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Piscicolid leech infestations affect Northern Pike physiology at extreme levels

Running footer: Intense leech infestation

0 tables, 2 figures

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Abstract

Recreational anglers noted abnormally high numbers of fish leeches (Piscicolidae) attached to Northern Pike at a shallow lake in Interior Alaska, anecdotally related to reduction in habitat availability during winter months. In response, we examined forty-two pike caught through the ice in 2023-2024 to characterize the prevalence and intensity of leech infestation, investigate the possible association of infestation with fish condition, and explore possible connections between leech load and contaminants that could impact fish immune response. Typical numbers of leeches found on fish in nearby water bodies are <10 per individual. However, we found Northern Pike with as many as 481 leeches, commonly attached to their skin, gills, mouth, and fins. This represents the most intense infestation of fish leeches ever recorded in wild freshwater fish. Qualitatively, pike carrying high numbers of leeches exhibited serious damage to the skin. Lipid content estimates indicated that pike body condition was negatively associated with leech load when infested by more than 2 leeches per cm of fish length. There appears to be no link between contaminants and leech infestation, although 27% of pike from the lake contained levels of total mercury up to 750 μg/kg. The effects of very high leech loads on the physiology, reproductive potential, and survival of individual pike are likely negative, and warrant future study. Overall, this investigation represents important documentation of a potential stressor to high latitude fishes, as well as data for comparison in scenarios where climate change or anthropogenic impacts affect parasite-host dynamics.

Key Points

- Pike in an Alaska lake exhibit the highest infestation of leeches ever seen in wild freshwater fish

- Extreme numbers of leeches caused damage to the skin of pike and relate to lower lipid content
- Contaminant loads were not associated with leech infestation level, but this could change with added climate or human stressors.

Keywords: Contaminants; Energetic status; Parasites; Subsistence

Introduction

Recent observations of abnormally high infestations of pisicolid fish leeches (i.e., > 10 per fish) on Northern Pike (*Esox lucius*) in an Interior Alaska lake (Figure 1a) have raised concerns about the potential impacts of parasites on high-latitude freshwater fishes. Northern Pike are commonly harvested by Indigenous and rural Alaskans for subsistence (Holen et al. 2012) in Alaska and other northern regions, comprising an important component of food security. Additionally, Northern Pike are a popular sport fish that represent a recreational attraction for local and tourist anglers, who contribute to regional economies and conservation through fishing license and gear purchases. Therefore, it is vital to assess and monitor any potential threats to the quality and abundance of Northern Pike resources.

Piscicolid leeches are ectoparasites of fish that attach to their hosts to feed on blood and tissues. They are present in lakes and slow-moving rivers in Interior Alaska (Meyers et al. 2019) and are often noticed by people who catch and harvest fish (Bielecki et al. 2011). There is very little contemporary peer-reviewed information regarding the taxonomy, biology, and ecology of Alaskan leeches, with most of the published studies dating from before the year 2000 (e.g., Becker and Katz 1965, Thomas 1969, Dies 1990). Only one recent agency report includes general ecological information about piscicolid leeches in Alaska (Meyers et al. 2019), while De

Carle et al. (2022) focuses narrowly on taxonomy of a new species that was observed in the state. The most common leech species in freshwaters of the Pacific Northwest, including Alaska, is *Piscicola salmositica* (Becker and Katz 1965, Myers et al. 2019), though the taxonomy of leeches in interior Alaska, where this study focuses, is unknown and was not explored here. Piscicolid leeches generally occupy substrate or vegetation of lake or rivers, employ phototaxis or chemotaxis to locate passing fish hosts (Bielecki et al. 2011), attach themselves to the exterior of the host and feed on blood and tissue, and then drop off the host to digest the meal (Meyers et al. 2019). This cycle is repeated, interspersed with reproductive efforts, though leech lifespan and frequency of reproduction is unknown.

Piscicolid leeches are typically considered only a nuisance to fish, but infestations can result in a number of different direct and indirect negative effects on hosts which can be modulated by various external factors. For example, wounds from leeches have been shown to predispose fish to secondary bacterial and fungal infections (Suyanti et al. 2021), and ectoparasites such as leeches have been linked to transmission of various infectious diseases in fish including viruses and blood-borne parasites (Woo 1992, Faisal and Schultz 2009, Pyrka et al. 2021). Typically, leeches are observed in low numbers when attached to fish (i.e., <10 individuals), levels that do not appear to cause noteworthy harm (Meyers et al. 2019). However, exceptions to this have been seen in hatchery settings with high fish densities or when hosts are immunocompromised. In cases of heavy infestation (i.e., > 45 leeches), piscicolid leeches can cause host fish to experience lesions (Figure 1b), stress, anemia, secondary infections, and even death (Thomas 1969, Dies 1990). Fish stress, such as from immune activation or osmotic stress from epithelial compromise, has been shown to have long-term consequences to fish populations (Schreck 2010, Lisle and Bolnick 2021).

Environmental stressors can impact the immune function of teleost fish and result in more vulnerability to parasitism. In the case of Interior Alaska Northern Pike, colder winter water temperatures lower the body temperature of fish, altering physiological processes and immune function (Abram et al. 2017). Hypoxic conditions that can occur in periods when bodies of water are covered by ice also take a toll on physiology (Sformo et al. 2017), while crowding of fish when habitat availability decreases in winter could increase infection transmission rates. Finally, heavy metals like mercury that bioaccumulate in fishes are also known to act as immunomodulators, and might therefore potentially influence fish susceptibility to pathogen burdens (Marcogliese et al. 2011). As apex predators, Northern Pike in Alaska are frequently documented with high levels of mercury (Jewett et al. 2003).

Piscicolid leech outbreaks may have negative effects on individual growth and fitness of wild freshwater fishes in high latitudes, and modulators and population-level rates of infestation have not been quantified. Therefore, our goals with this study were to increase understanding of piscicolid leech impacts on Northern Pike physiology in Healy Lake, Alaska, and explore which factors may modulate parasite load. Specifically, we hypothesize that 1) increased leech load will be negatively correlated with Northern Pike body condition and percent lipid content, either because fish in poorer condition may have decreased ability to avoid or shed parasites, or because higher parasite loads over time require fish to expend more energy; and 2) pike with higher concentrations of mercury in their tissues may be more susceptible to pathogens and exhibit significantly different leech burdens due to consequences of contaminant loads. Our findings may be useful for comparison in the event that similar pathogen outbreaks arise in other high-latitude waterbodies, especially in relation to climate change effects or human activities.

