

SHORT-TERM IMPACTS OF THE SITE C DAM ON THE THREATENED BANK
SWALLOW (*Riparia riparia*)

by

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B.Sc., Thompson Rivers University, 2022

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF SCIENCE, ENVIRONMENTAL SCIENCE

In the Department of Biological Sciences

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ABSTRACT

Bank Swallows (*Riparia riparia*) are a species of declining aerial insectivores that nest and breed primarily along rivers and streams across Canada. The causes of this decline are complex, with factors such as prey loss, large-scale ecosystem modifications, and environmental contaminants cited as potential drivers. One of the largest breeding populations of Bank Swallows in British Columbia is found along the Peace River in the province's northeastern region. This same river is also the location of the Site C dam, a decade-long construction project with the potential to introduce pollutants into the environment and alter aquatic ecosystems, thus potentially reducing the availability of aquatic emergent insects. Such changes can potentially contribute to two major drivers of Bank Swallow decline.

This thesis assessed dam construction effects on Bank Swallows by evaluating diet quality and trace element concentrations of nesting adults and juveniles upstream and downstream from dam construction activities. By analyzing long-chain polyunsaturated fatty acids Eicosapentaenoic acid (EPA), Docosahexaenoic acid (DHA), Arachidonic acid (ARA), Alpha-linolenic acid (ALA), and Linoleic acid (LA) in Bank Swallow blood plasma, I found that juveniles consumed higher-quality diets than their adult counterparts. Juveniles also had consistent high-quality diets, whereas adult Bank Swallows appeared to consume higher quality diets downstream from the construction. Significant differences were also found based on year, with 2021 exhibiting a lower quality diet overall than 2023. Analysis of Bank Swallow feathers revealed potentially harmful concentrations of lead and chromium in juveniles, indicating potential environmental contamination near the construction site. All other trace elements tested were under harmful thresholds. Together, these findings provide preliminary evidence that dam construction may negatively impact the health of nesting Bank Swallows, despite standard environmental mitigation efforts. As this data was collected during the construction phase before the reservoir was completed, further environmental impacts are expected in the coming years. Continued monitoring of diet quality and trace elements, particularly of methylmercury concentrations in the tissues of this at-risk species is strongly recommended.

Keywords: Aerial insectivore decline, Diet quality, Heavy Metals, Site C dam, Trace elements

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ACKNOWLEDGEMENTS

I would like to acknowledge that various aspects of this research were conducted on the traditional, ancestral, and unceded territories of Indigenous Peoples across what is now known as British Columbia and southern Ontario. These include the territories of the Tk'emlúps te Secwépemc, Doig River First Nation, Blueberry River First Nations, Halfway River First Nation, West Moberly First Nations, as well as the traditional lands of the Anishinaabek, Haudenosaunee, Lūnaapéewak, and Attawandaron peoples. These and many other Nations have cared for and stewarded these lands since time immemorial. I recognize the privilege and responsibility that comes with conducting research as an uninvited guest on Indigenous territories.

I would like to thank my amazing co-supervisors for all they have done for me in the last two years. As supervisors, they went above and beyond to consider my best interests during this degree, even when plans went awry. I feel incredibly lucky to have learned so much from them both. Thank you to Dr. Tara Imlay for your constant kindness, guidance, expertise, and for the hours we spent on calls while you helped me fix my R code errors. To Dr. Matt Reudink, my involvement in the BEAC lab over the past four years has undoubtedly changed the trajectory of my academic and professional career and I am immensely grateful. I'm proud to have conducted this research in the BEAC Lab, where we consistently demonstrate that academic excellence does not require exclusivity, but rather thrives on inclusivity. This lab has demonstrated countless times that meaningful research is enriched by diverse perspectives and a broad range of voices.

Thank you to my program cohort and everyone in the BEAC lab, especially Shae, Kelsey, Natalie, and Sydney for making my MSc experience so positive. I will always cherish these past two years of learning and collaborating with such passionate, like-minded women.

