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Concentrations of Metals in Fishes from the Athabasca and Slave Rivers of Northern Canada

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Abstract: There is growing concern about possible effects of exploitation of the Alberta Oil Sands on the ambient environment, including possible effects on populations of fishes in the Athabasca River and farther downstream in Lake Athabasca and the Slave River. In the present study, concentrations of metals in dorsal muscle tissue of 5 fish species—goldeye, northern pike, walleye, whitefish, and burbot—from the Slave, Peace, and Athabasca Rivers were quantified. A suite of 25 metals including As, Hg, Se, Tl, and V was analyzed. Most metals exhibited no significant variations in concentration among locations. Concentrations of 5 metals, As, Hg, Se, Tl, and V, revealed significant variations among locations and were of sufficient magnitude to be of interest. Concentrations of Hg did not vary significantly among locations; however, because it was detected at concentrations of concern and the use of the selected fishes was a local source of food for humans and pets, it was of interest. Concentrations of As, Se, Tl, and V in dorsal muscle of certain fishes in the farthest downstream sites on the Slave River were greater than those in the same tissues and species in the farther upstream sites on the Peace and Athabasca Rivers. This phenomenon was most prevalent with Tl and to a lesser extent with As and Se. Nevertheless, concentrations were not of concern for the health of human consumers. Although metals did not appear to be increased in fish in the Alberta Oil Sands region in the present study, further research is needed to understand the potential impacts. *Environ Toxicol Chem* 2020;39:2180–2195. © 2020 SETAC

Keywords: Metals; Bioavailability; Mercury; Thallium; Slave River; Athabasca River

INTRODUCTION

The Slave and Athabasca Rivers are 2 of the largest rivers in Canada. Their tributaries rise in the Rocky Mountains of Alberta and British Columbia as well as in areas of northern Saskatchewan. The Slave River provides approximately 75% of the inflow into the Great Slave Lake (Sanderson et al. 2012). The Peace River and Lake Athabasca are primary sources of water for the Slave River, which receives a large portion of its inflow from the Athabasca River. The Athabasca River flows through oil sands developments in Alberta and other developments including coal mining operations, forestry operations such as sawmills and pulp mills, and agriculture. The Peace River is affected by agricultural uses and receives effluents from industries such as pulp and paper and hydroelectric power. There are currently 6 pulp mills on the Peace River, with 5 releasing effluents and 2 major power-generating stations situated near Bennet Dam in British Columbia (Mackenzie River Basin Board 2003).

As a result of their proximity to industrial activity, primarily oil sands operations, the health of the Athabasca River and the downstream Slave River are of interest to local, northern communities that rely on these 2 rivers for food, water, and transportation. Public concerns have been raised about possible effects on these rivers from legacy, current and emerging industries and results of some research suggest that contaminants related to industry are entering the proximate aquatic system and potentially reaching downstream locations. Because fish are a source of food for communities along the Athabasca and Slave Rivers, these concerns also extend to potential effects on the health of humans. Due to concentrations of Hg in fish, there are fish consumption advisories for the Athabasca River and Lake Athabasca (Government of Alberta 2016). Previous studies have found that contaminants are entering these rivers through aerial deposition (Kelly et al. 2009; Kelly et al. 2010;

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Kirk et al. 2014). Snowpacks in the Athabasca region were found to be a source of contaminants, particularly polycyclic aromatic hydrocarbons (PAHs), that can be associated with fossil fuel production, and 13 metals including Sb, As, Be, Cd, Cr, Cu, Pb, Hg, Ni, Se, Ag, Tl, and Zn, all of which are considered priority pollutants by the US Environmental Protection Agency (USEPA; Kelly et al. 2009; Kelly et al. 2010). Because concentrations of some contaminants were greater near upgraders and other oil sands operations, compared with those in fishes from upstream and far-field sampling locations, these contaminants have been suggested as being released from oil sands operations. Currently, industries do not discharge oil sands process-affected water (OSPW) directly to the Athabasca River; however, in the future it is likely that OSPW will need to be treated and then released to the general environment. Oil sands process-affected waters can contain varying concentrations of metals depending on parameters such as source, extraction method, and ore quality. Analyses of OSPW have found concentrations of some metals exceeding Canadian Council of Ministers of the Environment (CCME) guidelines (Allen 2008; Li et al. 2014). Results of studies conducted in the laboratory have found exposure of fish larvae to OSPW or wastewater pond sediments that can cause craniofacial, spinal, and cardiovascular deformities, premature hatching, incomplete hatching, decreased hatching success, reduced size, and increased larval mortality (Colavecchia et al. 2004; Peters et al. 2007; He et al. 2012). Local anglers provide anecdotal evidence that there are increased numbers of lesions, tumors, and deformities in fishes of the Athabasca and Slave Rivers. However, currently, there is a lack of numerical data to either support or refute these claims.

Given all the activities currently ongoing in the Athabasca region and uncertainties associated with these activities, an investigation into concentrations of metals in populations of fishes in the Athabasca and Slave Rivers was performed. Concentrations of some organic chemicals and conditions of fishes have been previously reported (Ohiozebau et al. 2016a, 2016b). The present study presents findings of concentrations of selected metals in dorsal muscle of 5 native fishes that cover varying trophic levels and are traditionally eaten by people in local communities in the region.

MATERIALS AND METHODS

Collection of fishes

Five species of fish, northern pike (*Esox lucius*), walleye (*Sander vitreus*), whitefish (*Coregonus clupeaformis*), goldeye (*Hiodon alosoides*), and burbot (*Lota lota*) were collected from the Athabasca and Slave Rivers in 2011/2012, as previously described (Ohiozebau et al. 2016a, 2016b). Each sampling event consisted of capturing and dissecting up to the target of 30 fish of each species from each of the 5 locations in 2011 and 7 locations in 2012. Four sampling events took place during the summer, fall, and winter of 2011 and the spring of 2012. Original sampling locations for the 2011 and 2012 samplings were Fort McMurray and Fort Mackay on the Athabasca River, Fort Chipewyan on Lake Athabasca, and Fort Smith and Fort Resolution on the Slave River (Figure 1). Two additional sites were sampled in the spring of 2012 at Peace Point on the Peace River and Fort Fitzgerald on the Slave River. Peace Point was added to improve understanding of potential differences on the Peace River—a major headwater for the Slave River.

Fish were captured using gill nets from common local fishing sites and transferred, on ice, back to processing facilities. Fish were subjected to a detailed external and internal assessment before tissue samples were collected. Dorsal muscle tissues were stored in 125-mL amber jars at –18 °C. These samples were also analyzed for PAHs (Ohiozebau et al. 2016a, 2016b).

Quantification of metals

The first 10 fish of each species during each sampling period were subjected to metal analysis. The total number of fishes analyzed for each species, location, and sampling period is listed in Tables 1 and 2. Frozen dorsal muscle tissues were freeze-dried at –80 °C and <100 millibars until completely dry. Freeze-dried muscle of fishes was prepared by digestion of 0.1-g tissue with nitric acid (69%) and hydrogen peroxide (20%) in Nalgene Vials. Digestates were evaporated at 75 °C using a hot plate, and 5 mL of nitric acid (2%) were then added to preserve samples. The samples were filtered through 0.45-µm polyethersulfone syringe filters (VWR) and transferred into an 8-mL Nalgene Vial until analyses. Blank samples and Tort-2 lobster hepatopancreas (National Research Council of Canada), a certified reference material, were used for analysis and they were subjected to all the same laboratory procedures as the samples of fish muscle. Mean Tort-2 recoveries ($n = 39$) ranged from 79.57 to 128.12% for the certified elements in Tort-2. All glassware and laboratory equipment were carefully cleaned with soap and water, soaked in a 5%-nitric acid bath for a minimum of 4 h, and lastly rinsed 3 times with reverse-osmosis water and Nano-pure water. Analyses were performed using an inductively coupled plasma mass spectrometer (X Series II, Thermo Electron). Metals quantified were Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, Sr, Tl, U, V, and Zn. Analysis was for the total of each metal and metal speciation was not determined. Unless otherwise stated, Hg data discussed in the *Results and Discussion* section under the subheading *Mercury* are for total Hg. Data on Hg speciation for some samples are provided in the Supplemental Data, Tables S1 through S7.

Statistics

Normality of data was checked by use of the Kolmogorov–Smirnov test and homogeneity of variance was checked by use of Levine's test. This dataset contained data that met the assumptions of normality but also some data that even after $\log_{10}$ transformation did not meet the assumption of normality. Thus, less powerful nonparametric statistics were used for all data. Data were stratified by species and sampling

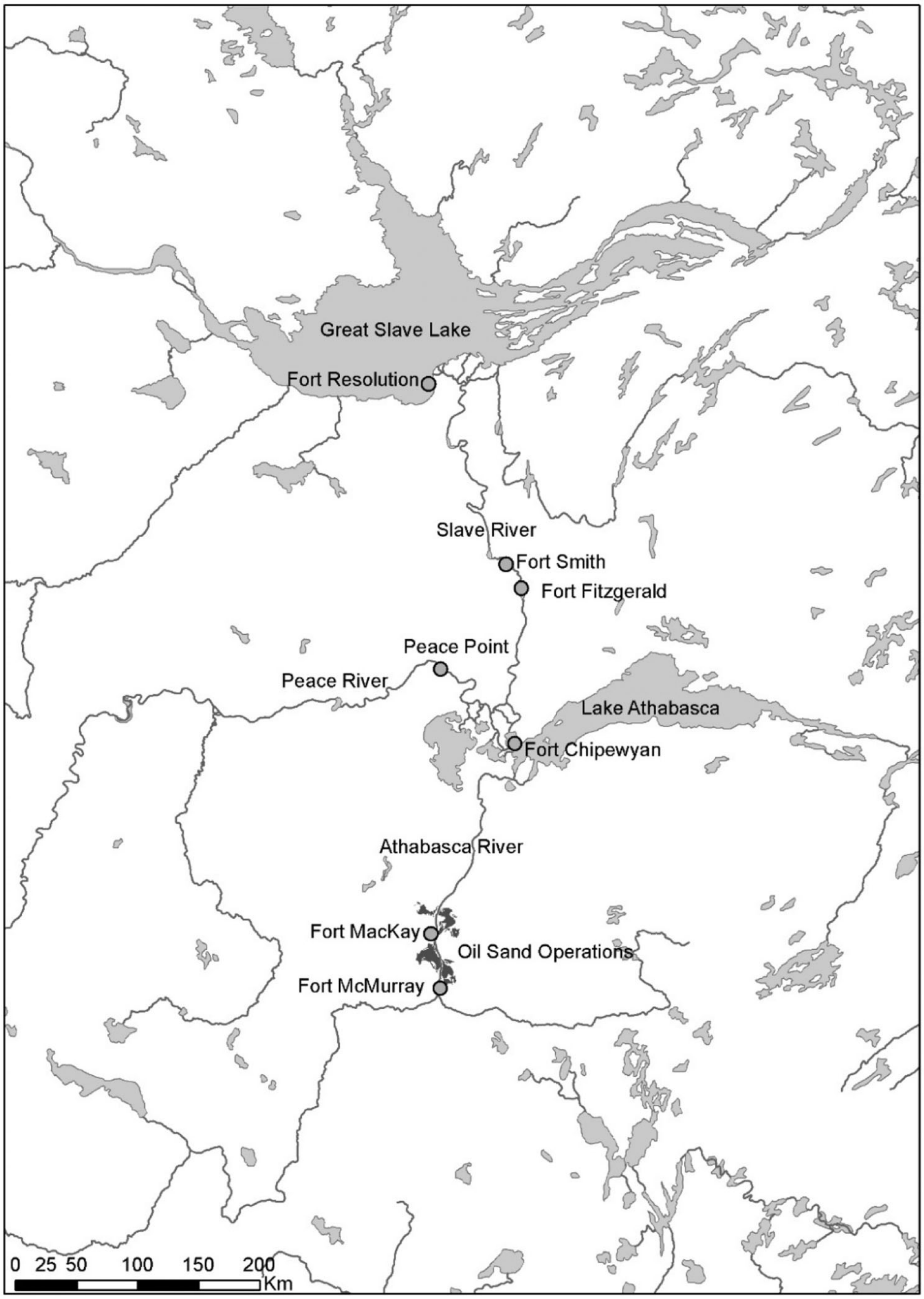

FIGURE 1: Map showing sampling locations and other areas of interest along the Slave, Athabasca, and Peace Rivers. Sampling locations are Fort McMurray, Fort MacKay, Fort Chipewyan, Peace Point, Fort Fitzgerald, Fort Smith, and Fort Resolution. Map created using ArcMap 10.4 (Environmental Systems Research Institute, Redlands, CA, USA).

period, and spatial differences were analyzed using a Kruskal–Wallis test followed by a Dunn's post hoc test. A Bonferroni correction was applied to the Dunn's tests to reduce the likelihood of false positives. All statistical analyses were performed by use of SPSS Ver 24.0 (IBM SPSS Statistics). Differences were considered statistically significant at $p < 0.05$. This made it more difficult to demonstrate a difference if in fact there was one. That is, there was a bias toward false negatives. All metals' data for fish muscle tissue are reported as wet mass. Dry mass metal concentrations were converted to wet mass using the sample's moisture content that was determined during freeze drying.

RESULTS AND DISCUSSION

Overall, 623 fish from 4 sampling periods were subjected to metal analysis. There were 150 goldeye, 154 northern pike, 141 walleye, 125 whitefish, and 53 burbot. All 5 species were collected during the summer, fall, and spring samplings.