Methods

Study Area

Healy Lake is a ~2,300-hectare shallow (<3m depth), weedy lake in Interior Alaska, approximately 48 km away from the community of Delta Junction that appears to be experiencing a period of lake drying (Callaway and Miller-Friend 2001, Roach et al. 2013). The lake is connected to the Tanana River via a 5.7-km outlet stream and is fed by rainfall and snowmelt from the Healy River and the surrounding basin. Healy Lake Village, a federally recognized Alaska Native community, is located on the north shore of the lake, and the Upper Tanana Athabascan people have maintained a village at this location dating back more than 11,000 years (Callaway and Miller-Friend 2001). Native Northern Pike, Burbot (*Lota lota*), Arctic Grayling (*Thymallus arcticus*), and Coregoninae whitefish are commonly harvested and eaten by subsistence and recreational fishers in the lake and its tributaries. Fish that overwinter in the lake spend over 6 months per year (late October-early May) under thick ice cover (0-1.5 m). The lake and its watershed are largely undeveloped, with only buildings and an airstrip at Healy Lake Village, private cabins along the lake, and fledgling mineral extraction prospects in the headwaters (Freeman 2018).

Fish Capture and Processing

Overwintering Northern Pike were captured in Healy Lake via hook-and-line angling in March 2023 and February 2024 (mid-winter), during the period when leech infestation was reported to be highest. All sampling occurred in a single location on the lake, a submerged remnant stream channel that provides some of the only fish habitat when the ice is at its thickest (most other areas of the lake freeze to the bottom). Immediately upon bringing a fish to the surface of the ice, the field crew used a knife and forceps to scrape all piscicolid leeches attached to the fish onto a large plastic tray. Leeches were subsequently counted and some were retained for contaminants analyses. Fish were immediately weighed with a digital scale (g) and measured (mm; fork length) to facilitate Fulton's Condition Factor calculations (K).

A subset of pike were euthanized for further data collection. On all euthanized fish, bioelectric impedance analysis (BIA) measurements were collected three times per fish following the methods and formulas of Cubbage (2022) to calculate an estimate of the percentage of body lipid and dry mass content. Briefly, resistance and reactance readings were taken from a handheld Seafood Analytics BIA meter (Certified Quality Foods, Clinton Township, MI) while the 5-mm 28-gauge needles attached to the device were inserted into the skin of each fish at reference locations along the fish's body, following methods of Cox and Hartman (2005). The fish's internal body temperature and distance between electrodes (mm) were also recorded to standardize the measurements. For a subset of euthanized fish, blood was also extracted via cardiac puncture using a 22g needle and preserved in trace element vacutainer tubes for subsequent contaminants assessment.

After BIA measurements were completed, the fish were frozen and brought back to a laboratory for further autopsy. Northern Pike cleithra were removed for aging and muscle tissue samples were excised for mercury concentration analyses. Cleithra were cleaned, photographed with reflected light, and annuli increments were counted by at least two trained readers to estimate pike age (Phelps et al. 2017, Cubbage 2022). Stomachs were opened, assessed for emptiness, and stomach contents were identified if possible. Muscle tissue was homogenized and analyzed for total mercury concentration (THg) at the University of Alaska Fairbanks Marine Ecotoxicology and Trophic Assessment Laboratory using a Milestone direct mercury analyzer (DMA-80) for 2023 samples. For 2024 fish, muscle tissue was sent to Eurofins TestAmerica's Seattle laboratory for mercury, arsenic, copper, zinc, and lead analyses using EPA Methods 7471A and 6020B. Concentrations of harmful Monomethylmercury+ (MeHg+) have been found to comprise 94% of THg in Northern Pike muscle tissue from the same drainage (Yukon River; Jewett et al. 2003), and THg is utilized by the State of Alaska to set fish consumption guidelines, so THg was used as a proxy for MeHg+.

Data Analyses

Fulton's condition factor was calculated from the length and weight of the Northern Pike. Additionally, models developed for Alaska Northern Pike from Cubbage (2022) were utilized to calculate the percentage of lipid and dry mass content from the BIA measurements taken for each euthanized fish. The resulting values were averaged across the three readings for each fish to generate estimates. Clearly erroneous values (e.g., -1.71% lipid content for sample ID P14) were omitted where present, before calculating a mean value per fish.

Leech counts were standardized for all fish to the number of leeches per cm of fish length, to account for differences in skin surface area among fish of varying sizes, and log-transformed for normality. Upon initial, exploratory examination of the data, northern Pike lipid content estimates from BIA were correlated with Fulton's Condition Factor, and thus we selected only lipid content as a response variable to quantitatively evaluate leech effects on pike physiology. Lipid content was categorized as normal (>7 %) or low (<7%) for Northern Pike, based on values from the literature where fish were considered "emaciated" at values below 7% (Robards 1999). Contaminant loads were categorized as above or below a 200 μg/kg State of Alaska fish consumption advisory threshold for THg in fish (AKDEC 2024). Relationships between leech count, lipid content categories (low, normal), and contaminant load categories (above or below consumption advisory threshold) were explored using analysis of variance (ANOVA). A

Levene's test was performed separately for percent lipid content and mercury concentration categorical variables to assess the samples for equal variance, in order to meet assumptions for the ANOVA. A generalized additive model (GAM) was constructed for relationships with predictors that were deemed significant by ANOVA, and evaluated for linearity, significance, and smoothness. Other attributes such as pike sex, age, and stomach emptiness, were qualitatively considered as factors influencing piscicolid leech loads, but were not included in statistical analyses due to low sample size and limited power of inference. All statistical analyses were evaluated for significance at $\alpha = 0.05$ and conducted in Program R version 4.4.2 (R Development Core Team 2015).