Thank you to my committee members Dr. Kara Lefevre and Dr. Kingsley Donkor for their thoughtful contributions to my manuscript drafts and encouragement throughout this process. Thank you especially to Dr. Donkor for your mentorship during my trace elements analysis and for taking on such a pivotal role in this research. Thank you as well to Devansh Sharma, Jasmine Ehler, and Romiel Richards for their contributions to my trace elements lab analysis. I am very grateful for the time volunteered by you all to help me get this done.

Thank you to Dr. Chris Guglielmo and especially Dr. Corrine Genier at the University of Western Ontario for hosting me during my LCPUFA analysis. I want to extend a heartfelt thank you to Corrine for patiently teaching me the lab protocol and for going above and beyond for me to ensure all samples of mine were carefully analyzed.

The field work for this project would not have been possible without the contributions and field planning conducted by Sydney Bliss, Dan Yip and Sean Vanderluit (ECCC). Thank you, Sydney, for being such a passionate, fun, and knowledgeable mentor in the field. Thank you, Sydney and Dan, for your incredibly helpful contributions to both manuscripts. I would also like to thank Harry Van Oort (BCHydro) for his contributions to my manuscripts and to Dr. Mateen Shaikh (TRU) for his statistical guidance for both my chapters. Additionally, thank you to Dr. Lisha Berzins for your expertise and contributions to my final manuscript. Finally, thank you to Dr. Nancy Flood for your support in my academic journey since 2020 and your regular words of encouragement.

This research was funded through a Mitacs Accelerate Award, a Ken Lepin Research Graduate Student Award, conference travel grants from the TRU Student Union, and further supported by Dr. Matt Reudink's NSERC Discovery Grant. All field data were collected under Environment and Climate Change Canada Animal Care Permit #20TI02 and AUP# 20T102.

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CHAPTER 1: INTRODUCTION

Bird populations serve as powerful reflections of environmental integrity, offering meaningful insight into the state of ecosystems and the pressures they face. As indicators of environmental change, birds reveal where conservation efforts are proving effective and where increased attention is needed. In North America, bird populations have undergone significant shifts over the past 50 years. Some species have increased, while others have experienced severe declines in abundance (Birds Canada & Environment and Climate Change Canada, 2024). Notably, since the 1970s, national monitoring programs have documented a 43% overall decline in aerial insectivores, highlighting an alarming trend for this ecological group (Birds Canada & Environment and Climate Change Canada, 2024).

Aerial insectivores, including swallows, swifts, nightjars, and flycatchers, are linked by their unique feeding strategy of catching insects in flight. It is widely accepted that no single factor is responsible for the declines in aerial insectivore populations (Imlay & Leonard, 2019; Kardynal & Imlay 2022; Moller, 2019; Spiller & Dettmers, 2019). Instead, current evidence suggests multiple factors including habitat loss, environmental contaminants, and climate change could be operating in combination at complex species-level, regional, and local scales. Given the strong dependence of these birds on flying insects, shifts in prey availability and composition are also likely to play a significant role in their observed declines (Garrett et al., 2022; Imlay & Leonard, 2019; Spiller & Dettmers, 2019).

Aerial insectivores began their steepest decline in the 1980s, with Bank Swallows *Riparia riparia* exhibiting the most dramatic decline (Smith et al., 2015). Their numbers plummeted by approximately 98% (COSEWIC 2013), with an estimated yearly 5.3% annual decline in abundance (Environment & Climate Change Canada, 2022). Based on Breeding Bird Survey results, the breeding population of the Bank Swallow in Canada was last estimated at 2.4 million adults, of which approximately 17% breed in British Columbia (BC) (Partners in Flight Science Committee. 2020). Bank Swallows typically nest in colonies, excavating burrows in vertical or near-vertical faces, often located along waterways. While colonies are commonly found along the coastlines of the Atlantic Provinces, they are rarely observed along the coast of BC (Environment & Climate Change Canada, 2022). In BC., Bank Swallows are most frequently found in the Southern Interior and Boreal Plains regions (Howie, 2015). One of the largest

confirmed breeding populations in the province occurs along the Peace River in the Boreal Plains ecoregion of northeastern British Columbia (Howie, 2015).