TABLE 1: Mean concentration of metals in muscle of goldeye and northern pike from sampling sites along the Slave, Athabasca, and Peace Rivers[a,b,c,d,e]

Location	Season	*N*	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
Goldeye																											
FMU	Summer	10	34	1.66	209	41.1	61.3	32.3	1.09	3.83	5.03	70.3	200	4.83	255	183	17.7	7.62	2.34	0.43	704	34.4	679	2.67	19.2	5.13	3.82
FM		10	38	0.81	51.8	56.6	35.2	20.7	1.99	0.58	2.82	88.8	211	3.13	228	139	14.6	3.71	1.6	0.27	457	109	937	2.37	49.4	5.75	3.32
FC		9	37	2.23	224	55.8	17.5	23.9	0.22	0.25	2.55	66.5	124	2.16	209	134	11.7	5.41	4.72	0.51	770	227	403	3.93	4.56	3.06	2.66
FS		10	29	4.22	225	60.4	1.92	249	0.35	2.72	12.1	54.4	185	4.56	233	462	15.6	33.1	3.72	0.81	588	80.0	4770	3.58	4.01	11.7	4.46
FR		2	38	0.72	1330	41.2	79.2	12.7	1.07	0.76	0.04	151	203	3.34	224	132	27.8	7.49	1	0.27	748	136	111	3.1	0.41	9.52	3.09
FMU	Fall	1	39	<0.01	121	12.4	–	58.7	0.1	2.12	3.46	0.06	119	3.25	226	199	5.12	0.06	2.55	0.13	142	0.62	992	0.01	1.64	3.67	3.52
FM		10	36	0.14	108	17.8	52.7	23.3	0.66	0.96	2.77	24.5	195	3.59	194	155	12.7	5.34	0.77	0.42	538	2.38	458	1.56	0.83	3.39	2.58
FC		9	37	2.19	132	30.8	–	67.4	0.74	1.9	4.65	22.9	126	2.81	188	264	7.77	8.16	0.38	0.61	518	13.1	1810	0.82	0.69	4.94	2.85
FS		10	35	0.84	167	35.4	–	11.5	0.41	2.85	2.67	60.8	151	3.08	159	128	13.8	10.8	4.96	0.32	844	0.63	308	1.9	108	2.64	2.34
FR		10	36	0.44	184	43.6	11.6	11.4	0.24	2.32	2.24	56.1	149	2.84	249	122	18.3	11.2	1.72	0.6	818	18.9	202	3.06	2.82	6.71	2.62
FMU	Spring	11	33	2.02	263	27.0	–	59.9	0.09	11.2	11.3	643	310	8.09	264	238	71.2	8.85	–	0.67	631	1.6	1089	3.17	7.74	8.46	5.30
FM		9	27	1.27	307	32.7	–	85.5	0.08	4.3	18.7	532	378	9.29	76.9	310	76.9	11.2	–	0.42	601	2.96	2000	3.08	0.41	9.12	5.57
FC		10	35	0.32	383	48.2	56.6	105	–	0.48	10.0	44.0	195	4.22	126	335	9.93	11.1	–	0.57	542	<0.01	1200	3.7	1.87	6.65	3.39
PP		9	40	0.02	6.53	26.0	19.7	66.4		0.01	3.28	34.3	157	3.09	260	150	1.75	9.36	–	0.21	408	<0.01	581	2.41	25.4	1.75	2.40
FF		10	26	2.29	243	32.8	162	75.0		1.84	5.63	31.8	208	5.29	78.3	264	7.66	2.87	–	6.13	488	3.96	1570	1.77	8.32	7.55	4.39
FS		10	35	0.68	220	20.7	72.4	17.8		2.65	3.29	24.4	668	3.83	133	116	21.7	86.6	–	0.03	682	1.88	280	2.84	3.57	2.12	2.62
FR		10	36	3.69	76.0	38.2	164	81.7		12.3	3.35	52.9	161	3.66	143	169	14.6	1.4	–	0.39	636	0.01	993	4.83	0.21	12.7	3.83
Northern Pike																											
FMU	Summer	10	57	1.32	618	62.5	54.3	72.3	0.65	2.15	2.38	75.4	112	3.06	230	359	16.6	13.9	2.65	0.46	246	65.9	774	3.51	57.8	5.14	3.71
FM		10	61	1.01	104	31.8	55.1	9.78	0.46	2.20	17.1	69.5	98.2	1.40	176	153	10.7	3.79	0.82	0.45	137	105	83.3	2.04	4.67	3.15	3.28
FC		10	67	2.21	81.92	68.8	20.3	3.55	0.78	0.43	1.41	120	88.1	1.92	195	105	20.0	2.82	0.78	0.53	357	151	76.8	5.00	2.80	4.81	3.03
FS		11	69	1.40	0.22	126	0.22	14.9	0.31	0.49	0.70	22.7	144	1.78	232	111	14.7	2.06	0.66	1.97	370	101	87.7	8.46	3.07	7.31	3.51
FR		11	67	7.22	144	141	16.7	13.6	0.79	2.17	1.07	143.3	291	2.59	175	83.4	16.8	7.16	23.76	0.72	360	247	106	11.0	4.41	2.77	5.42
FMU	Fall	3	72	<0.01	49.8	9.68	67.6	3.26	3.01	0.17	0.82	17.8	103	1.17	266	100	14.6	0.13	2.95	0.44	272	0.61	39.4	1.54	0.69	3.11	3.03
FM		9	68	0.03	143	15.5	23.5	10.5	0.47	0.45	0.92	34.9	145	1.50	400	119	18.0	7.80	1.86	0.44	210	4.00	98.7	1.23	0.15	3.65	2.72
FC		9	78	1.12	275	31.3	9.05	4.65	0.72	5.59	1.39	8.43	151	1.62	302	108	9.60	8.51	20.0	0.81	288	5.09	41.5	1.60	0.30	4.43	3.16
FS		10	70	0.81	413	94.9	40.7	10.8	0.71	0.49	1.13	38.2	97.9	1.41	338	87.5	16.0	1.53	65.3	0.68	375	4.06	121	4.60	2.13	2.60	2.52
FR		10	68	0.44	277	159	0.21	9.27	1.09	1.46	2.41	35.8	181	2.20	247	91.2	11.3	5.00	1.12	1.01	398	0.63	121	7.91	4.81	2.94	3.38
FMU	Spring	8	72	0.23	170	32.6	–	13.3	0.09	0.34	4.38	344	265	2.54	486	104	34.9	4.68	–	0.61	280	0.18	175	2.70	0.28	4.39	4.13
FM		4	69	0.15	195	32.0	–	6.22	0.08	2.09	3.22	178	132	2.00	252	98.6	36.7	0.33	–	0.28	215	4.04	92	3.26	0.04	2.85	3.76
FC		10	63	0.95	150	42.1	0.25	114	–	0.20	5.66	13.9	147	2.08	217	382	15.9	0.62	–	0.03	233	0.01	–	6.66	165	6.18	3.04
PP		10	70	0.84	208	30.9	40.1	43.9	–	1.14	2.01	99.0	131	2.92	243	150	7.16	17.2	–	0.22	285	0.40	201	4.57	0.85	1.04	2.48
FF		9	73	0.32	523	59.5	42.1	27.2	–	0.26	2.21	62.9	137	2.56	222	147	12.1	5.43	–	0.44	257	<0.01	151	3.76	0.21	11.12	6.13
FS		10	74	1.09	237	130	81.4	90.2	–	0.86	3.51	9.94	290	1.49	275	182	7.27	12.9	–	0.61	316	12.6	938	6.64	0.97	1.53	3.70
FR		10	67	0.57	134	120	74.9	88.9	–	0.01	1.93	39.9	152	1.94	180	223	15.8	8.64	–	4.26	288	1.28	834	13.2	0.10	3.95	3.93

[a]Concentrations are in ng/g wet mass unless otherwise stated.
[b]Locations are Fort McMurray (FMU), Fort MacKay (FM), Fort Chipewyan (FC), Peace Point (PP), Fort Fitzgerald (FF), Fort Smith (FS), and Fort Resolution (FR).
[c]*N* = number of individuals analyzed.
[d]Results below detection limit were included at the limit of detection value in calculation of the mean.
[e]Blank cells represent no analytical results produced for that specific cell.
Ag = silver; Al = aluminum; As = arsenic; B = boron; Ba = barium; Be = beryllium; Cd = cadmium; Co = cobalt; Cr = chromium; Cu = copper; Fe = iron; Hg = mercury; Mn = manganese; Mo = molybdenum; Ni = nickel; Pb = lead; Sb = antimony; Se = selenium; Sn = tin; Sr = strontium; Tl = thallium; U = uranium; V = vanadium; Zn = zinc.

TABLE 2: Mean concentration of metals in muscle of walleye, whitefish, and burbot from sampling sites along the Slave, Athabasca, and Peace Rivers[a,b,c,d,e]

Location	Season	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
Walleye																											
FMU	Summer	10	52	2.05	71.1	48.2	52.8	18.3	0.36	0.59	1.79	50.8	113	1.92	512	113	13.3	12.3	1.65	0.48	354	40.2	200	3.84	2.34	5.00	2.84
FM		10	45	1.20	10.7	44.9	54.2	12.9	0.84	0.52	2.45	115	144	2.10	262	123	20.7	5.79	0.71	0.26	296	74.4	175	4.51	15.4	4.09	2.98
FC		10	51	1.83	221	59.7	0.22	19	1.19	1.18	2.15	137	347	2.74	195	97.2	20.6	10.8	35.1	0.67	433	165	202	8.37	0.65	6.41	3.36
FS		10	37	1.52	291	56.3	0.21	74.2	0.86	1.87	5.11	186	103	2.75	234	150	35.3	22.7	1.34	0.83	448	69.4	609	10.9	22.3	8.60	2.67
FMU	Fall	3	42	1.15	181	35.7		14.7	0.11	0.04	1.72	0.06	129	1.36	169	153	7.76	2.23	0.30	1.37	302	0.65	595	5.71	0.70	5.57	2.22
FM		10	46	1.23	319	20.6	31.0	1.80	0.69	0.30	2.80	7.41	137	1.78	274	55.4	9.97	1.62	24.4	0.89	293	90.6	50.6	3.76	9.52	2.69	2.25
FC		5	50	1.24	555	30.5		6.41	0.65	0.04	2.04	22.4	107	2.92	122	91.4	12.0	2.80	11.4	0.67	409	61.2	59.0	6.59	1.37	3.10	2.32
FS		10	49	0.20	250	90.4	9.73	109	0.21	0.91	5.58	35.5	226	3.67	505	107	25.0	10.6	7.23	0.77	509	12.4	653	16.5	6.20	5.41	4.58
FR		10	47	0.61	140	55.4	0.20	3.50	0.34	2.82	5.85	30.1	123	1.47	272	56.1	15.4	4.35	1.07	0.56	455	4.21	34.3	15.7	14.4	3.50	2.79
FMU	Spring	7	47	2.30	187	25.9	–	24.7	0.09	3.11	4.69	609	196	4.55	308	125	806	20.8	–	0.66	325	4.91	495	5.38	0.12	6.05	3.86
FM		10	44	2.03	373	31.5	–	6.71	0.08	1.63	3.08	432	196	3.60	312	95.4	57.38	7.05	–	0.64	323	3.95	84.0	10.7	1.41	5.30	3.75
FC		8	49	0.54	114	32.6	4.05	27.9	–	1.23	2.71	24.0	327	2.70	232	120	7.83	18.4	–	0.31	321	0.01	641	10.6	306	3.13	3.21
PP		9	53	1.22	73.3	24.0	66.9	9.45	–	3.36	1.60	107	361	2.86	260	79.4	354	33.3	–	0.43	384	13.9	38.4	6.56	7.99	3.71	2.72
FF		10	56	0.98	295	32.5	82.5	11.7	–	1.08	1.40	5.86	139	1.60	244	117	30.4	33.0	–	0.07	376	0.01	92.1	6.29	4.33	1.23	2.80
FS		10	56	0.75	264	95.7	23.4	7.25	–	0.49	1.60	52.7	168	3.89	284	79.4	13.3	2.43	–	1.08	336	0.01	37.1	19.26	2.39	2.70	2.65
FR		9	47	2.13	258	67.8	55.2	16.8	–	3.44	1.73	28.4	199	3.47	223	103	13.1	3.67	–	1.12	370	38.9	103	18.84	0.07	3.98	3.24
Whitefish																											
FM	Summer	10	42	1.28	261	72.2	26.6	0.92	0.63	2.55	13.9	208	155	8.94	46.1	185	44.0	6.52	0.99	0.72	460	109.4	130	1.8	3.95	6.01	3.09
FC		10	41	0.92	55.1	118	0.28	62.8	0.77	0.99	6.95	52.0	142	2.24	36.1	139	18.1	6.52	1.68	0.86	337	0.75	452	2.59	1.19	10.5	3.38
FS		7	41	1.31	74.9	132	0.21	40.2	0.45	0.64	3.86	70.0	117	2.40	37.9	151	26.1	4.06	2.46	9.14	400	74.0	481	4.47	30.3	11.2	2.57
FR		10	39	7.31	162	89.4	0.22	57.5	0.12	0.4	4.21	147.1	157	1.75	42.5	144	16.8	11.92	3.08	0.17	457	381.9	814	3.64	1.3	5.58	2.79
FMU	Fall	9	42	0.30	78.8	12.6	23.6	6.22	0.55	0.89	5.59	17.6	235	3.00	101.6	144	16.9	2.67	15.2	0.54	305	2.04	124	1.37	1.82	5.85	2.36
FM		10	40	1.22	132	29.6	–	0.47	0.67	0.26	3.09	3.88	145	1.81	31.5	143	8.42	4.08	49.2	0.57	308	17.8	49.9	1.07	1.96	2.39	2.06
FC		10	39	0.42	153	37.3	29.8	10.2	1.35	1.13	4.48	75.1	131	1.76	49.2	191	12.8	2.41	0.24	0.66	333	0.7	509	0.57	0.68	7.22	2.62
FS		10	41	0.91	61.8	107	0.21	16.7	0.73	0.93	9.88	20.3	121	1.98	49.5	122	18.4	6.48	8.93	0.96	440	54.4	354	3.72	0.82	5.94	2.35
FR		10	44	0.28	297	230	53.6	93.2	0.62	2.74	2.03	63.1	115	2.93	106	176	31.2	6.5	1.11	0.92	478	53.3	842	3.78	4.53	13.6	2.48
FMU	Spring	4	42	0.01	243	39.1	–	4.01	0.10	0.01	12.4	340	140	2.56	85.8	158	40.9	4.58	–	0.36	234	0.01	239	1.54	2.19	7.77	3.35
FM		2	38	2.11	143	17.8	–	3.81	0.10	1.06	14.0	202	147	2.52	63.5	167	19.7	0.37	–	0.26	308	3.83	323	1.47	0.08	5.2	5.55
FC		10	43	0.23	371	72.2	38.4	28.5	–	0.01	12.9	76.1	165	2.17	47.8	209	6.87	30.3	–	4.26	249	0.01	99.3	3.45	298	6.26	2.83
FF		8	45	0.61	348	58.2	69.9	42.2	–	0.01	14.2	52.8	190	3.96	84.5	203	12.2	7.14	–	0.29	278	0.16	332	3.22	0.14	5.32	3.42
FS		5	41	1.02	24.1	71.1	38.3	45.8	–	1.13	5.19	16.2	128	1.50	49.3	167	8.44	10.7	–	0.35	348	0.01	512	5.01	399	13.2	2.43
FR		10	40	2.98	79.4	108	107	39.6	–	7.41	5.38	32.9	150	3.00	50.2	142	7.24	2.07	–	1.47	309	10.0	417	3.19	0.73	7.9	2.54
Burbot																											
FMU	Summer	3	41	1.85	6.32	99.7	27.4	33.7	0.26	2.41	3.37	189	184	2.61	112	140	35.9	10.3	0.47	0.74	384	71.7	470	1.84	0.08	9.65	4.88
FC		1	56	1.89	77.5	61.6	0.18	2.95	0.09	0.04	3.73	0.05	159	0.84	61.6	140	0.06	9.06	1.02	0.44	483	732.2	110	3.28	1.04	0.77	3.40
FS		3	48	2.32	93.8	221	26.7	2660	0.24	2.84	13.9	130	185	4.12	149	473	32.4	39.3	3.10	1.09	322	140.8	6450	2.23	1.86	20.4	5.31
FR		10	62	1.03	60.8	188	42.0	139	0.24	0.40	1.78	78.7	127	1.71	112	169	14.1	3.21	1.10	0.17	290	86.7	484	3.17	0.06	4.97	3.15
FM	Fall	2	55	2.16	177.6	51.1	–	9.18	0.10	1.76	2.76	2.45	137	2.51	127	155	7.66	0.93	15.4	0.33	272	0.58	131	0.01	0.29	3.77	3.16
FC		3	58	0.16	78.1	43.5	–	13.5	0.09	0.74	3.07	16.7	120	2.42	56.2	161	9.86	5.31	272	1.51	358	107.8	107	0.93	1.09	2.65	2.50
FS		3	61	<0.01	305	141	–	220	0.92	19.4	3.52	0.05	99	2.64	154	218	7.83	7.12	17.4	1.11	412	32.7	1473	0.99	0.67	3.07	2.84
FR		8	62	0.73	659	111	45.3	25.6	0.47	2.17	35.1	47.8	142	2.98	185	215	19.3	11.4	14.2	1.16	378	49.8	178	1.63	0.79	7.10	2.97
FR	Winter	10	64	2.62	423	151	0.17	13.3	0.09	0.96	0.83	19.8	127	1.63	158	115	13.7	1.80	1.91	0.67	301	43.2	75.2	3.51	1.00	3.35	3.17
FMU	Spring	3	39	0.98	258	92.5	–	238	0.06	1.03	8.32	151	290	4.50	109	421	29.0	0.31	–	0.36		0.01	1720	2.39	–	8.31	5.96
FS		1	74	0.01	0.87	90.8	–	7.04	–	0.01	2.93	0.02	176	2.37	368	358	1.97	0.35	–	1.07	439	0.01	57.11	1.58	–	5.14	3.80
FR		6	63	0.27	0.36	132	158.4	51.5	–	1.12	2.85	109	145	3.30	104	188	13.6	1.92	–	0.64	281	4.8	67.82	2.33	1.84	3.77	3.35

[a]Concentrations are in ng/g wet mass unless otherwise stated.
[b]Locations are Fort McMurray (FMU), Fort MacKay (FM), Fort Chipewyan (FC), Peace Point (PP), Fort Fitzgerald (FF), Fort Smith (FS), and Fort Resolution (FR).
[c]*N* = number of individuals analyzed.
[d]Results below detection limit were included at the limit of detection value in calculation of the mean.
[e]Blank cells represent no analytical results produced for that specific cell.
Ag = silver; Al = aluminum; As = arsenic; B = boron; Ba = barium; Be = beryllium; Cd = cadmium; Co = cobalt; Cr = chromium; Cu = copper; Fe = iron; Hg = mercury; Mn = manganese; Mo = molybdenum; Ni = nickel; Pb = lead; Sb = antimony; Se = selenium; Sn = tin; Sr = strontium; Tl = thallium; U = uranium; V = vanadium; Zn = zinc.