Results

Fish Capture and Processing

Twenty-five Northern Pike ranging from 529-690 mm in length, were captured in Healy Lake in 2023, and counts of piscicolid leeches on each fish were conducted (Table S1). Twenty-two of these pike were euthanized, BIA measurements were taken, muscle tissue was retained for contaminants analyses, and stomach contents were examined. Cleithra from all euthanized pike were cleaned and aged. In 2024, an additional seventeen pike from 460-762 mm were captured, and leech counts were undertaken, with fifteen of those euthanized for analyses. Several fish were released (not euthanized) after leech counts during each year due to permit limitations or logistical issues. All fish captured had at least seven individual leeches attached to them (leech prevalence = 100%, mean intensity = 59 leeches per fish), on various locations including the skin, gills, operculum, and fins (See Figure 1a). The maximum number of leeches observed on one fish was 481, which equates to 7.89 leeches per cm of the fish's length. The lowest number of leeches per cm of fish length was 0.10. Size of leeches observed varied and appeared to include different stages of development, perhaps of a single species (due to similar colorations and markings), though taxonomic conclusions were outside the expertise of the authors and their networks. Pike with heavier leech infestation exhibited skin abrasions, erythema, and petechial hemorrhaging where leeches had been attached (See Figure 1b). The majority of fish assessed were female (71%), though sex was not identified for some fish because they were released alive, or were not sexually mature (12%). Northern Pike retained for analyses ranged in age from two to six years old, with a median age of four. Most euthanized pike held no items in their stomachs, but nine individuals had eaten various prey including Least Cisco (*Coregonus sardinella*), Round Whitefish *(Prosopium cylindraceum*), smaller Northern Pike, and other unidentified fish.

Body Condition Metrics and Metals Concentrations

Fulton's Condition Factor values for 2023-2024 Healy Lake Northern Pike averaged 0.76, and ranged from 0.55 - 0.92. Estimated pike lipid content ranged from 1.2 - 20.0%, with a mean of 9.0%. Mean dry mass percentage was 25.8% (SD ±1.25%). Total mercury concentrations in pike muscle tissue ranged from 100 - 280 µg/kg, except for one female fish, which had notably higher levels (750 µg/kg; Table S1). Concentration of other metals in pike tissue were assessed for those collected in 2024 only, and lead was not detected in any of these specimens (minimum detection limits for all samples < 100 µg/kg), while total arsenic was detected in 3 of 15 fish at low levels (20% of fish; maximum concentration 89 µg/kg). Levels of zinc were found in all fifteen fish analyzed from the 2024 sample, ranging from 3200 - 6500 µg/kg, and copper was detected in the muscle of one fish (330 µg/kg; minimum detection limits for all samples < 290 µg/kg). Qualitatively, Fulton's Condition Factor, percent lipid content, total mercury concentrations, fish length, and fish age exhibited positive relationships with one another, following typical biological patterns well-established in the literature (Jewett et al. 2003; Froese 2006; Figure S1). Under cursory examination, values for the aforementioned factors of interest were not markedly different between male and female fish (Figure S2).

Leech Load and Related Factors

Because of a bias toward female fish in the sample (71%), we did not include sex as a potential predictor when constructing statistical models, and cursory plots did not indicate clear differences in any metric between sexes (Figure S2). Qualitatively, fish size and age were related to contaminant concentrations due to the effects of bioaccumulation (Jewett et al. 2003; Figure S1), and thus size and age were not included as predictors. The only contaminant that was assessed for both 2023 and 2024 pike samples was total mercury, with zinc, arsenic, copper, and lead evaluated for 2024 samples only. Thus, concentrations of other metals besides mercury were not formally evaluated as modulators of leech load due to small sample size, and leech load did not appear to be related to zinc concentration when assessing plots of the data (Figure S3), zinc was the only metal besides mercury that was detected in every fish that it was assessed for.

Levene's Tests for equal variance between samples for percent lipid content and mercury concentration categories confirmed that ANOVA assumptions were met (*p*-values = 0.08 and 0.10, respectively; null hypothesis of equal variance was not rejected). ANOVA results indicated that log-transformed Northern Pike leech load was significantly different between fish with "low" and "normal" percent lipid content (F-statistic = 5.07, *p*-value = 0.03), with fish categorized as "low" energetic status carrying higher numbers of leeches per cm length (Figure 2). GAM analysis for this predictor indicated a significant nonlinear relationship between log-transformed leech load and continuous values of percent lipid content (t-value = 17.52, *p*-value = <0.01, smooth term *p*-value = 0.03, expressive degrees of freedom = 2.15), with a negative threshold effect visible at approximately 2 leeches per cm pike length or more (Figure S4). However, leech loads were not significantly different between fish "below" or "above" the designated mercury concentration threshold (F-statistic = 0.25, p-value = 0.62; Figure 2), and thus a GAM model was not constructed or evaluated for this predictor.

Discussion

We observed that Northern Pike in Healy Lake, Alaska, can be hosts to extremely high numbers of piscicolid leeches during the overwintering period. This is a time when Northern Pike are crowded together and their activity is curtailed to save energy during the long, harsh winter months under the ice, however results demonstrate that these fish continue to feed during this period. Of the total 42 Northern Pike sampled across the two years of this study, many had piscicolid leech burdens described as heavy when observed in other fish stocks (Thomas 1969, Dies 1990, Meyers et al. 2019), including one individual that was host to 481 leeches. Previous publications including Azmey at al. (2020) and Sawyer et al. (1975) identify similarly heavy burdens of piscicolid leeches on cultured and diadromous fishes, however this study is to our knowledge the first within the scientific literature to document such intense piscicolid infections in wild freshwater fishes. Although concerns have been raised in other systems regarding the impact of these parasites on stock health (Pomposini et al. 2019) little is known regarding the impact of leeches in wild fishes. However, piscicolid leeches are considered a threat to aquaculture (Thomas 1969, Dies 1990), with heavy burdens that cause clinical changes such as anemia negatively impacting fish health.

As expected, leech infestations were negatively associated with estimated fish lipid content. Whether the low lipid content was a result of leech infestation or a contributing factor to it, remains unknown, but may be able to be addressed with an experimental approach. However, given the known feeding habits of piscicolid leeches and existing literature regarding impacts of ectoparasite infestations on other fish, heavy burdens might reasonably be assumed to alter Northern Pike metabolic function and growth. Other fish ectoparasites such as sea lice are well documented as negatively impacting fish growth, fecundity, and survival (Zhang et al. 2023), while previous studies of piscicolid leeches note important impacts on fish appetite and energy expenditure (Cruz-Lacierda et al. 2000). Additionally, circulating concentrations of nutritional parameters including glucose, cholesterol, and triglycerides, suggested infected fish become undernourished with reduced muscle mass due to energetic loss (Ceylik and Aydin 2006). Observations in this study includes noted presence of erythema and hemorrhage on the skin surface of sampled fish, gross changes that although not quantitatively assessed here do indicate there are physiological consequences of parasite attachment and feeding. The relationship between leech infestation and lipid content in this study was driven primarily by two Northern Pike that exhibited the highest amounts of leeches per unit fish length (4.03 and 7.89 leeches per cm). However, it is possible that a greater proportion of the population exhibited similar or higher infestation rate but were not detected due to parasite-induced mortality prior to the sampling periods. Ideally, assessment of additional pike specimens from Healy Lake and other waterbodies that carried similar or greater numbers of leeches per cm would strengthen inferences around this trend, and an increased sample size in general would be beneficial. However, this was a pilot study limited in funding and personnel time, and we sought to avoid euthanizing large numbers of fish from Healy Lake in an effort to minimize impact on pike populations that are important for subsistence and recreational harvest.