The Peace River has undergone substantial riverine alteration due to hydroelectric development (Sims, 2017). In 1968, the province completed construction of the W.A.C. Bennett Dam, creating the massive 1,761 Km² Williston Lake reservoir. At the time, it was the largest earth-filled dam ever built. A second structure, the Peace Canyon Dam, was completed in 1980 further downstream near Hudson's Hope (Figure 1.1). Although several studies assessed the environmental impacts of these projects following their completion (Environment Canada, 2002a, 2002b; Sims, 2017), there are virtually no data on how these developments affected bird populations at the time. Now, the construction of a new hydroelectric project ("Site C") underway on the same watercourse, presents an opportunity to study the real-time impacts of dam creation on a species already at risk: the Bank Swallow.

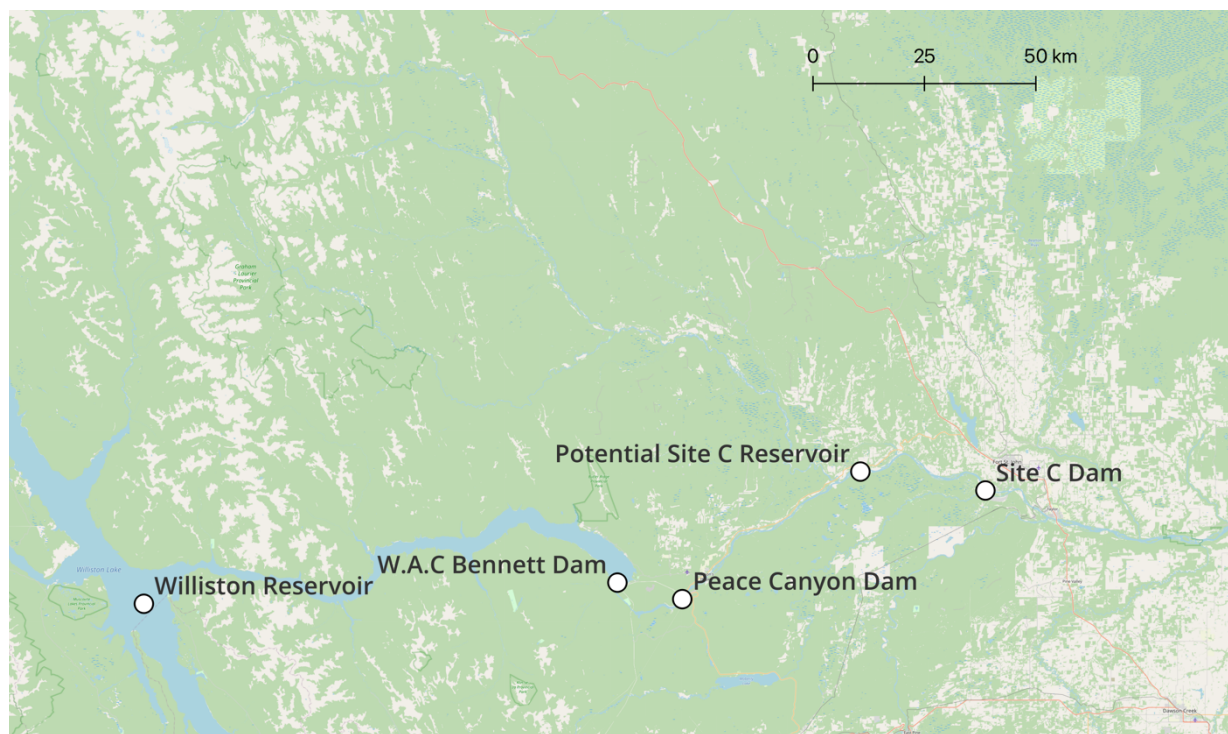


Figure 1.1. Map of hydro development along the Peace River. The Site C dam is the latest hydro development by BC Hydro, with construction starting in 2015. The reservoir was filled in spring of 2025 but was not completed at the time of this study.