Burbot were the only species collected during the winter sampling. Four of the fishes, goldeye, northern pike, walleye, and whitefish, were gathered in sufficient numbers during each sampling period to perform further statistical analysis. The number of burbot gathered was limited, with 34 of 53 captured from Fort Resolution. As such, burbot were not included in further statistical analysis. Variations in sizes of fish analyzed can have a significant effect on metal concentrations; however, no statistical difference in size among sites was found.

The majority of metals, Ag, Al, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Sb, Sn, Sr, U, and Zn, analyzed in muscle tissue of fishes varied little among locations and few metals were detected at sufficient concentrations to be of concern (Tables 1 and 2). Concentrations of 5 metals (Hg, As, V, Se, and Tl) either varied among locations or were present at concentrations considered to be of interest (Tables 3–6 and Figures 2–6). These 5 metals have been associated with extraction and upgrading of bitumen by oil sands operations in Alberta (Gomez-Bueno et al. 1981; Kelly et al. 2009). Apart from Hg, concentrations of these metals (As, V, Se, and Tl) were not considered to be of concern.

Mercury

Concentrations of total Hg were not significantly different among locations (Figure 2); However, in some locations mean concentrations of Hg exceeded the Health Canada guideline for general consumption (500 ng/g wet mass) or the subsistence consumption advice (200 ng/g wet mass) recommended by Health and Welfare Canada, which is now integrated into Health Canada (Wheatley 1979; Health Canada 2007). The consumption guideline and advice for Hg are based on total mercury, not methylmercury, which is the chemical species of mercury predominately found in muscle of fishes (Bloom 1992). The general Health Canada guideline (500 ng/g wet mass) was exceeded in 2.6% of the mean concentrations separated by species/season/locations (2/76). These exceedances occurred in walleye collected from Fort McMurray during the summer sampling and walleye collected from Fort Smith during the fall. The subsistence advice (200 ng/g wet mass) was exceeded in 46.7% of samples (36/77). Exceedances of concentrations suggested for subsistence consumers were most prevalent for northern pike (13/17) and walleye (13/16), and were less frequent but still observed for goldeye (9/16). Fewer exceedances (1/12) were observed for burbot and there were no exceedances observed for whitefish. The greatest concentrations of mercury were measured in the upper trophic level species northern pike and walleye. This is consistent with the ability of methylmercury to be biomagnified (Watras and Bloom 1992).

Concentrations of Hg in fishes collected from the Athabasca and Slave Rivers during the present study were consistent with previously reported concentrations. Mean concentrations of Hg in northern pike and walleye from the Slave River, sampled during 1988 to 1990, were 340 ng/g wet mass for both species (Grey et al. 1995). Furthermore, northern pike and walleye collected in the period of 1990 to 1993 from the Slave River had concentrations of 187 to 296 ng/g wet mass and 202 to 261 ng/g wet mass, respectively (McCarthy et al. 1997). The majority of measured Hg concentrations was less than the general guideline for Hg in fish given by Health Canada, and should not pose significant risks to the mean consumer but could pose risks to those consuming more than mean amounts of fish such as subsistence fish consumers given the greater number of exceedances of the Hg subsistence advice.

Arsenic

Concentrations of As were greater in northern pike from the lower Slave River (Forts Resolution and Smith) compared with the upper Slave River (Fort Fitzgerald) and Athabasca River (Fort McMurray, Fort Mackay, and Fort Chipewyan; Figure 3 and Table 3). This trend was consistent for northern pike among summer, fall, and spring samplings. Concentrations of As in whitefish followed a trend similar to that of northern pike, although it was not as significant. The trend in whitefish was most pronounced for the sampling during fall, with concentrations of As being significantly different between the upper Slave and Athabasca Rivers. Concentrations of As in whitefish collected from the lower Slave River sites during spring were not significantly different from those in the upper Slave River and Fort Chipewyan sites; however, these concentrations were significantly different from the sites on the Athabasca River. Goldeye and walleye did not exhibit the same pattern as northern pike and whitefish. Concentrations were significantly less in goldeye than in northern pike, walleye, and whitefish.

Arsenic in fishes exists primarily in organic forms and, contrary to some other organo-metals, As does not appear to biomagnify (US Environmental Protection Agency 2003; Williams et al. 2006). Inorganic As is the primary concern for human health. One possible explanation for greater concentrations of As in the lower Slave River is industrial activity on the Great Slave Lake, in particular gold mining. Gold was discovered on the northern shore during the 1930s and led to the development of 2 major gold mines, Giant Mine (1948–2004) and Con Mine (1938–2003; Mackenzie River Basin Board 2003). Arsenic is commonly found in significant concentrations in gold deposits; therefore, mobilization of As is a concern with gold mining activities (Straskraba and Moran 1990). Arsenic concentrations in locations on Great Slave Lake were less than those in the Giant Mine effluent receiving waters, with As concentrations of 190 ng/g wet mass compared with 490 ng/g wet mass (Cott et al. 2016). Whitefish As concentrations in Fort Resolution increased to 230 ng/g wet mass in the fall compared with 89.4 ng/g wet mass and 108 ng/g wet mass in summer and fall, respectively. Fish species such as whitefish are known to migrate upstream during the fall and could be a source of movement of As upstream into the Slave River (Morrow 1980).

Mean concentrations of As in northern pike, calculated for each location during each season, ranged from 9.68 to 159 ng/g wet mass and those in whitefish ranged from 12.6 to

TABLE 3: Mean concentration of arsenic in fish muscle tissue from sampling sites along the Slave, Athabasca, and Peace Rivers[a,b,c,d]

	Mean arsenic concentration by location (ng/g wm)						
Species	FMU	FM	FC	FS	FR	PP	FF
Summer 2011							
GE	41.1	56.6	55.8	60.4	41.2		
NP	62.5B	31.8A	68.8B	126C	140C		
WE	48.2	44.9	59.7	56.3	–		
WF		72.2A	118B	132AB	89.4AB		
Fall 2011							
GE	12.4	17.8	30.8	35.4	43.6		
NP	9.68A	15.5A	31.3A	94.9B	159B		
WE	35.7	20.6	30.5	90.4	55.4		
WF	12.6A	29.6B	37.3B	107C	230C		
Spring 2012							
GE	27	32.7	48.2	20.7	38.2	26	32.8
NP	32.6A	32.0A	42.1A	130B	120B	30.9A	59.5A
WE	25.9A	31.5A	32.6A	95.7B	67.8B	24.0A	32.5A
WF	39.1AB	17.8A	72.2AB	71.1AB	108B	–	58.2AB

[a]Locations sharing a letter show no statistically significant difference ($p > 0.05$) in mean arsenic concentrations.
[b]Sampling events that showed no significant differences among locations have no letters listing significance.
[c]Locations are Fort McMurray (FMU), Fort MacKay (FM), Fort Chipewyan (FC), Peace Point (PP), Fort Fitzgerald (FF), Fort Smith (FS), and Fort Resolution (FR).
[d]Species are goldeye (GE), northern pike (NP), walleye (WE), and whitefish (WF).
wm = wet mass.

230 ng/g wet mass. These concentrations are similar to or less than those observed during other studies. Another study investigated trace metals in David Lake, Delta Lake, and Unknown Lake in northern Saskatchewan for possible contamination from the Key Lake uranium facility (Kelly 2007). David Lake was the reference lake, Delta Lake was the low exposure lake, and Unknown Lake was the high exposure lake. The study analyzed muscle of juvenile northern pike for trace metals. Mean concentrations of As in juvenile northern pike were 26.6 ng/g wet mass in David Lake, 154 ng/g dry mass in Delta Lake, and 856 ng/g wet mass in Unknown Lake. Concentrations of As in whitefish collected from 2 northern Saskatchewan lakes, Montreal and Reindeer Lakes, were 380, 40, and 36 ng/g dry mass in Montreal Lake and 728, 273, and 104 ng/g wet mass in Reindeer Lake, during the fall of 2008 and summer and fall of 2009, respectively (Hursky and Pietrock 2012).

The Health Canada guideline for As in fish protein is 3.5 ppm (μg/g; Health Canada 2018). The guideline is for the edible form of the fish that can be both dry and wet mass. Hazards posed by observed concentrations of As measured in fishes during the present study were de minimis for human

TABLE 4: Mean concentrations of vanadium in fish muscle tissue from sampling sites along the Slave, Athabasca, and Peace Rivers[a,b,c,d]

	Mean vanadium concentrations by location (ng/g wm)						
Species	FMU	FM	FC	FS	FR	PP	FF
Summer 2011							
GE	5.13	5.75	3.06	11.7	9.52		
NP	5.14	3.15	4.81	7.31	2.77		
WE	5.00	4.09	6.41	8.60	–		
WF		6.01	10.5	11.2	5.58		
Fall 2011							
GE	3.67AB	3.39A	4.94AB	2.64A	6.71AB		
NP	3.11AB	3.65AB	4.43B	2.6B	2.94B		
WE	5.57	2.69	3.1	5.41	3.5		
WF	5.85AB	2.39A	7.22B	5.94AB	13.63B		
Spring 2012							
GE	8.46C	9.12C	6.65C	2.12AB	12.7BC	1.75A	7.55ABC
NP	4.39AB	2.85AB	6.18B	1.53A	3.95AB	1.04A	11.1AB
WE	6.05	5.3	3.13	2.7	3.98	3.71	1.23
WF	7.77	5.2	6.26	13.2	7.9	–	5.32

[a]Locations sharing a letter show no statistically significant difference ($p > 0.05$) in mean vanadium concentrations.
[b]Sampling events that showed no significant differences among locations have no letters listing significance.
[c]Locations are Fort McMurray (FMU), Fort MacKay (FM), Fort Chipewyan (FC), Peace Point (PP), Fort Fitzgerald (FF), Fort Smith (FS), and Fort Resolution (FR).
[d]Species are goldeye (GE), northern pike (NP), walleye (WE), and whitefish (WF).
wm = wet mass.

TABLE 5: Mean concentrations of selenium in fish muscle tissue from sampling sites along the Slave, Athabasca, and Peace Rivers[a,b,c,d]

	Mean selenium concentrations by location (ng/g wm)						
Species	FMU	FM	FC	FS	FR	PP	FF
Summer 2011							
GE	704B	457A	770B	588AB	748B		
NP	246B	137A	357C	370C	360C		
WE	354AB	296A	433AB	448B	–		
WF	–	460AB	337A	400AB	458B		
Fall 2011							
GE	142A	538AB	518A	844B	818AB		
NP	271ABC	210A	288AB	375BC	398C		
WE	302A	293A	409AB	508B	455B		
WF	305A	308A	332A	440B	478B		
Spring 2012							
GE	630.6	600.7	542.5	682.0	635.8	408.2	488.5
NP	280AB	215AB	233A	316B	288AB	285B	257AB
WE	324.8	323.5	321.2	336.1	369.9	383.9	376.0
WF	234.1	308.0	249.1	348.4	308.8	–	278.0

[a]Locations sharing a letter show no statistically significant difference ($p > 0.05$) in mean selenium concentrations.
[b]Sampling events that showed no significant differences among locations have no letters listing significance.
[c]Locations are Fort McMurray (FMU), Fort MacKay (FM), Fort Chipewyan (FC), Peace Point (PP), Fort Fitzgerald (FF), Fort Smith (FS), and Fort Resolution (FR).
[d]Species are goldeye (GE), northern pike (NP), walleye (WE), and whitefish (WF).
wm = wet mass.

health because the determined mean concentrations in all fish were less than 0.25 µg/g wet mass.

Vanadium

Concentrations of V exhibited trends that were similar to those observed for As, with concentrations in goldeye greater in the lower Slave River (Figure 4 and Table 4). Concentrations of V in northern pike and walleye were not significantly different among locations. Concentrations of V were greater in whitefish in the lower Slave River but only in fall when concentrations at Fort Resolution were greater than those in whitefish from locations on the Athabasca. Due to its association with oil sands operations in Alberta, V was of particular interest in the present study. Appreciable concentrations of V can be found in petroleum coke fly ash (Gomez-Bueno et al. 1981).

Mean concentrations of V in northern pike and whitefish, calculated for each location during each season collected during the present study, ranged from 1.04 to 11.12 ng/g wet mass and 2.39 to 13.6 ng/g wet mass, respectively. These concentrations are comparable to or less than concentrations reported previously. Walleye, northern pike, whitefish, and burbot collected during a 1992 and 1993 sampling from sites near Fort Resolution found V concentrations in all muscle

TABLE 6: Mean concentrations of thallium in fish muscle tissue from sampling sites along the Slave, Athabasca, and Peace Rivers[a,b,c,d]

	Mean thallium concentrations by location (ng/g wm)						
Species	FMU	FM	FC	FS	FR	PP	FF
Summer 2011							
GE	2.67	2.37	3.93	3.58	3.1		
NP	3.51A	2.04A	5.00B	8.46C	11.03C		
WE	3.84A	4.51A	8.37B	10.9B	–		
WF	–	1.8A	2.59B	4.47B	3.64B		
Fall 2011							
GE	0.01A	1.56AB	0.82A	1.9AB	3.06AB		
NP	1.54A	1.23A	1.6A	4.60B	7.91AB		
WE	5.71A	3.76A	6.59A	16.5B	15.7B		
WF	1.37A	1.07A	0.57A	3.72B	3.78B		
Spring 2012							
GE	3.17AB	3.08AB	3.7B	2.84AB	4.83AB	2.41AB	1.77A
NP	2.7A	3.26A	6.66B	6.64B	13.2C	4.57AB	3.76A
WE	5.38A	10.7C	10.6BC	19.3D	18.8D	6.56ABC	6.29AB
WF	1.54A	1.47A	3.45B	5.01B	3.19B	–	3.22B

[a]Locations sharing a letter show no statistically significant difference ($p > 0.05$) in mean thallium concentrations.
[b]Sampling events that showed no significant differences among locations have no letters listing significance.
[c]Locations are Fort McMurray (FMU), Fort MacKay (FM), Fort Chipewyan (FC), Peace Point (PP), Fort Fitzgerald (FF), Fort Smith (FS), and Fort Resolution (FR).
[d]Species are goldeye (GE), northern pike (NP), walleye (WE), and whitefish (WF).
wm = wet mass.