Increasing concentrations of mercury and other metals in pike muscle tissue did not appear to be associated with leech load. The State of Alaska Department of Health and Human Services unrestricted fish consumption guideline for THg is 200 µg/kg (ADEC, 2024), and at higher concentrations, fish consumption advice is issued for sensitive populations such as children and pregnant women. Ten of thirty-seven pike sampled (27%) were above the 200 µg/kg threshold for 16 meals per month, and one pike exhibited markedly higher levels in the 4 meals per month category (750 µg/kg). These levels of mercury are within the range of values reported by other studies on Northern Pike in Alaska (Jewett et al. 2003, AKDEC 2024). Mercury concentrations in muscle tissue at these levels likely do not translate to significant immunomodulation or toxicity impacts on pike, which are relatively tolerant of higher contaminant loads (Jewett et al. 2003). Therefore, it is not particularly surprising that fish mercury concentration was not significantly correlated with leech load. However, if input of mercury and other contaminants into the Healy Lake drainage increases, through vectors such as permafrost thaw (Smith et al. 2024) or mining (Jewett et al. 2003, Smith et al. 2024), pike may be subject to increased immunomodulation effects. Innate and adaptive immune mechanisms of mucosal epithelia are well-documented to be responsive against ectoparasites in fish (Esteban 2012), so host immune function may not influence piscicolid leech attachment and feeding. However, varied host susceptibility to other ectoparasites which feed on fish blood has been conclusively demonstrated (Godwin et al. 2022), and mercury toxicity in humans has been associated with immunotoxic effects and hematological consequences, including altered clotting function (Blanco-Abad et al. 2018). Bioaccumulation of heavy metals such as mercury are known to result in multifactorial stress in teleost fish (Kumar et al. 2024), and future studies could explore concurrent mercury accumulation and ectoparasitism by piscicolid leeches with regards to the antihemostatic feeding adaptations of leeches and divergent immunological responses of parasitized fish.

While fish leech infestations are visually unappealing to subsistence fishers and anglers, the leeches themselves do not pose a risk for people harvesting and consuming fish. At Healy Lake, the leech infestations likely only affect individual pike physiology at extreme levels (i.e., at > 2 leeches per cm fish length as indicated by the GAM model). Only three of forty-two pike examined (7%) exhibited this level of infestation and may ultimately have been subject to anemia, secondary infection, starvation, reproductive impacts, and death due to the high leech loads (Thomas 1969, Hurst, 2007). Despite a potentially small proportion of fish that were likely negatively affected, we only sampled during 1-2 day periods over two years, so the full extent of such infestations and their impacts on the overall population could be different than what was observed based on seasonal and annual differences. Existing literature regarding impacts of piscicolid leeches on other fish stocks notes variable impacts of parasitism with varied environmental parameters, a factor that was unexplored here but may importantly influence clinical outcomes of leech burdens on Northern Pike.

Although there is a great deal more to learn regarding the biology and life cycle of piscicolid leeches, with research in some cases inhibited by the short residence time of leeches on fish hosts (Bielecki et al. 2011), it is understood that cold adapted species in environments feed even at temperatures close to 0° C (Goffredi et al. 2012). While research documents that some piscicolids cease feeding and enter a state of dormancy within lake or river substrates during winter months (Becker and Katz 1965), the leeches documented in this study were observed actively attached to and feeding from (i.e., engorged with blood) fish hosts in winter at water temperatures close to 1° C (as measured by thermometer by Healy Lake fieldwork crew). Infestation intensity at Healy Lake is reported by anglers to be variable between summer and winter, with lower numbers of leeches on fish in summer. This may be due to less crowding for and more activity of the host fish in summer, or it could be related to the life cycle of Piscicolidae, which is variable among taxa and not well understood (Meyers et al. 2019).

Seasonal trends in infestation is a topic that bears future study to understand how variable leech burdens influence fish health and condition throughout the year. For Northern pike, a heavy burden and associated anemia might influence winter survival, given the continued feeding behavior of this fish during winter months, however leech burdens during the energetically taxing summer months when the fish are more active, potentially migrating and reproducing, could also impact fish fitness. Given the limited ability of fish such as Northern Pike to regulate their temperature, and the influence of thermal conditions on many important physiological functions including immune response, wound healing, and enzymatic action in functions such as blood clotting, winter parasitism by leeches might present with different health concerns for this population than summer infestation. While occurrence of secondary bacterial infections might be inhibited through impaired microbial growth at cooler temperatures, host response to disease is likely also inhibited (Abram et al. 2017), suggesting that vector transmission of viral pathologies might be more impactful in winter (Ahne 1985, Mulcahy et al. 1990).

Overall, results from this investigation represent important information on parasite impacts on high-latitude fishes harvested for subsistence and recreational purposes, and suggest that while piscicolid leeches can affect fish physiology in extreme cases, they may not have a population-level effect at the rates of parasitism described here. Additionally, this study underlines the importance of assessing fish population status if habitat availability decreases (e.g., lake drying as observed at Healy Lake) or human activities occur that may alter parasite-host dynamics.

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Conflicts of Interest

None to declare.

Data Availability

Project data are available in the Supplementary Material, and are also available from the corresponding author upon request.

Ethics Statement

Animal Care and Use Committees were not available for field study review through the institutions of the authors, but all work was reviewed and approved in accordance with Alaska Department of Fish and Game Aquatic Resource Permit stipulations and guidelines (Permits SF2023-050 and SF2024-021) and was consistent with ethical guidelines of the American Fisheries Society.

Author Contributions

Kevin Fraley: Conceptualization, Methodology, Writing- Original draft preparation; William Samuel: Methodology, Data analysis, Writing- Reviewing and Editing, Resources; Morag Clinton: Writing- Reviewing and Editing, Resources, Data analysis; Taylor Cubbage: Data analysis; Joseph Spencer: Writing- Reviewing and Editing, Resources.