Site C Dam Construction

The Site C dam—completed in 2025 but under construction at the time of this study—on the Peace River in northeastern British Columbia creates an 83-kilometre-long reservoir that inundates approximately 5,550 hectares of land, with a total surface area of about 9,330 hectares (BC Hydro, 2025). Large hydroelectric projects like this are known to cause significant and often irreversible changes to surrounding ecosystems, altering habitat structure, hydrology, and the wildlife communities that rely on them. Studies regarding impacts of dams on wildlife are often associated with the creation of artificial lakes or reservoirs (Gowns et al., 2014; Guo et al., 2023; Kennedy et al., 2016; Reitan & Thingstad, 1999; Silverthorn et al., 2018; Wu et al., 2019). However, there are few to no studies about pre-impoundment phase and its impact on wildlife. This becomes a significant gap in research particularly in light of the extensive 10-year construction period associated with the Site C dam.

Prior to the onset of construction, BC Hydro’s environmental impact statement identified four key valued components projected to experience losses as a result of the project: fish and fish habitat, vegetation and ecological communities, migratory birds, and the traditional use of heritage areas by First Nations (Canada, Impact Assessment Agency of “Site C Clean Energy, 2013). A critical question arises: are these losses solely attributable to the impacts of the Site C reservoir, or more likely, are these environmental impacts the cumulative result of both reservoir formation and prolonged habitat alteration and contamination during the construction phase? This study aims to address that question by offering insights into the impacts of dam development on Bank Swallows prior to reservoir inundation. These findings will not only provide a meaningful point of comparison for post-reservoir studies but also contribute to a broader understanding of how extended dam construction may affect surrounding wildlife.

Dietary and Sublethal Consequences of Habitat Modification

Construction of the Site C dam was authorized at the federal level and undertaken with extensive environmental compliance requirements, as is standard for infrastructure projects of this scale (Canada, Impact Assessment Agency of Site C Clean Energy, 2018). However, the project is also exempt from several permitting requirements under the Hydro and Power Authority Act and is further complicated by numerous uncertainties regarding its potential environmental impacts. I predicted that dam construction activities may negatively impact

nesting Bank Swallows in two distinct ways: 1) by reducing the availability of aquatic emergent insects, the preferred food source of Bank Swallows, resulting in a shift of prey availability and prey composition. and 2) by introducing toxic heavy metals and other trace elements into the environment.

As aerial insectivores, Bank Swallows preferentially feed on aquatic emergent insects, which have an aquatic larval stage and are therefore rich in long-chain polyunsaturated fatty acids (LCPUFAs) essential for immune function, neural development, and the growth of offspring (Brenna et al., 2009; Parrish, 2013; Simopoulos, 2011; Twining et al., 2016a). These aquatic insects are uniquely valuable in providing two high-quality LCPUFAs - Eicosapentaenoic Acid (EPA) and Docosahexaenoic acid (DHA) - that are largely unavailable from terrestrial insect sources (Twining et al, 2018). However, dam construction activities can degrade water quality through increased sedimentation, pollution, alterations in temperature and light regimes, and fluctuations in water levels. Such changes may reduce the availability of LCPUFA-rich aquatic insects, potentially impacting the diet quality available to Bank Swallows (Manning & Sullivan, 2021; Yan et al., 2023). Further sublethal effects in the form of trace element and heavy metal contamination may also be present in the environment. Once introduced into ecosystems, these pollutants can accumulate in biological tissues and persist over time, leading to chronic toxicity in wildlife (Ackerman et al., 2016; Kirin et al, 2022; Outridge and Scheuhammer, 1993; Sharma & Agrawal, 2005).

Publicly available construction bulletins by BC Hydro summarize the works that took place during construction periods prior to my data collection. Direct work activities that may impact the availability of aquatic emergent insects and/or introduce concerning pollutants into the environment include recorded increased sedimentation levels, river diversion and headpond formation upstream—both of which contributed to abrupt fluctuations in water levels—as well as the excavation of approach channels and riparian zones, shoreline vegetation removal, dam trench excavation, and on-site concrete production (BC Hydro 2021; BC Hydro 2023 various bulletins).