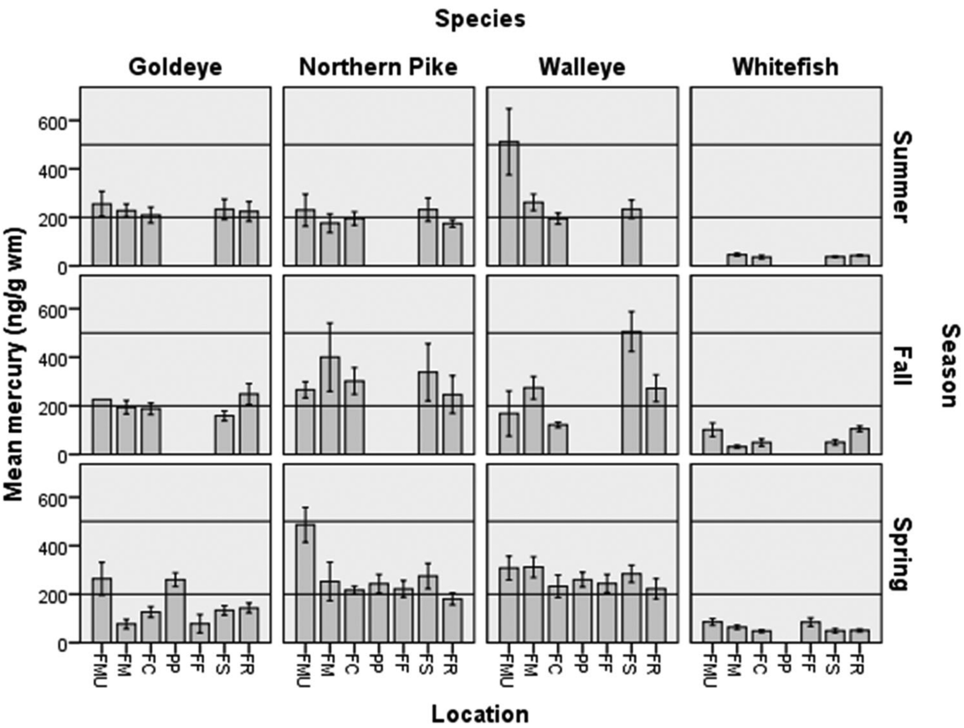

FIGURE 2: Mean concentrations of mercury in fish muscle tissue from sampling sites along the Slave and Athabasca Rivers. Error bars represent one standard error. Graphs are separated by (**top**) species and (**right**) season. Horizontal lines on the graphs indicate Health Canada guidelines. Upper line identifies general guideline and lower line denotes subsistence advice. FMU = Fort McMurray; FM = Fort Mackay; FC = Fort Chipewyan; PP = Peace Point; FF = Fort Fitzgerald; FS = Fort Smith; FR = Fort Resolution; wm = wet mass.

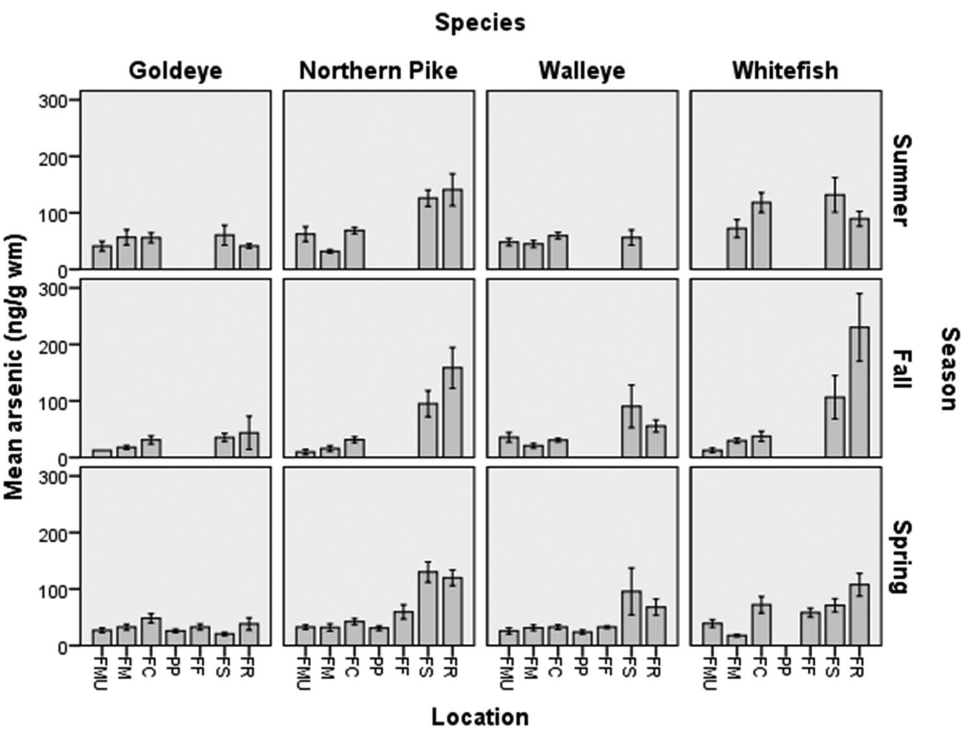

FIGURE 3: Mean concentrations of arsenic in fish muscle tissue from sampling sites along the Slave and Athabasca Rivers. Error bars represent one standard error. Graphs are separated by (**top**) species and (**right**) season. FMU = Fort McMurray; FM = Fort Mackay; FC = Fort Chipewyan; PP = Peace Point; FF = Fort Fitzgerald; FS = Fort Smith; FR = Fort Resolution; wm = wet mass.

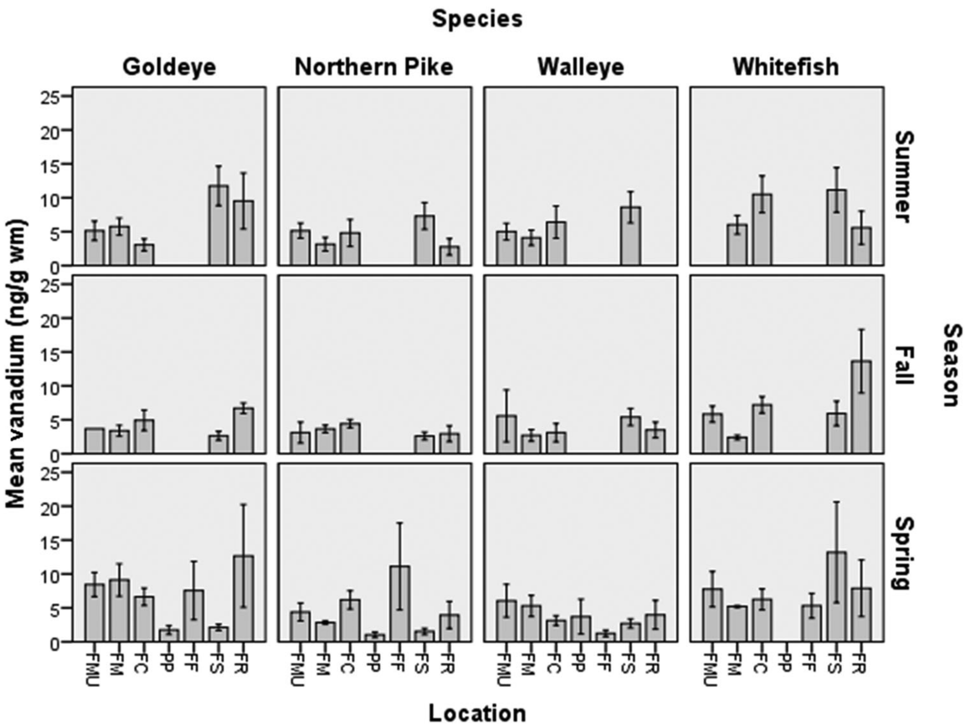

FIGURE 4: Mean concentrations of vanadium in fish muscle tissue from sampling sites along the Slave and Athabasca Rivers. Error bars represent one standard error. Graphs are separated by (**top**) species and (**right**) season. FMU = Fort McMurray; FM = Fort Mackay; FC = Fort Chipewyan; PP = Peace Point; FF = Fort Fitzgerald; FS = Fort Smith; FR = Fort Resolution; wm = wet mass.

samples less than their detection limit of 100 ng/g wet mass (Lafontaine 1997; Sanderson et al. 1997). The detection limit of 100 ng/g wet mass is considerably greater than the measured concentrations from fish muscle collected during 2011 and 2012. Vanadium concentrations in fish muscle from the present study were also less than V concentrations from other northern locations. Mean concentrations of V in juvenile northern pike from David Lake were 22.4 ng/g wet mass, whereas those in

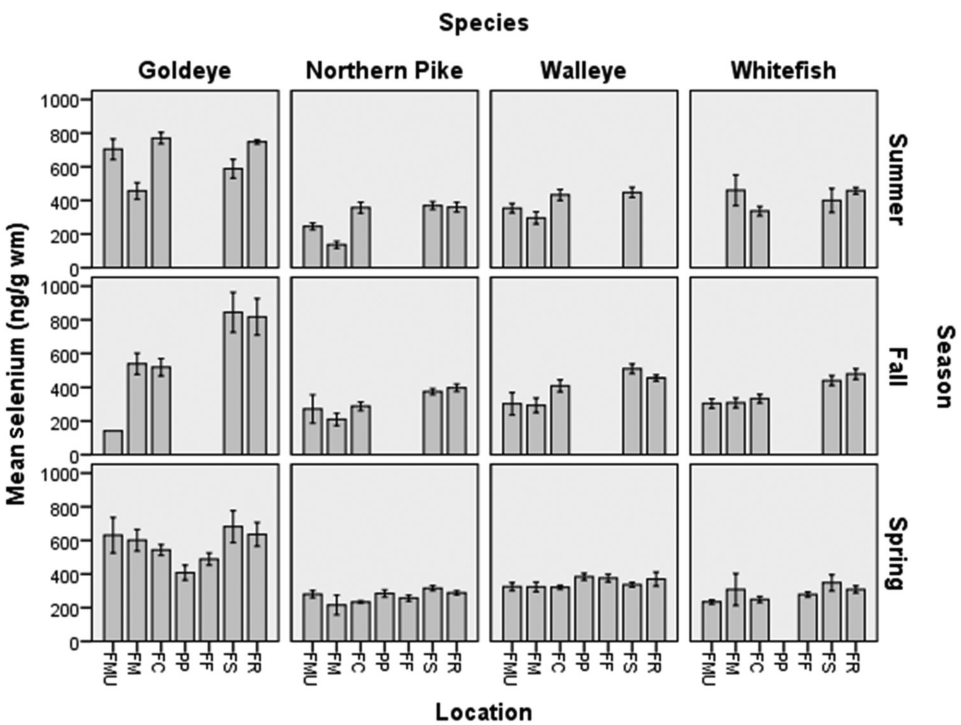

FIGURE 5: Mean concentrations of selenium in muscle of fishes from sampling sites along the Slave and Athabasca Rivers. Error bars represent one standard error. Graphs are separated by (**top**) species and (**right**) season. FMU = Fort McMurray; FM = Fort Mackay; FC = Fort Chipewyan; PP = Peace Point; FF = Fort Fitzgerald; FS = Fort Smith; FR = Fort Resolution; wm = wet mass.

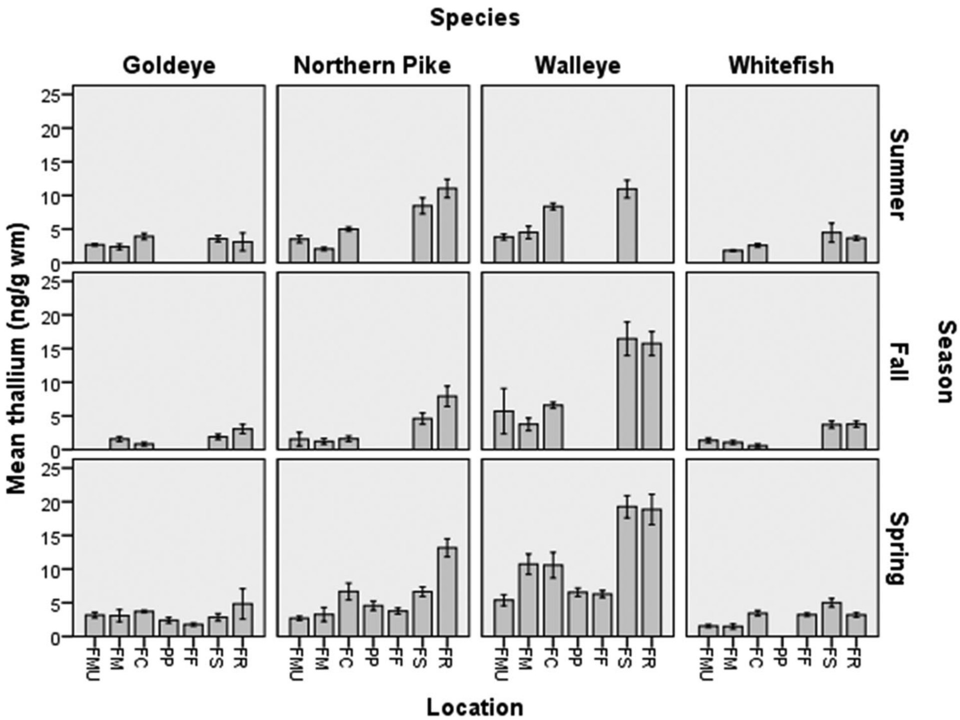

FIGURE 6: Mean concentrations of thallium in fish muscle tissue from sampling sites along the Slave and Athabasca Rivers. Error bars represent one standard error. Graphs are separated by (**top**) species and (**right**) season. FMU = Fort McMurray; FM = Fort Mackay; FC = Fort Chipewyan; PP = Peace Point; FF = Fort Fitzgerald; FS = Fort Smith; FR = Fort Resolution; wm = wet mass.

Delta Lake were 26.4 and 21.4 ng/g wet mass in Unknown Lake (Kelly 2007). Concentrations of V in fishes from lakes in northern Saskatchewan in the fall of 2008 and summer and fall of 2009 were 18, 14, and 15 ng/g wet mass in fishes collected from Montreal Lake and 16, 13, and 14 ng/g wet mass in fishes collected from Reindeer Lake (Hursky and Pietrock 2012).