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Figures

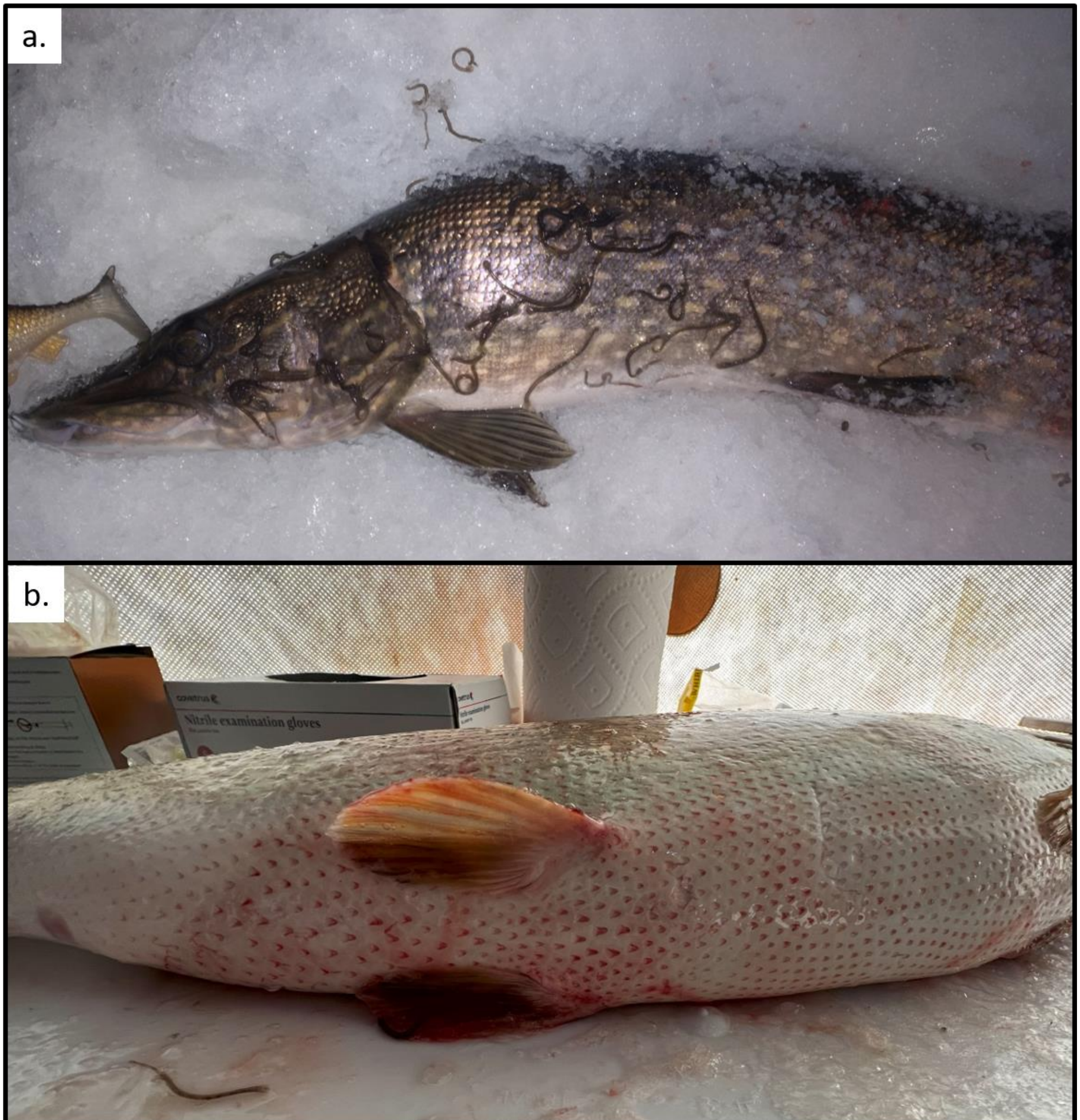

Figure 1. Healy Lake Northern Pike caught for the project exhibiting heavy Piscicolidae leech infestation (a) and associated skin damage and erythema (b).

