were highly correlated, or known to have biological redundancy (e.g. fork-length and age) were not included in the same model.

Table 3.11
Ranking of the models* that best support variation in dorsal muscle (top) and liver (bottom) Cd concentrations (mg·kg^{-1}) of anadromous Deception River Arctic charr determined through *AICc* model selection.

Model	K	RSS	$AICc$	Δ_i	e^i	w_i	ER_i
Season, Condition, δ^{15}N, Condition*δ^{15}N	6	3.81	18.52	0	1	0.46	1
Season, Fork-Length, Condition, δ^{15}N, Condition*δ^{15}N	7	3.68	19.02	0.50	0.18	0.36	1.28
Season, Age, Condition, δ^{15}N, Condition*δ^{15}N	7	3.65	20.36	1.84	0.40	0.18	2.50
Season, Age, Condition, δ^{15}N, Age*δ^{15}N, Condition*δ^{15}N	8	2.09	-10.66	0	1	0.37	1
Fork-Length, Condition, δ^{15}N, Fork-Length*δ^{15}N	6	2.43	-10.00	0.67	0.72	0.27	1.40
Season, Fork-Length, Condition, δ^{15}N, Fork-Length*δ^{15}N	7	2.35	-9.32	1.34	0.51	0.19	1.95
Season, Fork-Length, Condition, δ^{15}N, Fork-Length*δ^{15}N, Condition*δ^{15}N	8	2.21	-9.07	1.59	0.45	0.17	2.21

* General linear models were inclusive of the following variables: season (summer 2016 and post-winter 2017), fork-length (mm), age (years), somatic condition (K), δ^{13}C (‰), and δ^{15}N (‰), and significant two-way interactions. Explanatory variables that were highly correlated, or known to have biological redundancy (e.g. fork-length and age) were not included in the same model.

Table 3.12
Summary of the best ranked models* for dorsal muscle (top) and liver (bottom) Cr concentrations (mg·kg^{-1}) of anadromous Deception River Arctic charr determined through *AICc* model selection.

Model	K	RSS	AICc	Δ_i	e^i	w_i	ER_i
Season, $\delta^{13}C$	4	0.35	-128.80	0	1	0.68	1
Season, $\delta^{13}C$, $\delta^{15}N$	5	0.35	127.26	1.54	0.46	0.32	2.16
Season Condition	4	0.17	-174.17	0	1	0.29	1
Season, Condition, $\delta^{13}C$	5	0.16	173.10	1.07	0.59	0.17	1.70
Season, Condition, $\delta^{15}N$	5	0.16	-172.84	1.33	0.51	0.15	1.94
Season, $\delta^{13}C$	4	0.17	-172.71	1.46	0.48	0.14	2.08
Season, Condition, Season*Condition	5	0.16	-172.52	1.65	0.44	0.13	2.28
Season, Condition, $\delta^{13}C$, $\delta^{15}N$	6	0.16	-172.35	1.82	0.40	0.12	2.48

* General linear models were inclusive of the following variables: season (summer 2016 and post-winter 2017), fork-length (mm), age (years), somatic condition (K), $\delta^{13}C$ (‰), and $\delta^{15}N$ (‰), and significant two-way interactions. Explanatory variables that were highly correlated, or known to have biological redundancy (e.g. fork-length and age) were not included in the same model.

Table 3.13

Summary of the models* that best describe variation in Ni dorsal muscle (top) and liver (bottom) concentrations (mg·kg^{-1}) from anadromous Deception River Arctic charr determined through *AICc* model selection.

Model	K	RSS	AICc	Δ_i	e^i	w_i	ER_i
Season	3	2.66	-11.50	0	1	0.31	1
Season, Age	4	2.50	-10.44	1.06	0.59	0.18	1.70
Season, Fork-Length, δ^{15}N	5	2.53	-10.04	1.46	0.48	0.15	2.07
Season, Fork-Length	4	2.64	-9.77	1.72	0.42	0.13	2.37
Season, Condition	4	2.65	-9.53	1.97	0.37	0.12	2.68
Season, δ^{15}N	4	2.65	-9.52	1.98	0.37	0.11	2.69
Season, Age, Condition	5	1.65	-32.60	0	1	0.65	1
Season, Age, Condition, Season*Condition	6	1.61	-31.37	1.23	0.54	0.35	1.85

* General linear models were inclusive of the following variables: season (summer 2016 and post-winter 2017), fork-length (mm), age (years), somatic condition (K), δ^{13}C (‰), and δ^{15}N (‰), and significant two-way interactions. Explanatory variables that were highly correlated, or known to have biological redundancy (e.g. fork-length and age) were not included in the same model.

Table 3.14

AICc model* selection ranking for dorsal muscle (top) and liver (bottom) Pb concentrations (mg·kg^{-1}) from anadromous Deception River Arctic charr.

Model	K	RSS	$AICc$	Δ_i	e^i	w_i	ER_i
Age, Condition, δ^{13}C, δ^{15}N, Condition*δ^{15}N, Age*δ^{15}N	8	6.54	56.94	0	1	0.72	1
Season, Age, Condition, δ^{13}C , δ^{15}N, Condition*δ^{15}N, Age*δ^{15}N	9	6.44	58.87	1.93	0.38	0.28	2.62
Season, Condition	4	3.38	5.31	0	1	0.40	1
Season, Condition, Season*Condition	5	3.31	6.53	1.22	0.54	0.22	1.84
Season, Condition, δ^{15}N, Condition*δ^{15}N	6	3.18	6.54	1.24	0.54	0.22	1.86
Season, Condition, δ^{13}C	5	3.35	7.15	1.85	0.40	0.16	2.52

* General linear models were inclusive of the following variables: season (summer 2016 and post-winter 2017), fork-length (mm), age (years), somatic condition (K), δ^{13}C (‰), and δ^{15}N (‰), and significant two-way interactions. Explanatory variables that were highly correlated, or known to have biological redundancy (e.g. fork-length and age) were not included in the same models.