There is no guideline for safe concentrations of V in edible muscle of fishes consumed by humans. There is a Health Canada guideline for tolerable upper daily intake for V—1.8 mg/d (Health Canada 2010). The upper daily intake is defined as the greatest mean daily intake that is likely to pose no risk of adverse effects to almost all individuals of a specified life stage and gender (Health Canada 2010). The greatest mean concentration of V was found in whitefish collected from near Fort Resolution during the fall. To exceed the tolerable upper daily intake, an adult would need to consume more than 132 kg/d of whitefish muscle from this location. The typical portion of fish muscle for an adult is 150 g (Health Canada 2007). Concentrations of V in fishes collected during the present study pose de minimis risk to humans who might consume them.

Selenium

Concentrations of Se were greater in goldeye, northern pike, walleye, and whitefish collected from the lower Slave River during fall compared with these species collected from the upper Slave River and Athabasca River (Figure 5 and Table 5). This gradient in concentrations of Se was observed only in fall. It is not apparent why the Se concentrations were greater in the lower Slave River relative to the upper Slave River, Peace River, and Athabasca River only during fall. Concentrations of Se were significantly greater in goldeye, relative to those in other species, with mean concentrations of 614 ng/g wet mass, whereas concentrations in other species ranged from 292 to 375 ng/g wet mass. Concentrations of Se in northern pike were also significantly less than Se concentrations in goldeye and walleye.

Mean concentrations of Se in muscle of northern pike, calculated for each location during each season, collected during the present study ranged from 137 to 398 ng/g wet mass, whereas those in whitefish ranged from 234 to 478 ng/g wet mass. A study investigating metals in the Athabasca River, Lake Athabasca, and the Slave River before merging with the Peace River found similar mean Se concentrations in the dorsal muscle of fishes, with mean Se concentrations ranging from 150 to 420 ng/g wet mass in northern pike and 350 to 410 ng/g wet mass in whitefish (Lutz and Hendzel 1976). These ranges of concentrations of Se are similar to those reported previously for fishes from locations with limited industrial impact but considerably less than those in fishes from lakes near the uranium mine at Key Lake, Saskatchewan. Mean concentrations of Se in juvenile northern pike from David Lake were 136 ng/g wet mass, whereas those in muscle of fishes from David Lake and Unknown Lake were 3380 ng/g wet mass and 4580 ng/g wet mass, respectively (Kelly 2007). During fall of 2008 and summer and fall of 2009, concentrations of Se in whitefish from northern

Saskatchewan lakes were 132, 156, and 154 μg/g wet mass in Montreal Lake and 302, 408, and 320 ng/g wet mass in Reindeer Lake, respectively (Hursky and Pietrock 2012).

There is no guideline for safe concentrations of Se in fish muscle consumed by humans. There is a Health Canada guideline for tolerable upper daily intake for Se of 400 μg/d for adults, 150 to 280 μg/d for children ages 5 to 11 yr, and a range of 90 to 150 μg/d for children ages 1 to 4 yr (Health Canada 2010). The greatest mean concentration of Se in muscle of fishes from any location was 844 ng/g wet mass in goldeye collected from Fort Smith during fall of 2011. An adult consumer would need to consume more than 474 g/d of goldeye muscle tissue from this location to exceed the tolerable upper daily intake. Children ages 5 to 11 yr would have to consume 178 to 333 g of goldeye muscle from Fort Smith in the fall to exceed the tolerable upper daily intake. Children ages 1 to 4 yr would need to consume 107 to 178 g/d of goldeye muscle from Fort Smith to exceed the tolerable upper daily intake. Health Canada recommends 40 g/d for adults, 33 g/d for children ages 5 to 11 yr, and 20 g/d for children ages 1 to 4 yr as representative rates of consumption for subsistence consumers of fish (Health Canada 2007). Concentrations of Se would be de minimis for healthy, adult human consumers.

Selenium can be a concern for the health of aquatic life including fish, and dietary intake can be an important route of exposure (Lemly and Smith 1987). Because of these concerns, the USEPA has set Se guidelines in fish muscle at 11.3 μg/g dry mass for protection of aquatic life (US Environmental Protection Agency 2016). The guideline when converted to wet mass using an average moisture content of 80% would be 2.26 μg/g wet mass. The greatest mean Se concentration in muscle tissue from the present study was 844 ng/g wet mass; this is below the USEPA guideline. Thus, these Se concentrations are unlikely to negatively impact aquatic life.

Thallium

There appears to be a strong spatial distribution of Tl along the Slave and Athabasca Rivers. Concentrations of Tl were greater at the lower Slave River sites than in the upstream Slave River and Athabasca sites (Figure 6 and Table 6). The trend was most significant for higher trophic level species such as northern pike and walleye; however, it was still observable for lower trophic species such as goldeye and whitefish. This spatial trend in concentrations was observed during each sampling period, although not for all species. Goldeye did not show statistically significant location-associated variability during the summer sampling but did for the fall and spring samplings. Mean Tl concentrations were greater in the upper trophic level species of northern pike and walleye, with mean Tl concentrations in northern pike and walleye ranging from 1.23 to 13.2 ng/g wet mass and 3.76 to 18.8 ng/g wet mass, respectively. Mean Tl concentrations in muscle from the lower trophic species of goldeye and whitefish were 0.01 to 4.83 ng/g wet mass and 0.57 to 5.01 ng/g wet mass, respectively.

There is no specific Canadian guideline for protection of the health of humans established for ingestion of Tl in fish tissue. The CCME guideline for Tl in sediment is based on a reference dose of 0.07 μg/kg/d that has been set by the USEPA (Canadian Council of Ministers of the Environment 1999). This reference dose was based on a no-observed-adverse-effect level of 0.2 mg/kg of body mass per day determined from results of a study in which rats were fed Tl in their diet and to which a safety factor of 3000 was applied (Stoltz et al. 1986). The USEPA has since removed this reference dose because of uncertainties with the study on which it was based (US Environmental Protection Agency 2009). To exceed this reference dose to stay consistent with CCME and the greatest mean concentration of Tl observed during the present study, a consumer would need to eat in excess of 254 g wet mass of walleye muscle per day.

Although thallium was found in snowpacks at greater concentrations near oil sands operations compared with more far-field collected samples, Tl was not found at greater concentrations in fish from sites in closer proximity to oil sands operations (Kelly et al. 2010). It is unclear why concentrations of Tl were greater in fishes from the lower Slave River compared with those in fishes of the upper Slave River and Athabasca River. It is possible that differences in oxidation state or other speciation phenomena could affect bioavailability in the upper Slave River that could result in differential accumulation efficiencies between the upper and lower stretches of the Slave River. Thallium has 2 oxidation states: Tl^{1+} and Tl^{3+}. Limited ability to form organic complexes in aquatic environments is inherent in Tl^{1+} (O'Shea 1972). This lack of complex formation leads to greater bioavailability of Tl^{1+}. However, Tl^{3+} readily forms complexes in the aquatic environment that can lead to a reduction in bioavailability (Ralph and Twiss 2002). It is possible that Tl^{1+} is the predominant species of Tl in the lower Slave River, leading to greater uptake of Tl in fish.

Greater concentrations of Tl in fishes of higher trophic levels such as walleye and northern pike are also of interest. Greater concentrations in higher trophic level species suggest there is potential for trophic magnification of Tl. If Tl is biomagnifying, this could be evidence of an organic form of Tl as the dominant species of Tl being incorporated into these fishes. The most likely organic form of Tl would be dimethyl thallium. It has been shown in laboratory experiments that benthic organisms in freshwater sediments are able to biomethylate inorganic Tl to dimethyl thallium (Schedlbauer and Heumann 2000).

Walleye and northern pike have a smaller home range than the other species studied. This might indicate that the source or cause of the increased Tl concentrations is in the lower Slave River. This source of Tl could be due to natural differences in geology of the lower Slave River compared with the upper Slave River and Athabasca River. Another possibility is industrial activities in regions surrounding the lower Slave River and Great Slave Lake. There is a former lead–zinc mine at Pine Point on the southern side of Great Slave Lake. There are also 2 gold mines on the northern shore that add to the industrial footprint on the Great Slave Lake. The presence of mining industries could lead to increased Tl concentrations due to potential liberation of Tl as the land is disturbed. The presence of mines in the region could indicate a greater likelihood for increased background concentrations due to baseline geology.

Concentrations of Tl in fish measured during the present study were generally less than those in fishes from other regions. Lake trout from Lake Michigan had mean concentrations of 141 ng/g wet mass (Lin et al. 2001). In another study that investigated trace metals in David Lake, Delta Lake, and Unknown Lake in northern Saskatchewan for possible contamination from the Key Lake uranium facility, concentrations of Tl were 6.5, 26.2, and 32.4 ng/g wet mass, respectively (Kelly 2007). In the present study, the greatest concentration of 13.2 ng Tl/g wet mass was observed in northern pike from the Slave River and was greater than in the Saskatchewan reference lake but less than lakes nearer the Key Lake uranium facility.

There is evidence of industry-related deposition of metals in the Athabasca region (Kelly et al. 2010; Kirk et al. 2014); however, it does not appear that this deposition is leading to increased metal concentrations in fish muscle tissue to levels of concern or greater than downstream locations. Whereas concentrations of Tl in tissues of fishes would not be toxic to the fishes or consumers, including humans, this phenomenon offers an opportunity to further investigate the environmental chemodynamics of this poorly understood element.

Environmental factors

One common theme among the metal data was the difference in specific metal concentrations (As, Se, Tl, and V) in fishes from the lower Slave River compared with the upper Slave River and Athabasca River. Migration of fishes could be a factor, with other studies indicating that whitefish and walleye populations in the lower Slave River are a mix of river residents and Great Slave Lake residents, and northern pike are only river residents (Carr et al. 2017). Migration from the Great Slave Lake could be blocked by the series of 4 river rapids upstream of Fort Smith preventing, or at least deterring, lake-resident fish from migrating farther upstream. This could explain certain metal concentration differences between Fort Smith and Fort Fitzgerald that are closer together, geographically, than Fort Smith and Fort Resolution.

Mean concentrations of As in certain species from the present study were found to be greater in the lower Slave River than in the upper Slave River and the Athabasca River. All mean concentrations of As were less than the Health Canada guideline for fish protein of 3.5 ppm (μg/g; Health Canada 2018). One potential explanation for this phenomenon is mining operations on the Great Slave Lake. Environmental As releases have been related to gold mining activities that are present on the Great Slave Lake (Straskraba and Moran 1990; Cott et al. 2016; Schuh et al. 2018). Concentrations of As in lake whitefish were found to be 490 ng/g wet mass in Baker Pond, connected to the Great Slave Lake by Baker Creek—the receiving environment for effluent from the Giant Mine on the northwest corner of Great Slave Lake (Cott et al. 2016). Arsenic concentrations in the same study were 190 ng/g wet mass in Yellowknife Bay near Giant Mine but part of the Great Slave Lake and 190 ng/g wet mass near Hay River on the southeast corner of the lake. Given the difference in As concentration between Baker Pond and Yellowknife Bay and the similar As concentrations between Yellowknife Bay and Hay River, Giant Mine does not appear to have increased As concentrations in the Great Slave Lake whitefish. Concentrations of As in whitefish from Fort Resolution and Fort Smith ranged from 71.1 to 230 ng/g wet mass, which is considerably less than that of fishes collected in close proximity to the receiving waters of the mine effluent and similar to the whitefish collected in Yellowknife Bay and near Hay River. It is possible that migratory populations of whitefish from the Great Slave Lake were a portion of the whitefish collected in the present study. In the fall, whitefish migrate to shallow spawning grounds that coincide with the most pronounced difference in concentrations of As in whitefish from the lower Slave River compared with the upper Slave River and Athabasca River (Morrow 1980). There are sets of rapids upstream of Fort Smith that could provide a barrier to farther upstream migration of whitefish and could explain lesser concentrations in the upper Slave River.

Concentrations of As in northern pike followed the same trend in all 3 of the sampling periods. The cause of this trend is less apparent than for whitefish. Northern pike are piscivorous and it is possible they consume whitefish migrating from Great Slave Lake, which leads to greater concentrations of As. This theory does not agree with a study of gut contents in Slave River that did not find significant quantities of whitefish in northern pike guts (Little et al. 1998). Sampling for the gut content study might not have coincided with whitefish migration through the Slave River that could explain the absence of whitefish in northern pike stomachs. Northern pike are territorial fish and do not typically undertake significant migrations; thus, it is unlikely that northern pike are migrating from areas of greater contamination by As (Morrow 1980).

Concentrations of V were greater in whitefish in the lower Slave River during the fall sampling when concentrations at Fort Resolution were greater than those in whitefish from locations on the Athabasca. Whitefish migration from the Great Slave Lake could be an explanation for seasonal differences because stable sulfur isotope analysis suggests the whitefish population at Fort Resolution consists of a mix of river residents and lake migrants (Carr et al. 2017).

The rapids upstream of Fort Smith may be a contributing factor as well. River rapids are sections of increased turbulence and water velocity with typically shallower water levels. River rapids lead to aeration of the water and the turbulence can keep particulates suspended. The rapids could be increasing the bioavailability of metals that are typically bound in sediment. The increase in bioavailability would be in effect downstream of the rapids but not upstream, which is consistent with the concentration differences between Fort Smith and Fort Fitzgerald. Aeration of sediment slurries has been shown to affect speciation of Cd, and exposure of freshwater sediments to oxygen has resulted in both increases (Ni, Pb, Cu, Cd, and Zn) and decreases (Fe and Mn) of metal mobility (Kersten and Förstner 1986). Oxidation of dredged sediment can significantly affect metal mobility (Calmano et al. 1993; Förstner 1995; Tack et al. 1996). Sediment-bound Se can become bioavailable through oxidation (Lemly and Smith 1987).

Rapids would aerate a relatively small distance of river and its sediment but the change in oxygenation could affect the sediment and particulate being carried from upstream. This could lead to fish that prefer to reside near the rapids, due to habitat or prey opportunity, to be in waters with the potential for greater metal bioavailability.

In these northern rivers flow is less during winter, which could lead to less sediment disturbance in the winter. This could lead to an influx of metals during the spring when river flows increase dramatically due to snowmelt. Snowmelt could also lead to an influx of metals from aerial deposition that had accumulated on the snow. Snowmelt can also lead to increased dilution as the flow increases. An influx of metals during snowmelt does not immediately agree with the increase in fall concentrations, unless there is a delay in the metal influx reaching the fish such as requiring uptake into food or requiring time to reach the new equilibrium. If this is the case, there would be an expected trend of increased metal concentrations in summer to a lesser degree than in fall. A more plausible scenario would be an influx in bioavailable metal concentrations as flow increases due to snowmelt, followed by a decrease as the increased flow carries the water, particulates, and metals onward to the Great Slave Lake, among the 30 million metric tons of sediment carried through the Slave River to the Great Slave Lake each year (Mollard 1981).

Thallium exhibited the most significant associations with locations among the metals analyzed. It is a poorly understood metal and the reason for greater concentrations in the lower Slave River is not apparent. Biomethylation of Tl to dimethyl thallium by benthic organisms is possible in sediments (Schedlbauer and Heumann 2000). Sediment-bound Tl would not be available or have reduced availability for uptake into fishes. Disturbances caused by the rapids upstream of Fort Smith could mobilize sediment-bound Tl that could have been methylated into dimethyl thallium. An organic form of Tl, dimethyl thallium could have greater potential for bioaccumulation similar to some other organometallics.