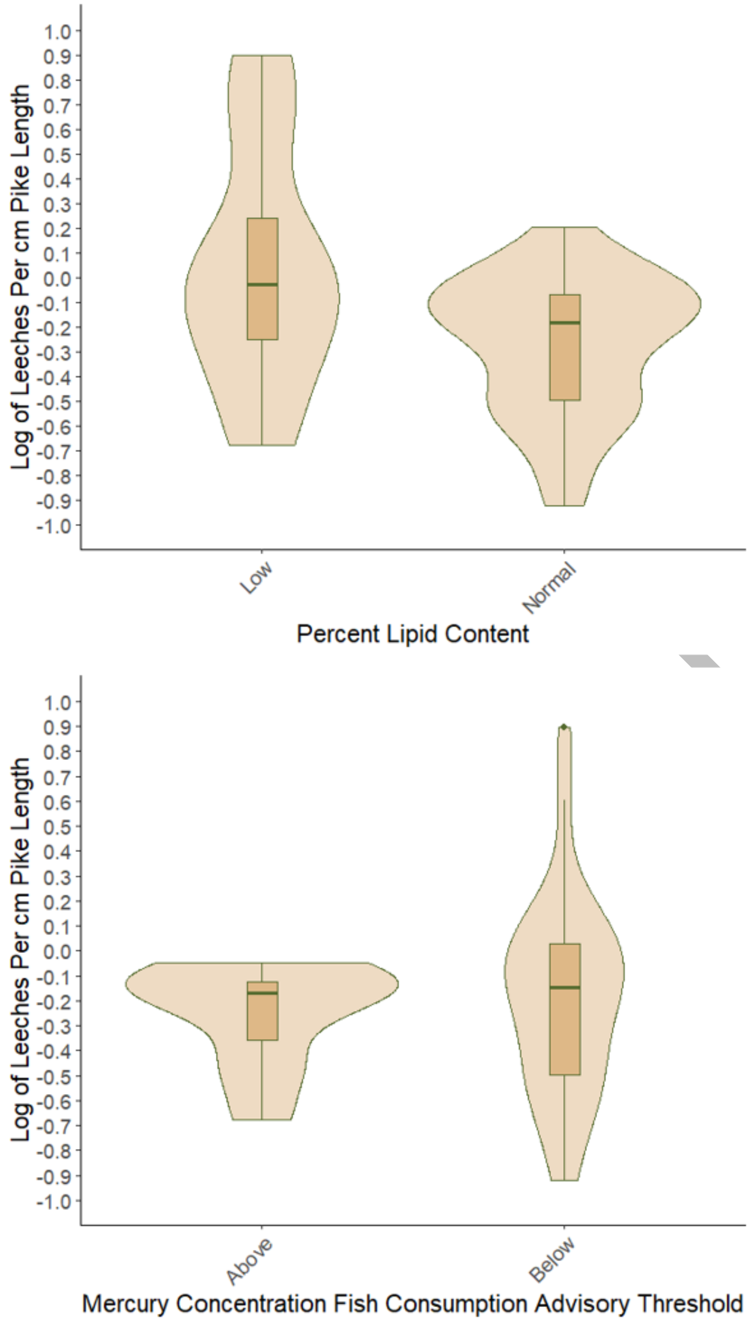

Figure 2. Violin plot showing log-transformed piscicolid leech load (leeches per cm fish length) between Healy Lake, Alaska Northern Pike with normal (>7%) and low (< 7%; Robards et al. 1999) estimated percent lipid content (top panel) and pike above and below State of Alaska fish consumption advisory levels for mercury concentration.

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Supplemental Material

Table S1. 2023-2024 Healy Lake Northern Pike size, body condition, and contaminant information. F=female. M=male, U=unknown (not euthanized), ND=not detected, and N/A=not sampled. BIA metrics are averaged over three resistance and reactance measurements per fish. Limited results from three Burbot caught in 2023 sampling efforts are also included (B1-B3). Underlined values denote pike with total mercury concentrations that are high enough to warrant meal recommendations by the SOA DOH fish consumption guidelines for pregnant women, nursing mothers, and children (See Figure S3).

Year	ID	Sex	Age	Fork Length (mm)	Weight (kg)	Condition Factor (K)	BIA Dry Mass (%)	BIA Lipid Content (%)	Total mercury (ppb)	Leech count	leeches/cm length	Stomach empty?
2023	P1	F	3	587	1.391	0.69	25.79	6.73	133	67	1.14	Y
	P2	F	3	637	1.97	0.76	26.89	9.45	172	64	1.00	Y
	P3	F	5	690	2.19	0.67	24.88	6.13	187	91	1.32	Y
	P4	F	4	630	2.02	0.81	26.07	9.36	227	46	0.73	Y
	P5	F	4	620	2.05	0.86	26.72	10.78	152	44	0.71	N
	P6	M	2	544	1.0234	0.64	23.39	2.72	172	219	4.03	Y
	P7	F	4	627	2.2	0.89	26.69	12.71	153	32	0.51	Y
	P8	M	3	588	1.4375	0.71	25.59	7.27	138	9	0.15	Y
	P9	F	2	551	1.2912	0.77	25.26	7.18	164	16	0.29	Y
	P10	F	3	575	1.47	0.77	25.52	6.96	151	92	1.6	N
	P11	F	2	569	1.4584	0.79	24.71	7.09	140	18	0.32	Y
	P12	F	3	597	1.57	0.74	24.17	19.99	142	55	0.92	Y
	P13	F	4	615	2.05	0.88	26.96	11.70	153	32	0.52	Y
	P14	M	3	539	0.9194	0.59	22.96	6.23	157	42	0.78	Y
	P15	F	2	529	1.0888	0.74	25.24	7.22	128	32	0.60	Y
	P16	F	3	560	1.4106	0.80	26.20	9.96	126	16	0.29	Y
	P17	F	4	640	2.26	0.86	27.37	10.97	256	38	0.59	N

	P18	U	N/A	560	1.3061	0.74	24.55	4.91	N/A	31	0.55	N/A
	P19	F	3	533	1.22	0.81	25.85	9.13	174	35	0.66	Y
	P20	F	2	430	0.5668	0.71	24.17	5.52	180	9	0.21	Y
	P21	U	N/A	550	1.2825	0.77	25.60	7.98	N/A	25	0.45	N/A
	P22	U	N/A	606	N/A	N/A	N/A	N/A	N/A	32	0.53	N/A
	P23	F	3	596	1.72	0.81	25.28	7.18	159	56	0.94	Y
	P24	F	4	587	1.6	0.79	26.39	8.78	219	53	0.90	N
	P25	F	3	605	1.78	0.80	26.40	8.54	165	69	1.14	Y
	B1	F	N/A	674	1.92	N/A	N/A	N/A	N/A	34	0.50	N
	B2	U	N/A	600	1.16	N/A	N/A	N/A	N/A	25	0.42	N/A
	B3	M	N/A	685	1.81	N/A	N/A	N/A	N/A	31	0.45	Y
2024	24_01	F	5	650	2.53	0.920.	26.04	11.49	280	20	0.31	Y
	24_02	M	4	590	1.632	0.79	26.23	10.57	160	7	0.12	Y
	24_03	F	6	740	3.16	0.78	27.55	14.07	170	27	0.36	Y
	24_04	F	4	520	1.178	0.84	25.69	9.27	140	41	0.79	Y
	24_05	F	3	460	0.796	0.82	25.10	8.39	250	34	0.74	N
	24_06	F	5	675	2.54	0.83	28.35	15.14	170	79	1.17	Y
	24_07	F	4	640	2.132	0.81	26.78	11.61	160	53	0.83	N
	24_08	F	4	655	2.043	0.73	26.69	10.04	750	14	0.21	Y
	24_09	F	4	600	1.67	0.77	26.20	9.93	220	51	0.85	N
	24_10	M	4	555	1.284	0.75	25.67	9.80	140	18	0.32	Y
	24_11	F	4	610	1.258	0.55	23.21	1.21	100	481	7.89	N
	24_12	M	3	505	0.816	0.63	24.25	4.00	240	32	0.63	Y

	24_13	F	6	725	3.02	0.79	28.09	13.91	210	55	0.76	Y
	24_14	F	4	653	1.887	0.68	25.64	6.40	220	26	0.40	Y
	24_15	M	4	585	1.452	0.73	25.48	7.31	140	15	0.26	Y
	24_16	U	N/A	660	N/A	N/A	N/A	N/A	N/A	65	0.10	N/A
	24_17	U	N/A	762	N/A	N/A	N/A	N/A	N/A	245	3.22	NA