Given the range and intensity of these disturbances associated with construction of the Site C dam, it is critical to evaluate the project's ecological consequences through both real-time assessment and long-term monitoring. Long-term impacts on bird populations can be systematically studied through methods such as individual tagging and tracking studies with

various tracking systems, or repeated biological surveys. However, detecting and interpreting ecological changes in real time remains more challenging due to the complex and often subtle nature of immediate responses in wildlife and habitat conditions. To evaluate the real-time impacts associated with the Site C dam construction on Bank Swallows, I assessed diet quality in both adults and juveniles by analyzing blood plasma LCPUFA profiles and stable isotope analysis of juvenile feathers. These methods allowed us to identify the dietary sources during the construction period and determine whether Bank Swallows had access to their traditionally high-quality, aquatic-based diet. Additionally, I investigated potential pollutant exposure within the food web by analyzing 19 trace elements, including heavy metals, in Bank Swallow feathers. By integrating these techniques, I gained real-time insight into the environmental effects of the Site C dam construction on Bank Swallows.

Study System

Field work for this study was conducted along the Peace River in northeastern British Columbia from approximately Hudson's Hope (56.117 -121.751, 440 m above sea level) to the British Columbia-Alberta border (56.123, -120.059, 380 m above sea level). The goal of my field work was to collect samples that would allow me to assess stable isotopes, fatty acids, and trace elements including heavy metals in a population of nesting Bank Swallows along the Peace River upstream and downstream from the Site C dam construction (Figure 1.2).

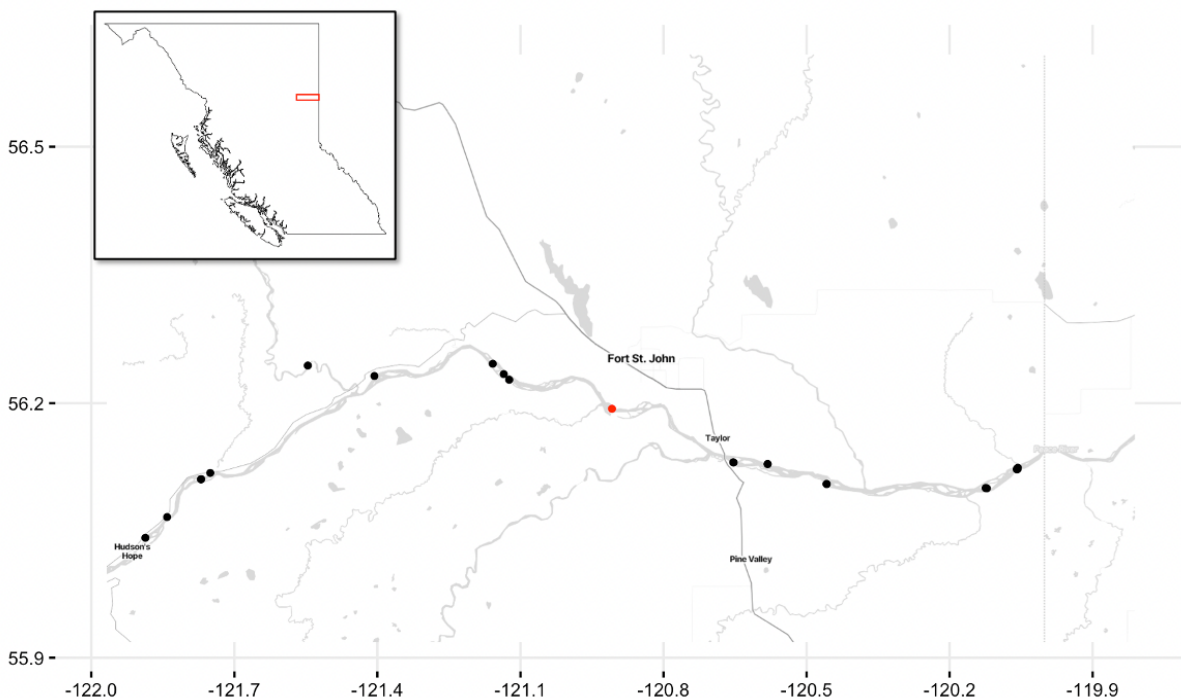


Figure 1.2. Map of study sites along the Peace River in northeastern British Columbia, Canada where samples were collected upstream and downstream of Site C dam construction in 2021 and 2023. Red dot indicates Site C dam location.