Concentrations of Se were greater in goldeye than in the other species sampled. Northern pike had significantly lower concentrations than goldeye and walleye. One potential cause of the greater Se concentrations in goldeye is dietary differences. Goldeye consume greater quantities of invertebrates than northern pike and walleye, which are primarily piscivorous as adults. Selenium has been shown to bioconcentrate from water to primary producers that are more directly consumed by goldeye (Lemly and Smith 1987; Skorupa 1998; Stewart et al. 2010; Janz 2011). It is possible that Se is transferring from the goldeye diet at greater rates than the walleye and northern pike diets. Whitefish diets are similar to the diets of goldeye; however, this doesn't explain the greater concentrations of Se in goldeye tissues although the migratory nature of whitefish could make the differences clear. Selenium can be a major concern for fish health and dietary concentrations exceeding 3.0 µg/g dry mass, approximately 15 µg/g wet mass, can be toxic to aquatic organisms. The mean concentrations of Se were well below this concentration, with the greatest mean concentration of Se at 0.844 µg/g wet mass.

Trends in concentrations of Se and V are not as pronounced as the trend for Tl and As. Increasing the dataset either through increasing the sample size by analyzing collected samples or adding sampling seasons could provide more confidence in the potential trends and insight into potential causes.

Geological differences could be another explanation for the metal concentration differences. The sampling locations covered a significant distance and it is plausible that differences in geology could lead to the differences in metal concentrations. There are reasons to doubt geological differences as an explanation. Geological differences wouldn't necessarily explain why there are differences only in certain seasons. There is not a large distance between Fort Smith and Fort Fitzgerald, although there are significant differences between the metal concentrations at each location. Fort Fitzgerald has metal concentrations in line with the Athabasca River locations, whereas Fort Smith has concentrations similar to Fort Resolution that is farther from Fort Smith than Fort Fitzgerald.

It is possible that continued expansion of oil sands activities is not leading to increasing metal concentrations in fish relative to previous fish samplings, possibly due to improvements in the emissions technology and stricter emission guidelines leading to lower metal concentrations in the emissions. National Pollutant Release Inventory (Environment and Climate Change Canada 2020) data have reported annual emissions to air, water, and land from oil sands extraction companies from Fort McMurray for a suite of chemicals including metals of interest to this research—As, Hg, Se, and V. Overall, Hg emissions have decreased from 34 kg in 2000 to 6.3 kg in 2017. The greatest annual Hg emission was in 2007 with emissions of 82 kg. Mercury emissions had a noticeable decrease during 2013, 2014, and 2015, with emissions of 60, 31, and 9.9 kg, respectively. The number of reporting operations decreased from 4 to 3 in 2015; this would have contributed, however, the total emissions decreased by approximately 50% between 2013 and 2014 without a decrease in the number of reporting operations. Vanadium emissions appear to have had a significant reduction event as well, with a reduction of 18 metric tons in 1995 to 6.4 metric tons in 1996. There was only one reporting facility between 1993 and 2000, which eliminates facility differences in the emission reduction. Arsenic emissions have also decreased, with per capita emissions decreasing from 35 kg per reporting operation in 2002 to 20.4 kg per reporting operation in 2017. The major drop appears to have occurred in the reporting between 2005 and 2006, where the number of reporting operations increased from 2 to 4 with emission increasing from 78 to 98 kg. Arsenic emissions did have spikes in 2007 and 2010 that brought per capita emissions to pre-2007 levels. Selenium emissions have increased, according to the National Pollutant Release Inventory data. Selenium emissions have increased from 86 kg in 2009 to 205 kg in 2017. An additional facility began reporting in 2011; this coincides with the beginning of the Se emission increase and would indicate that increasing oil sands development could lead to greater Se emissions. The National Pollutant Release Inventory has data beginning in 1993 for V, in 2000 for Hg, in 2002 for As, and in 2006 for Se. The large-scale development of the oil sands in the Athabasca region began in

1964; this leaves a gap of 30 or more years lacking emissions reporting. There does appear to be improvement in the emissions of some metal from individual oil sands operations; nevertheless, the total emission amount is still greatly impacted by the number of functioning operations that would indicate increasing operations in the region would likely counteract improvements in metal emissions. Reported emissions may be lower for Hg and V but the extent of emissions such as leaching from coke could be leading to unaccounted for releases of these metals.

Although metals have been shown to be entering the Athabasca/Slave river system (Kelly et al. 2010; Kirk et al. 2014) and there are reported releases of metals from oil sands companies in the National Pollutant Release Inventory, they may not be appreciably entering the resident fish populations. Determining possible impacts of oil sands extraction can be quite difficult because there is little-to-no baseline information from before the start of extraction of bitumen from the oil sands deposits. There were also no significant environmental monitoring activities until the Regional Aquatics Monitoring Program began in 1997. There were some individual sampling efforts before the Regional Aquatics Monitoring Program such as the Hg samplings of walleye in 1975, 1984, and 1992, with mean Hg concentrations of 0.27 to 0.43 μg/g wet mass (Lutz and Hendzel 1976; Moore et al. 1986; Donald et al. 1996). These Hg concentrations are similar to the concentrations from the present study that had mean Hg concentrations in walleye ranging from 0.122 to 0.512 μg/g wet mass.

CONCLUSIONS

Concentrations of metals in fishes from the Slave, Athabasca, and Peace Rivers were relatively consistent and less than those in fishes from other regions. Only 4 metals (As, Se, V, and Tl) showed location-related variations in concentration and one metal (Hg) was found at concentrations that may approach human consumption guidelines. However, it is of note that there are significant seasonal differences in the concentrations of metals in fish muscle. These observations might be due to migration and reproductive patterns of fishes as well as by seasonal alterations in metal inputs. The Hg concentrations in the sampled fish are not a novel development; these have been investigated previously and should continue to be monitored, given the concentrations approach and, on occasion, exceed levels of concern. For the other metals analyzed, although not currently at concentrations of concern for human consumers, the increased concentration of some metals in the lower Slave River warrant continued vigilance in the face of ever-increasing upstream development.

Supplemental Data—The Supplemental Data are available on the Wiley Online Library at https://doi.org/10.1002/etc.4852.

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Table A1: Mean concentration and standard deviation of metals in muscle from goldeye from sampling sites along the Slave, Athabasca, and Peace Rivers. The upper value is the mean and the lower value is the standard deviation. Concentrations are in ng/g wet mass unless otherwise stated. Locations are Fort McMurray (FMU), Fort MacKay (FM), Fort Chipewyan (FC), Peace Point (PP), Fort Fitzgerald (FF), Fort Smith (FS), and Fort Resolution (FR). N= number of individuals analyzed.

												Summer														
Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	10	34	1.66	209	41.1	61.3	32.3	1.09	3.83	5.03	70.3	200	4.83	255	183	17.7	7.62	2.34	0.43	704	34.4	679	2.67	19.2	5.13	3.82
		4	2.22	338	27.1	70.3	60.7	1.80	8.63	4.15	74.5	94	3.02	163	219	15.0	10.4	3.29	0.68	194	71.8	1245	0.58	36	4.50	1.65
FM	10	38	0.81	51.8	56.6	35.2	20.7	1.99	0.58	2.82	88.8	211	3.13	228	139	14.6	3.71	1.60	0.27	457	109	937	2.37	49.4	5.75	3.32
		2	0.84	85.5	42.7	27.3	53.1	2.66	1.06	3.30	128.5	193	2.51	85.2	112	18.5	5.62	2.28	0.26	156	131	2266	1.27	152	4.02	1.33
FC	9	37	2.23	224	55.8	17.5	23.9	0.22	0.25	2.55	66.5	124	2.16	209	134	11.7	5.41	4.72	0.51	770	227	403	3.93	4.56	3.06	2.66
		1	2.81	340	26.1	16.5	25.3	0.30	0.37	2.04	136	28.0	1.29	96.7	46.6	11.9	5.10	5.95	0.42	100	341	471	1.33	6.681	2.69	0.42
FS	10	29	4.22	225	60.4	1.92	249.0	0.35	2.72	12.1	54.4	185	4.56	233	462	15.6	33.1	3.72	0.81	588	80.0	4770	3.58	4.01	11.7	4.46
		4	8.55	389	55.7	3.86	292.7	0.40	4.89	21.1	77.7	82.8	2.09	132	459	12.6	74.6	4.34	0.84	176	109	6159	1.47	11.673	9.22	1.94
FR	2	38	0.72	1330	41.2	79.2	12.7	1.07	0.76	0.04	151	203	3.34	224	132	27.8	7.49	1.00	0.27	748	136	111	3.1	0.41	9.52	3.09
		2	0.92	1883	5.4	111.7	13.4	1.35	1.01	0.001	38	11.0	1.3	57.2	59.4	7.91	8.67	1.41	0.38	17.7	191	80.8	1.87	0.58	5.82	0.23
												Fall														
Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	1	39	**<0.01**	121	12.4		58.7	0.10	2.12	3.46	0.06	119	3.25	226	199	5.12	0.06	2.55	0.13	142	0.62	992	0.01	1.64	3.67	3.52
FM	10	36.20	0.14	108	17.8	52.7	23.3	0.66	0.96	2.77	24.5	195	3.59	194	155	12.7	5.34	0.77	0.42	538	2.38	458	1.56	0.83	3.39	2.58
		1	0.31	227	10.6	28.7	25.5	1.17	1.72	1.89	42.8	98.4	1.85	87.8	79.1	10.7	9.57	1.31	0.32	200	4.91	456	1.17	1.32	2.54	0.47
FC	9	37	2.19	132	30.8		67.4	0.74	1.90	4.65	22.9	126	2.81	188	264	7.77	8.16	0.38	0.61	518	13.1	1810	0.82	0.69	4.94	2.85
		2	2.89	176	21.4		158.4	1.25	5.57	4.78	68.2	31.7	0.84	71.1	339	10.4	8.84	0.83	0.32	152	37.2	4244	0.77	0.68	4.541	1.43
FS	10	35	0.84	167	35.4		11.5	0.41	2.85	2.67	60.8	151	3.08	159	128	13.8	10.8	4.96	0.32	844	0.63	308	1.9	108	2.64	2.34
		2	2.07	190	22.8		30.9	0.97	7.26	1.79	119	50.8	1.28	64.3	120	20.5	18.0	11.1	0.28	375	0.05	830	1.22	337.1	2.06	0.42
FR	10	36	0.44	184	43.6	11.6	11.4	0.24	2.32	2.24	56.1	149	2.84	249	122	18.3	11.2	1.72	0.60	818	18.9	202	3.06	2.82	6.71	2.62
		1	0.7	116	93.1	28.0	12.6	0.23	2.07	1.87	48.2	34.7	1.32	136	53.9	8.65	17.7	5.43	0.50	343	57.7	238	2.16	7.03	2.45	0.56
												Spring														
Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	11	33	2.02	263	27.0		59.9	0.09	11.2	11.3	643	310	8.09	264	238	71.2	8.85		0.67	631	1.60	1089	3.17	7.74	8.46	5.30
		3	3.92	152	12.7		92.5	0.04	20.0	7.3	820	180	3.49	224	233	98.1	13.7		1.29	352	3.513	1512	1.40	24.2	5.91	1.90
FM	9	27	1.27	307	32.7		85.5	0.08	4.30	18.7	532	378	9.29	76.9	310	76.9	11.2		0.42	601	2.96	2000	3.08	0.41	9.12	5.57
		5	2.78	220	15.4		105.7	0.04	5.19	12.3	817	313	5.59	58.7	278	104	17.0		0.47	192	8.32	2573	2.66	0.436	7.13	2.10
FC	10	35	0.32	383	48.2	56.6	104.7		0.48	10.0	44.0	195	4.22	126	335	9.93	11.1		0.57	542	0.01	1200	3.7	1.87	6.65	3.39
		3	0.72	404	25.6	113.4	101.9		1.40	5.9	70.2	101	2.15	69.5	217	12.4	13.1		0.76	101	0.002	1182	0.60	2.93	4.02	1.09
PP	9	40	0.02	6.53	26.0	19.7	66.4		0.01	3.28	34.3	157	3.09	260	150	1.75	9.36		0.21	408	**<0.01**	581	2.41	25.4	1.75	2.40
		2	0.04	19.07	10.2	42.5	90.0		0.00	2.63	26.0	95.1	1.13	89.3	89.6	3.19	16.7		0.21	141		708	1.30	59.9	2.08	0.42
FF	10	26	2.29	243	32.8	162.4	75.0		1.84	5.63	31.8	208	5.29	78.3	264	7.66	2.87		6.13	488	3.96	1570	1.77	8.32	7.55	4.39
		7	3.97	657	15.3	171.9	69.7		2.68	3.63	44.5	94.4	3.03	113	119	6.34	2.37		17.0	108	11.9	1894	0.65	12.5	12.9	2.14
FS	10	35	0.68	220	20.7	72.4	17.8		2.65	3.29	24.4	668	3.83	133	116	21.7	86.6		0.03	682	1.88	280	2.84	3.57	2.12	2.62
		5	1.54	601	8.8	77.6	27.2		5.12	2.40	60.3	1254	1.95	61.0	42.6	42.3	173		0.08	300	5.94	408	1.68	9.40	1.47	0.96
FR	10	36	3.69	76.0	38.2	164	81.7		12.3	3.35	52.9	161	3.66	143	169	14.6	1.40		0.39	636	0.01	993	4.83	0.21	12.7	3.83
		6	8.72	194.1	34.0	280	99.0		30.0	1.89	74.2	37.1	1.07	63.4	125	7.83	1.92		0.43	223	0.002	1085	7.10	0.28	24.0	2.61

Table A2: Mean concentration and standard deviation of metals in muscle from northern pike from sampling sites along the Slave, Athabasca, and Peace Rivers. The upper value is the mean and the lower value is the standard deviation. Concentrations are in ng/g wet mass unless otherwise stated. Locations are Fort McMurray (FMU), Fort MacKay (FM), Fort Chipewyan (FC), Peace Point (PP), Fort Fitzgerald (FF), Fort Smith (FS), and Fort Resolution (FR). N= number of individuals analyzed.