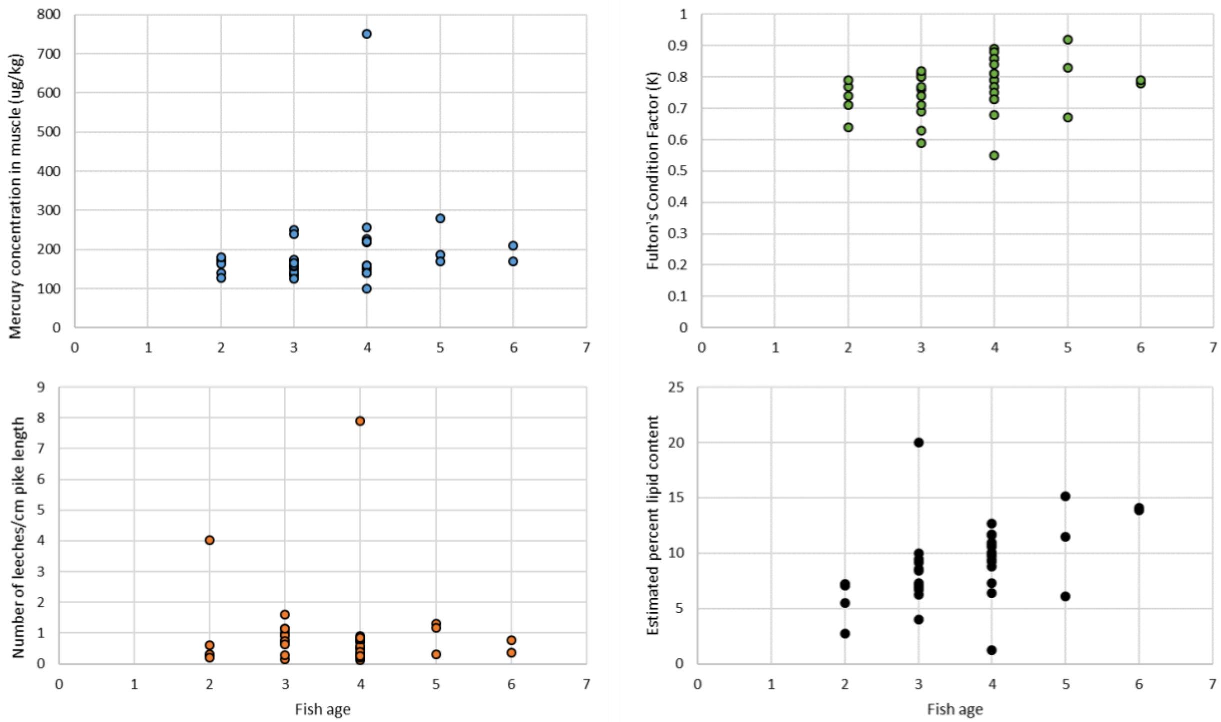

Figure S1. Raw data plots comparing relevant factors related to Northern Pike collected in 2023-2024 from Healy Lake, Alaska.

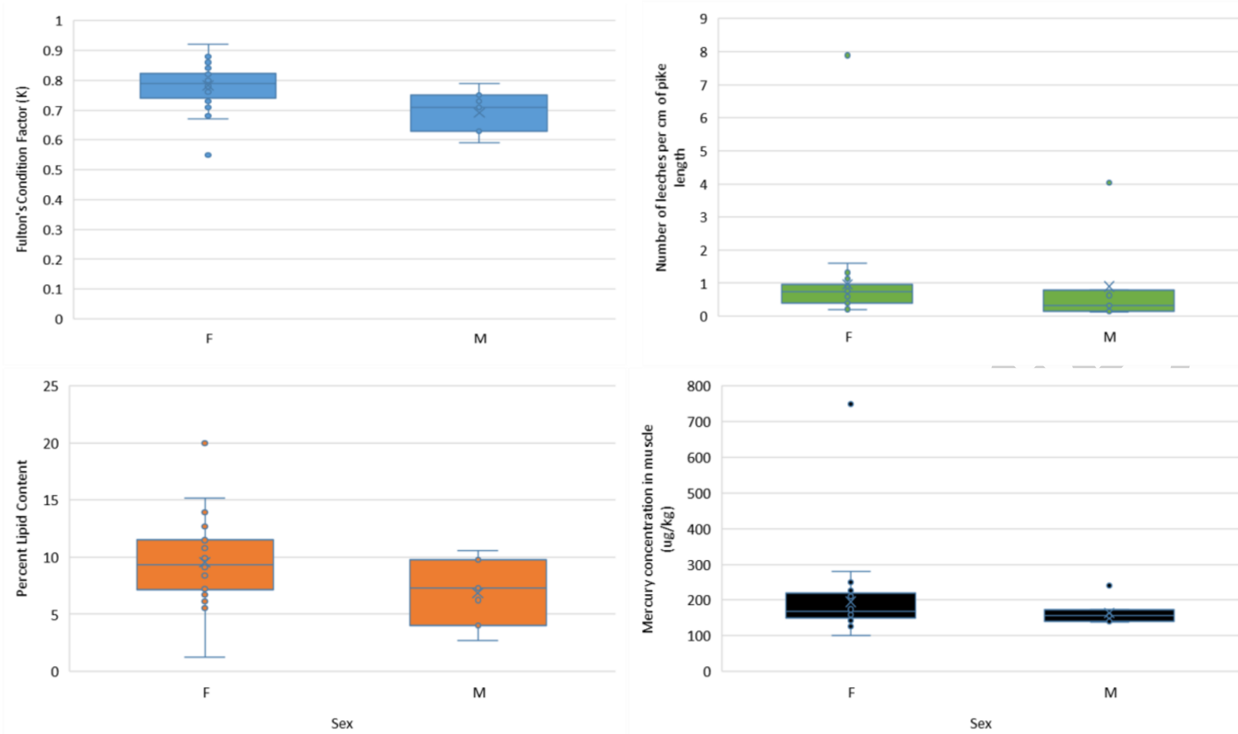

Figure S2. Raw data plots comparing relevant factors between male and female Northern Pike collected in 2023-2024 from Healy Lake, Alaska.

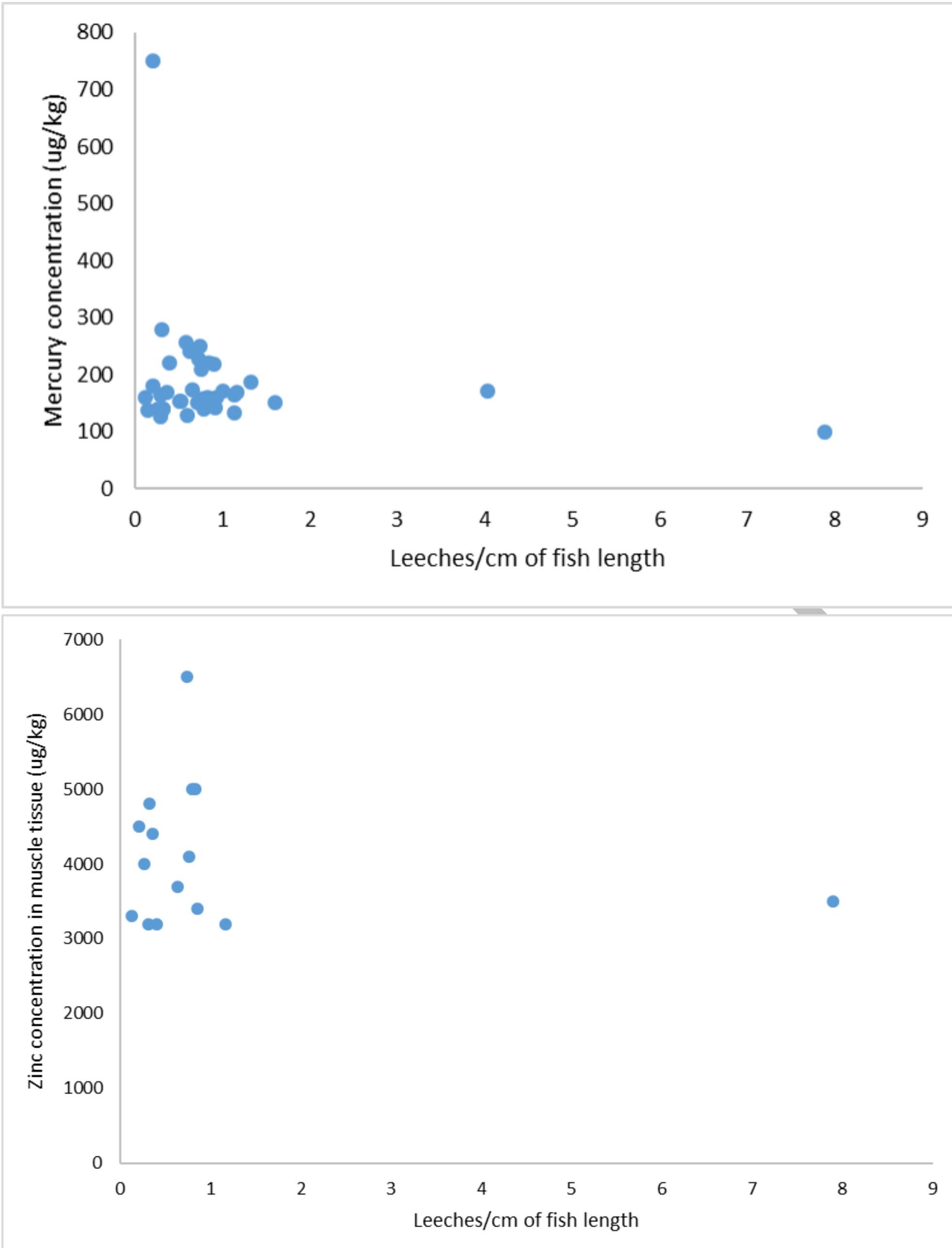

Figure S3. Mercury (top panel) and zinc concentrations (µg/kg) and leech loads (leeches per cm of pike length) observed in Northern Pike collected in 2024 from Healy Lake, Alaska. Pike samples from 2023 were not assessed for zinc concentration.

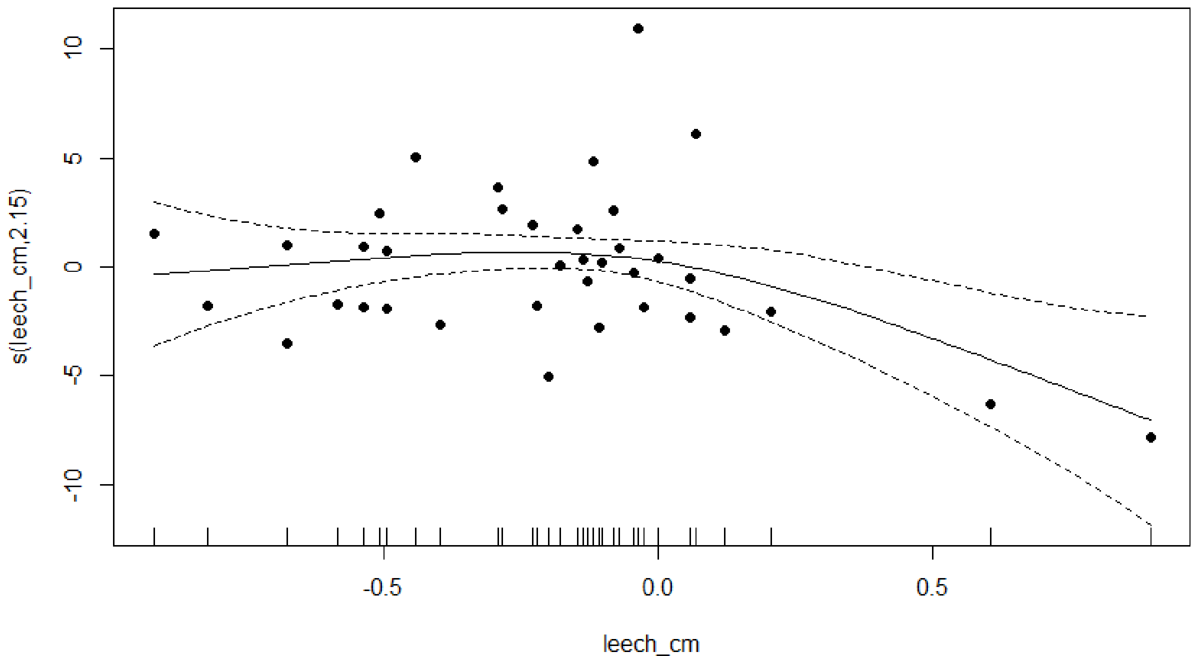

Figure S4. Plot of residuals for a GAM model relating log-transformed leech load and percent lipid content for Healy Lake Northern Pike. A threshold effect of leech load occurs at a value of approximately 0.3, which equates to approximately 2 leeches per cm pike length when back-transformed.