Summer																										
Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	10	57	1.32	618	62.5	54.3	72.3	0.65	2.15	2.38	75.4	112	3.06	230	359	16.6	13.9	2.65	0.46	246	65.9	774	3.51	57.8	5.14	3.71
		20	1.40	1649	41.6	83.1	109	1.04	4.45	3.47	96.8	23.3	3.02	208	305	16.2	29.9	2.37	0.41	63.7	89.3	1150	1.67	93.0	3.51	1.00
FM	10	61	1.01	104	31.8	55.1	9.78	0.46	2.20	17.1	69.5	98.2	1.40	176	153	10.7	3.79	0.82	0.45	137	105	83.3	2.04	4.67	3.15	3.28
		10	1.47	164	9.69	75.0	15.1	0.64	5.76	50.4	108	19.7	1.04	122	76.3	15.6	4.36	0.96	0.48	62.3	145	84.2	0.75	11.1	3.16	1.00
FC	10	67	2.21	81.9	68.8	20.3	3.55	0.78	0.43	1.41	120	88.1	1.92	195	105	20.0	2.82	0.78	0.53	357	151	76.8	5.00	2.80	4.81	3.03
		9	3.66	138	18.1	29.2	3.19	1.86	0.58	1.27	225	27.6	1.70	86.6	16.3	37.1	8.03	1.05	0.30	101	316	17.7	1.02	4.83	6.30	0.61
FS	11	69	1.40	0.22	126	0.22	14.9	0.31	0.49	0.70	22.7	144	1.78	232	111	14.7	2.06	0.66	1.97	370	101	87.7	8.46	3.07	7.31	3.51
		8	1.58	0.02	47.7	0.02	11.7	0.41	0.67	0.79	26.7	70.2	0.64	159	49.1	13.1	3.66	0.87	1.91	76.5	118	57.8	3.90	6.78	6.51	0.80
FR	11	67	7.22	144	141	16.7	13.6	0.79	2.17	1.07	143	291	2.59	175	83.4	16.8	7.16	23.8	0.72	360	247	106	11.0	4.41	2.77	5.42
		9	9.67	110	93.3	36.9	15.2	0.95	4.02	1.23	207	429	2.32	49.4	27.0	21.6	6.64	74.0	0.67	94.0	290	183	4.48	13.6	4.02	0.00
Fall																										
Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	3	72	<0.01	49.8	9.68	67.6	3.26	3.01	0.17	0.82	17.8	103	1.17	266	100	14.6	0.13	2.95	0.44	272	0.61	39.4	1.54	0.69	3.11	3.03
		14	0	84.2	8.08	.	5.64	2.96	0.23	1.01	12.9	23.6	0.12	57.8	20.9	9.26	0.14	5.10	0.11	146	0.02	22.4	1.74	0.65	2.67	1.64
FM	9	68	0.03	143	15.5	23.5	10.5	0.47	0.45	0.92	34.9	145	1.50	400	119	18.0	7.80	1.86	0.44	210	4.00	98.7	1.23	0.15	3.65	2.72
		13	0.10	200	14.9	40.4	26.9	1.09	0.63	0.84	55.2	85.3	0.71	420	89.3	14.5	19.2	5.47	0.36	108	10.1	261	1.31	0.18	1.65	0.51
FC	9	78	1.12	275	31.3	9.05	4.65	0.72	5.59	1.39	8.43	151	1.62	302	108	9.60	8.51	20.0	0.81	288	5.09	41.5	1.60	0.30	4.43	3.16
		5	3.15	452	15.1	12.5	6.41	1.21	13.9	1.39	13.5	120	0.88	162	17.8	11.7	10.1	51.8	0.30	76.6	13.3	45.0	1.25	0.18	1.78	1.71
FS	10	70	0.81	413	94.9	40.7	10.8	0.71	0.49	1.13	38.2	97.9	1.41	338	87.5	16.0	1.53	65.3	0.68	375	4.06	121	4.60	2.13	2.60	2.52
		11	1.41	977	72.9	57.2	22.7	1.14	1.04	0.71	66.9	24.8	0.38	372	28.7	18.7	2.71	163	0.36	56.8	11.0	227	2.62	2.44	1.79	0.35
FR	10	68	0.44	277	159	0.21	9.27	1.09	1.46	2.41	35.8	181	2.20	247	91.2	11.3	5.00	1.12	1.01	398	0.63	121	7.91	4.81	2.94	3.38
		11	0.83	387	114	0.01	19.0	1.96	2.35	2.61	97.9	124	1.50	244	31.3	11.6	7.49	3.51	0.64	69.7	0.03	177	4.82	12.0	3.70	0.46
Spring																										
Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	8	72	0.23	170	32.6		13.3	0.09	0.34	4.38	344	265	2.54	486	104	34.9	4.68		0.61	280	0.18	175	2.70	0.28	4.39	4.13
		13	0.63	85.7	10.5		11.8	0.03	0.96	1.45	564	166	1.63	202	26.0	49.2	7.17		0.64	59.3	0.49	48.6	0.86	0.36	3.71	1.20
FM	4	69	0.15	195	32.0		6.22	0.08	2.09	3.22	178	132	2.00	252	98.6	36.7	0.33		0.28	215	4.04	92	3.26	0.04	2.85	3.76
		18	0.29	94.9	12.7		4.15	0.03	3.24	0.48	176	17.5	0.60	160	11.9	24.6	0.05		0.24	117	8.07	16.1	2.07	0.06	0.53	1.12
FC	10	63	0.95	150	42.1	0.25	114		0.20	5.66	13.9	147	2.08	217	382	15.9	0.62		0.03	233	0.01		6.66	165	6.18	3.04
		7	2.99	164	16.9	0.72	171		0.41	5.72	25.6	83.8	0.84	51.4	611	10.7	0.03		0.10	23.8			3.96	170	4.22	0.67
PP	10	70	0.84	208	30.9	40.1	43.9		1.14	2.01	99.0	131	2.92	243	150	7.16	17.2		0.22	285	0.40	201	4.57	0.85	1.04	2.48
		13	1.19	621	12.4	44.2	113		2.15	1.30	153	54.6	2.70	116	223	9.03	20.8		0.35	63.7	1.2	502	2.06	1.10	1.23	0.78
FF	9	73	0.32	523	59.5	42.1	27.2		0.26	2.21	62.9	137	2.56	222	147	12.1	5.43		0.44	257	**<0.01**	151	3.76	0.21	11.1	6.13
		9	0.61	1279	40.0	60.0	63.6		0.80	2.77	85.6	64.8	2.29	109	184	11.3	6.83		0.44	54.2		364	1.41	0.36	20.2	9.80
FS	10	74	1.09	237	130	81.4	90.2		0.86	3.51	9.94	290	1.49	275	182	7.27	12.9		0.61	316	12.6	938	6.64	0.97	1.53	3.70
		12	2.20	391	56.9	71.9	82.6		2.35	1.57	17.9	284	0.68	165	106	11.5	17.0		0.44	47.0	39.9	913	2.283	2.31	1.45	1.72
FR	10	67	0.57	134	120	74.9	88.9		0.01	1.93	39.9	152	1.94	180	223	15.8	8.64		4.26	288	1.28	834	13.2	0.10	3.95	3.93
		7	0.95	199	43.9	101	140		0.00	1.82	39.4	33.6	0.56	77.5	221	11.2	15.3		8.79	34.7	4.03	1233	4.19	0.12	6.34	0.86

Table A3: Mean concentration and standard deviation of metals in muscle from walleye from sampling sites along the Slave, Athabasca, and Peace Rivers. The upper value is the mean and the lower value is the standard deviation. Concentrations are in ng/g wet mass unless otherwise stated. Locations are Fort McMurray (FMU), Fort MacKay (FM), Fort Chipewyan (FC), Peace Point (PP), Fort Fitzgerald (FF), Fort Smith (FS), and Fort Resolution (FR). N= number of individuals analyzed.

													Summer													
Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	10	52	2.05	71.1	48.2	52.8	18.3	0.36	0.59	1.79	50.8	113	1.92	512	113	13.3	12.3	1.65	0.48	354	40.2	200	3.84	2.34	5.00	2.84
		10	2.06	183	20.8	35.2	26.9	0.58	1.13	2.18	61.8	28.1	2.17	431	120	11.8	13.3	1.89	1.02	87.6	52.3	370	1.31	7.08	3.89	0.48
FM	10	45	1.20	10.7	44.9	54.2	12.9	0.84	0.52	2.45	115	144	2.10	262	123	20.7	5.79	0.71	0.26	296	74.4	175	4.51	15.4	4.09	2.98
		11	1.74	22.4	19.6	40.3	17.0	1.27	1.01	2.92	138	50.5	1.75	107	53.6	23.2	7.74	1.06	0.27	113	115	262	2.95	35.0	3.58	0.37
FC	10	51	1.83	221	59.7	0.22	19.0	1.19	1.18	2.15	137	347	2.74	195	97.2	20.6	10.8	35.1	0.67	433	165	202	8.37	0.65	6.41	3.36
		3	3.34	216	18.1	0.03	27.1	2.07	1.92	2.20	238	536	2.02	71	19.5	31.7	14.3	84.9	0.67	104	347	333	1.47	1.04	7.50	1.27
FS	10	37	1.52	291	56.3	0.21	74.2	0.86	1.87	5.11	186	103	2.75	234	150	35.3	22.7	1.34	0.83	448	69.4	609	10.94	22.3	8.60	2.67
		8	1.46	594	43.2	0.01	134	1.64	3.15	11.9	282	24.9	1.60	119	105	36.0	38.8	1.06	0.79	96.7	111	1341	4.10	62.7	7.28	0.58
													Fall													
Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	3	42	1.15	181	35.7		14.7	0.11	0.04	1.72	0.06	129	1.36	169	153	7.76	2.23	0.30	1.37	302	0.65	595	5.71	0.70	5.57	2.22
		11	1.99	243	14.6		24.8	0.01	0.00	0.83	0.00	26.0	0.14	161	158	0.30	1.88	0.51	1.25	115	0.03	962	5.85	0.62	6.63	0.30
FM	10	46	1.23	319	20.6	31.0	1.80	0.69	0.30	2.80	7.41	137	1.78	274	55.4	9.97	1.62	24.4	0.89	293	90.6	50.6	3.76	9.52	2.69	2.25
		5	2.50	904	12.9	.	2.95	1.24	0.81	5.56	14.5	72.1	0.67	146	16.4	9.58	1.89	44.3	1.26	137	136	30.9	2.96	28.5	2.72	0.64
FC	5	50	1.24	555	30.5		6.41	0.65	0.04	2.04	22.4	107	2.92	122	91.4	12.0	2.80	11.4	0.67	409	61.2	59.0	6.59	1.37	3.10	2.32
		3	2.58	794	7.06		8.04	1.21	0.00	0.90	43.9	34.2	1.85	25.1	42.5	4.86	2.30	22.9	0.41	79.4	69.4	33.2	1.01	2.31	3.03	0.26
FS	10	49	0.20	250	90.4	9.73	109	0.21	0.91	5.58	35.5	226	3.67	505	107	25.0	10.6	7.23	0.77	509	12.4	653	16.5	6.20	5.41	4.58
		6	0.46	431	119	21.3	187	0.31	1.18	10.2	37.2	197	3.06	260	86.1	15.6	14.5	13.4	0.25	90.1	24.1	1139	7.88	9.89	3.97	2.48
FR	10	47	0.61	140	55.4	0.20	3.50	0.34	2.82	5.85	30.1	123	1.47	272	56.1	15.4	4.35	1.07	0.56	455	4.21	34.3	15.7	14.4	3.50	2.79
		7	1.55	162	33.8	0.02	7.60	0.72	6.29	13.9	44.0	22.8	0.49	173	14.0	11.0	6.21	2.52	0.13	53.4	9.82	18	5.61	27.1	3.62	0.38
													Spring													
Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	7	47	2.30	187	25.9		24.7	0.09	3.11	4.69	609	196	4.55	308	125	806	20.8		0.66	325	4.91	495	5.38	0.12	6.05	3.86
		3	2.46	136	14.4		56.9	0.03	7.19	4.30	1169	127	4.78	129	107	1881	31.5		1.19	63.0	7.21	1170	2.15	0.12	6.39	1.29
FM	10	44	2.03	373	31.5		6.71	0.08	1.63	3.08	432	196	3.60	312	95.4	57.4	7.05		0.64	323	3.95	84.0	10.7	1.41	5.30	3.75
		3	6.12	398	15.3		7.66	0.04	2.92	1.02	719	78.2	2.84	134	30.5	89.4	11.0		0.51	91.3	5.49	24.8	4.78	4.01	4.91	0.61
FC	8	49	0.54	114	32.6	4.05	27.9		1.23	2.71	24.0	327	2.70	232	120	7.83	18.4		0.31	321	0.01	641	10.6	305.62	3.13	3.21
		7	0.95	172	11.6	10.4	68.7		3.46	2.74	29.5	461	1.98	131	27.6	3.56	43.5		0.53	32.3	0.00	1055	5.36	626	1.99	0.87
PP	9	53	1.22	73.3	24.0	66.9	9.45		3.36	1.60	107	361	2.86	260	79.4	354	33.3		0.43	384	13.9	38.4	6.56	7.99	3.71	2.72
		9	2.51	121	9.90	120	11.3		7.99	0.73	233	708	1.56	90.1	32.1	832	89.8		0.92	59.5	31.7	24.9	1.88	10.00	7.68	0.90
FF	10	56	0.98	295	32.5	82.5	11.7		1.08	1.40	5.86	139	1.60	244	117	30.4	33.0		0.07	376	0.01	92.1	6.29	4.33	1.23	2.80
		6	1.53	585	7.45	66.9	23.3		3.41	1.09	18.5	55.5	1.90	118	116	58.8	98.5		0.20	72.3	0.00	167	1.65	7.50	1.51	0.65
FS	10	56	0.75	264	95.7	23.4	7		0.49	1.60	52.7	168	3.89	284	79.4	13.3	2.43		1.08	336	0.01	37.1	19.3	2.39	2.70	2.65
		3	1.74	438	131	28.9	8.80		1.51	2.29	50.0	66.0	5.99	111	37.8	18.3	3.18		1.79	41.4	0.00	10.5	5.22	4.54	2.11	0.65
FR	9	47	2.13	258	67.8	55.2	16.8		3.44	1.73	28.4	199	3.47	223	103	13.1	3.67		1.12	370	38.9	103	18.8	0.07	3.98	3.24
		9	4.55	426	42.5	84.3	37.6		10.2	1.42	30.5	95.4	3.01	125	38.3	17.6	6.20		1.28	124	113	174	6.76	0.16	6.33	1.20

Table A4: Mean concentration and standard deviation of metals in muscle from whitefish from sampling sites along the Slave, Athabasca, and Peace Rivers. The upper value is the mean and the lower value is the standard deviation. Concentrations are in ng/g wet mass unless otherwise stated. Locations are Fort McMurray (FMU), Fort MacKay (FM), Fort Chipewyan (FC), Peace Point (PP), Fort Fitzgerald (FF), Fort Smith (FS), and Fort Resolution (FR). N= number of individuals analyzed.

Summer

Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FM	10	42	1.28	261	72.2	26.6	0.92	0.63	2.55	13.9	208	155	8.94	46.1	185	44.0	6.52	0.99	0.72	460	109	130	1.80	3.95	6.01	3.09
		4	1.74	355	50.0	31.3	1.36	1.09	5.95	21.1	284	42.1	18.4	18.7	110	53.0	6.23	0.55	0.67	287	154	26.5	0.45	5.85	4.34	0.67
FC	10	41	0.92	55.1	118	0.28	62.8	0.77	0.99	6.95	52.0	142	2.24	36.1	139	18.1	6.52	1.68	0.86	337	0.75	452	2.59	1.19	10.5	3.38
		3	1.59	95.5	55.1	0.06	161	1.21	1.49	5.63	107	37.5	0.87	23.0	63.8	18.6	7.62	2.33	0.74	89.0	0.16	621	0.85	1.88	8.54	0.96
FS	7	41	1.31	74.9	132	0.21	40.2	0.45	0.64	3.86	70.0	117	2.40	37.9	151	26.1	4.06	2.46	9.14	400	74.0	481	4.47	30.3	11.2	2.57
		3	1.39	160	80.8	0.02	71.9	0.40	0.75	2.42	152	53.0	1.64	7.22	31.7	32.7	5.14	4.44	23.1	187	93.4	636	3.73	78.4	8.71	0.51
FR	10	39	7.31	162	89.4	0.22	57.5	0.12	0.40	4.21	147	157	1.75	42.5	144	16.8	11.9	3.08	0.17	457	382	814	3.64	1.30	5.58	2.79
		2	10.6	145	41.6	0.02	124	0.05	0.67	2.40	156	132	1.49	11.3	35.4	25.9	3.29	3.50	0.20	60.7	422	1816	0.99	2.77	7.71	0.78

Fall

Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	9	42	0.30	78.8	12.6	23.6	6.22	0.55	0.89	5.59	17.6	235	3.00	102	144	16.9	2.67	15.2	0.54	305	2.04	124	1.37	1.82	5.85	2.36
		4	0.59	99.3	11.1	20.7	7.79	1.05	0.89	6.15	19.1	243	3.75	83.1	32.2	11.8	4.14	31.1	0.48	83.9	4.34	181	1.02	3.28	3.53	0.77
FM	10	40	1.22	132	29.6		0.47	0.67	0.26	3.09	3.88	145	1.81	31.5	143	8.42	4.08	49.2	0.57	308	17.8	49.9	1.07	1.96	2.39	2.06
		2	2.25	236	14.1		1.47	1.79	0.68	2.30	11.2	113	1.00	18.1	34.1	2.50	6.89	155	0.30	93.2	37.4	22.8	0.82	2.66	1.11	0.52
FC	10	39	0.42	153	37.3	29.8	10.2	1.35	1.13	4.48	75.1	131	1.76	49.2	191	12.8	2.41	0.24	0.66	333	0.70	509	0.57	0.68	7.22	2.62
		3	0.73	233	28.5	23.3	27.3	2.19	1.96	3.76	137	47.3	0.70	47.9	96.4	14.5	1.70	0.56	0.47	80.8	0.06	1450	0.80	0.49	3.85	0.36
FS	10	41	0.91	61.8	107	0.21	16.7	0.73	0.93	9.88	20.3	121	1.98	49.5	122	18.4	6.48	8.93	0.96	440	54.4	354	3.72	0.82	5.94	2.35
		2	1.20	89.4	121	0.01	36.0	1.96	1.41	13.3	29.0	45.9	0.53	35.5	48.7	12.2	6.71	16.0	1.20	88.4	63.9	837	1.67	1.67	5.72	0.42
FR	10	44	0.28	297	230	53.6	93.2	0.62	2.74	2.03	63.1	115	2.93	105.8	176	31.2	6.50	1.11	0.92	478	53.3	842	3.78	4.53	13.63	2.48
		3	0.48	376	189	137	210	1.59	3.10	3.72	66.6	42.8	2.28	36.5	75.4	9.89	8.02	1.70	0.47	96.6	63.5	2010	1.40	4.42	14.8	0.25

Spring

Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	4	42	0.01	243	39.1		4.01	0.10	0.01	12.4	340	140	2.56	85.8	158	40.9	4.58		0.36	234	0.01	239	1.54	2.19	7.77	3.35
		2	0.00	123	13.8		4.23	0.04	0.00	1.97	656	18.8	2.60	28.2	24.1	67.2	8.42		0.37	25.3	0.00	39.4	0.44	3.87	5.21	0.43
FM	2	38	2.11	143	17.8		3.81	0.10	1.06	14.0	202	147	2.52	63.5	167	19.7	0.37		0.26	308	3.83	323	1.47	0.08	5.20	5.55
		2	2.98	52.7	3.13		2.05	0.01	1.50	6.53	250	20.2	1.13	11.5	50.3	8.04	0.04		0.37	134	5.41	15.0	0.52	0.11	0.19	1.38
FC	10	43	0.23	371	72.2	38.4	28.5		0.01	12.9	76.1	165	2.17	47.8	209	6.87	30.27		4.26	249	0.01	99.3	3.45	298	6.26	2.83
		6	0.36	751	45.7	57.6	40.4		0.00	5.45	192	74.5	1.19	16.6	97.2	7.05	56.8		12.8	56.3	0.00	50.8	1.30	716	4.88	0.65
FF	8	45	0.61	348	58.2	69.9	42.2		0.01	14.2	52.8	190	3.96	84.5	203	12.2	7.14		0.29	278	0.16	332	3.22	0.14	5.32	3.42
		8	0.59	984	22.2	88.2	85.3		0.00	13.0	71.0	93.8	4.01	50.0	140	13.8	11.9		0.69	42.5	0.42	470	0.70	0.22	5.17	1.01
FS	5	41	1.02	24.1	71.1	38.3	45.8		1.13	5.19	16.2	128	1.50	49.3	167	8.44	10.7		0.35	348	0.01	512	5.01	399	13.2	2.43
		1	1.60	52.5	26.3	57.4	37.7		1.68	5.25	22.4	40.8	0.40	18.0	43.5	9.61	12.1		0.44	107	0.00	424	1.40	779	16.6	0.26
FR	10	40	2.98	79.4	108	107	39.6		7.41	5.38	32.9	150	3.00	50.2	142	7.24	2.07		1.47	309	10.01	417	3.19	0.73	7.90	2.54
		3	4.86	105	63.5	205	105		17.8	4.35	52.4	106	1.66	18.0	62.7	11.1	2.81		3.20	65.2	31.6	996	0.99	1.34	13.1	0.54

Table A5: Mean concentration and standard deviation of metals in muscle from burbot from sampling sites along the Slave, Athabasca, and Peace Rivers. The upper value is the mean and the lower value is the standard deviation. Concentrations are in ng/g wet mass unless otherwise stated. Locations are Fort McMurray (FMU), Fort MacKay (FM), Fort Chipewyan (FC), Peace Point (PP), Fort Fitzgerald (FF), Fort Smith (FS), and Fort Resolution (FR). N= number of individuals analyzed.

Summer

Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	3	41	1.85	6.32	99.7	27.4	33.7	0.26	2.41	3.37	189	184	2.61	112	140	35.9	10.3	0.47	0.74	384	71.7	470	1.84	0.08	9.65	4.88
		3	0.81	10.6	48.0	38.0	11.0	0.26	3.72	2.70	156	32.9	1.33	29.4	16.6	21.9	5.40	0.43	0.24	78.5	10.2	76.8	0.04	0.07	1.09	0.40
FC	1	56	1.89	77.5	61.6	0.18	2.95	0.09	0.04	3.73	0.05	159	0.84	61.6	140	0.06	9.06	1.02	0.44	483	732	110	3.28	1.04	0.77	3.40
FS	3	48	2.32	93.8	221	26.7	2660	0.24	2.84	13.9	130	185	4.12	149	473	32.4	39.3	3.10	1.09	322	141	6450	2.23	1.86	20.37	5.31
		10	0.45	153	256	45.9	4555	0.25	4.21	24.0	143	72.5	1.09	93.4	505	20.6	68.0	3.17	0.02	61.4	66.9	10933	0.73	3.22	7.46	2.94
FR	10	62	1.03	60.8	188	42.0	139	0.24	0.40	1.78	78.7	127	1.71	112	169	14.1	3.21	1.10	0.17	290	86.7	484	3.17	0.06	4.97	3.15
		5	1.33	86.4	30.9	57.3	423	0.31	0.63	2.48	93.6	28.8	1.02	43.2	59.9	18.0	4.36	0.92	0.20	39.4	186	1243	1.89	0.18	4.21	0.48

Fall

Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FM	2	55	2.16	178	51.1		9.18	0.10	1.76	2.76	2.45	137	2.51	127	155	7.66	0.93	15.4	0.33	272	0.58	131	0.01	0.29	3.77	3.16
		1	3.05	34.1	25.7		2.12	0.00	2.44	0.29	3.38	13.7	0.36	41.4	9.22	1.23	0.28	21.7	0.01	29.6	0.00	5.31	0.00	0.35	0.51	0.90
FC	3	58	0.16	78.1	43.5		13.5	0.09	0.74	3.07	16.7	120	2.42	56.2	161	9.86	5.31	272	1.51	358	108	107	0.93	1.09	2.65	2.50
		3	0.28	135	15.4		8.78	0.01	0.69	0.82	21.9	8.6	1.61	7.26	84.5	3.27	1.78	243	0.90	30.0	69.9	43.0	0.27	0.94	0.94	0.21
FS	3	61	**<0.01**	305	141		220	0.92	19.4	3.52	0.05	98.9	2.64	154	218	7.83	7.12	17.4	1.11	412	32.7	1473	0.99	0.67	3.07	2.84
		5		527	81.8		166	1.42	33.1	2.01	0.00	26.4	1.76	61.5	14.5	2.01	7.05	30.2	0.72	134	29.1	1251	0.71	0.59	1.95	0.64
FR	8	62	0.73	659	111	45.3	25.6	0.47	2.17	35.14	47.8	142	2.98	185	215	19.3	11.4	14.2	1.16	378	49.8	178	1.63	0.79	7.10	2.97
		5	1.38	985	61.9	71.6	39.8	0.81	2.19	95.6	48.2	31.5	0.72	113	37.6	10.1	10.1	20.2	1.04	52.0	46.1	254	0.50	0.89	2.55	0.61

Winter

Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FR	10	64	2.62	423	151	0.17	13.3	0.09	0.96	0.83	19.8	127	1.63	158	115	13.7	1.80	1.91	0.67	301	43.2	75.2	3.51	1.00	3.35	3.17
		4	5.74	687	41.8	0.02	29.3	0.01	1.68	0.78	22.7	31.0	0.60	123	24.7	13.0	2.22	4.03	0.32	32.4	63.9	38.5	0.87	0.83	2.12	0.78

Spring

Location	N	Length (cm)	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe (µg/g)	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	Sr	Tl	U	V	Zn (µg/g)
FMU	3	39	0.98	258	92.5		238	0.06	1.03	8.32	151	290	4.50	109	421	29.0	0.31		0.36		0.01	1720	2.39		8.31	5.96
		3	1.69	143	29.2		315	0.04	1.77	3.82	223	215	2.32	13.0	570	10.6	0.07	.	0.32		0.00	2283	0.13		1.90	1.94
FS	1	74	0.01	0.87	90.8		7.04		0.01	2.93	0.02	176	2.37	368	358	1.97	0.35		1.07	439	0.01	57.1	1.58		5.14	3.80
FR	6	63	0.27	0.36	132	158	51.5		1.12	2.85	109	145	3.30	104	188	13.6	1.92		0.64	281	4.76	67.8	2.33	1.84	3.77	3.35
		3	0.36	0.09	50.9	215	106		2.73	2.37	188	44.8	1.51	40.3	43.8	10.6	2.68		0.78	50.1	11.6	40.8	0.61	3.47	4.08	1.20

Table A6: Analyzed concentrations of methylmercury (MeHg) and inorganic mercury (Hg) in muscle from goldeye (GE), northern pike (NP), walleye (WE), whitefish (WF), and burbot (BB) from Fort Resolution. Concentrations are in µg/g dry mass.

Sample ID	Location	Species	MeHg Concentration	Hg Concentration	Total Hg	ICP-MS Total Hg	%MeHg
FR091	FR	BB	1.72	0.19	1.91	0.82	89.9
FR194			0.71	0.06	0.77	0.22	92.6
FR197			1.26	0.26	1.52	1.47	83.0
FR199			1.19	0.19	1.38	0.72	86.2
FR202			0.93	0.09	1.02	0.52	90.8
FR079		GE	0.89	0.17	1.07	0.51	83.8
FR080			1.05	0.29	1.34	2.05	78.5
FR081			1.69	0.31	2.00	0.89	84.3
FR082			1.32	0.42	1.75	2.14	75.7
FR083			4.26	0.53	4.79	0.67	88.8
FR089		NP	10.35	4.53	14.88	4.65	69.6
FR090			1.59	0.34	1.93	0.72	82.2
FR092			5.67	0.02	5.69	1.41	99.6
FR095			0.96	0.14	1.10	0.45	87.6
FR096			0.93	0.46	1.40	0.58	66.8
FR097		WE	2.04	0.50	2.53	0.94	80.4
FR099			5.35	0.63	5.98	1.67	89.4
FR100			1.93	0.01	1.93	0.99	99.7
FR167			0.99	0.16	1.16	1.59	85.8
FR193			0.65	0.10	0.76	1.14	86.2
FR155		WF	0.30	0.13	0.43	0.23	70.6
FR164			0.36	0.13	0.50	0.58	72.9
FR168			0.58	0.11	0.68	0.78	84.5
FR169			0.33	0.02	0.35	0.43	93.3
FR170			0.22	0.03	0.24	0.59	89.6

Table A7: Analyzed concentrations of methylmercury (MeHg) and inorganic mercury (Hg) in muscle from goldeye (GE), northern pike (NP), walleye (WE), whitefish (WF), and burbot (BB) from Fort MacKay (FM) and Fort Chipewyan (FC). Concentrations are in µg/g dry mass (dm).

Sample ID	Location	Species	MeHg Concentration	Hg Concentration	Total Hg	ICP-MS Total Hg	% MeHg
FC161	FC	GE	2.15	0.46	2.61	1.30	82.2
FC162			1.09	0.32	1.41	0.54	77.4
FC163			0.43	0.13	0.57	-	76.5
FC164			3.00	0.43	3.43	1.17	87.4
FC166			2.53	0.43	2.96	1.08	85.4
FC108		NP	6.38	0.61	6.99	1.82	91.3
FC109			1.59	0.06	1.65	0.69	96.6
FC110			4.28	0.03	4.32	0.95	99.2
FC151			1.92	0.09	2.01	2.35	95.8
FC152			2.78	0.01	2.79	0.92	99.5
FC160		WE	0.53	0.00	0.53	0.46	100.0
FC201			1.80	0.06	1.86	0.61	96.6
FC202			1.21	0.28	1.49	0.60	81.0
FC203			2.91	0.08	2.99	0.87	97.4
FC204			1.40	0.41	1.81	0.58	77.4
FC170		WF	0.34	0.00	0.35	0.81	100.0
FC171			0.28	0.00	0.28	0.14	100.0
FC172			0.11	0.00	0.11	0.08	100.0
FC173			0.09	0.00	0.09	0.24	100.0
FC174			0.20	0.01	0.21	0.14	97.4
FM165	FM	BB	0.90	0.36	1.25	0.53	71.6
FM172			1.24	0.02	1.26	0.85	98.6
FM103		GE	3.83	0.42	4.26	0.93	90.0
FM105			2.10	0.16	2.27	0.60	92.8
FM107			2.08	0.60	2.68	0.89	77.7
FM129			2.36	0.64	3.00	1.10	78.6
FM133			1.51	0.46	1.98	1.73	76.6
FM136		NP	2.16	0.14	2.30	3.34	93.9
FM149			1.43	0.21	1.63	2.67	87.4
FM158			2.46	0.49	2.94	1.11	83.4
FM159			2.68	0.02	2.70	0.83	99.4
FM121		WE	1.52	0.32	1.85	0.70	82.4
FM122			1.28	0.01	1.28	0.66	99.3
FM140			2.06	0.42	2.49	2.97	83.0
FM144			3.06	1.27	4.33	1.52	70.7
FM151			2.53	0.67	3.20	1.37	79.0
FM099		WF	0.18	0.03	0.21	0.17	86.9
FM106			0.11	0.00	0.11	0.08	100.0
FM108			0.11	0.01	0.11	0.11	92.9
FM110			0.09	0.01	0.10	0.10	94.3
FM111			0.80	0.08	0.88	0.39	90.4