Research Goal

The purpose of this thesis is to assess whether a declining aerial insectivore, the Bank Swallow, is experiencing potentially negative health effects due to the construction of the Site C dam. Chapter 2 is focused on assessing the diet quality of the adult and juvenile populations nesting upstream and downstream from the construction by analyzing blood plasma and feathers. Chapter 3 is focused on determining whether concerning amounts of trace elements including heavy metals are present in the population during the time of construction. This thesis concludes with Chapter 4, in which the significance of this study's results is summarized to the broader field and their implications for environmental management. 91% of the electricity supplied to residents of British Columbia is generated by hydroelectric facilities operated by BC Hydro. Given the ongoing reliance on these facilities and the common nesting behavior of this threatened bird species, it is essential to assess the potential impacts of dam construction on the health of Bank Swallows. Enhancing our understanding of impacts on this species will be critical

for informing conservation strategies and ensuring their protection in the context of certain future river modification projects

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CHAPTER 2: UTILIZING LONG CHAIN POLYUNSATURATED FATTY ACIDS AND STABLE ISOTOPES TO ASSESS BANK SWALLOW DIET QUALITY NEAR LARGE SCALE DAM CONSTRUCTION

ABSTRACT

Diet quality plays an important role in the health and reproductive success of many insectivorous birds. An important indicator of diet quality is the availability of long-chain polyunsaturated fatty acids (LCPUFAs), which are essential nutrients. For Bank Swallows (*Riparia riparia*), a Threatened aerial insectivore, aquatic emergent insects are a key dietary source of these LCPUFAs that cannot otherwise be found in terrestrial insects. However, anthropogenic disturbances, such as large-scale infrastructure like dams may reduce the availability of high-quality aquatic insect prey. This study investigated the diet composition and quality of Bank Swallows nesting along the Peace River near Site C, a large earthfill hydroelectric dam construction site. Using both stable isotope analysis and LCPUFA profiling, I assessed spatial variation in diet quality in adult and juvenile nesting Bank Swallows during the 2021 and 2023 breeding seasons. Stable isotopes showed minimal differences in diet origin, while fatty acid profiles revealed significant variation in diet quality by year and age. Juveniles consumed more eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), than adults, suggesting selective provisioning of high-quality prey by adults for young. Juvenile LCPUFA intake also remained consistent across sites, suggesting potential buffering by parental foraging through the selective targeting of higher-quality prey. Adults appeared to consume higher quality prey downstream from construction, and overall diet appeared more aquatic based in 2023 than in 2021. These results highlight the value of LCPUFAs over stable isotopes alone in detecting diet changes and provide a critical pre-reservoir baseline for monitoring long-term ecological impacts of dam construction on aquatic habitats.

INTRODUCTION

Diet quality plays a crucial role in the health, development, and reproductive success of wildlife (Birnie-Gauvin et al., 2017; Twining, 2016a). While diet quality has traditionally received less attention from researchers compared to resource availability, it is now increasingly clear that food quality can surpass food availability in importance for aerial insectivores (Twining et al., 2016a, Twining et al., 2018). For many aquatic and terrestrial vertebrates, including insectivorous birds, high-quality diets include foods rich in long-chain polyunsaturated fatty acids (LCPUFAs) that support immune response, neural development, and growth of young (Brenna et al., 2009; Parrish, 2013; Simopoulos, 2011; Twining et al., 2016a). Omega-3 LCPUFAs, including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), are particularly important in avian diets and have been linked to increased reproductive success and survival (Twining et al., 2016b; Yan et al., 2024). While some species possess the capacity for internal DHA and EPA synthesis from omega-3 precursors (Figure 2.1), this pathway is highly limited, and thus many species' ability to obtain these fatty acids is constrained to diet. DHA and EPA are synthesized in high amounts by aquatic primary producers and are passed through the food web to aquatic emergent insects, which are critical dietary components for many riparian consumers (Brett and Müller-Navarra, 1997; Galloway and Winder, 2015; Hixson et al., 2015; Twining et al., 2016a). Because terrestrial ecosystems lack the capacity to produce these high-quality LCPUFAs, aquatic prey provide a vital nutrient source to terrestrial vertebrates living near aquatic environments (Sayanova and Napier, 2004).

Anthropogenic disturbances, such as building large infrastructure like dams, can significantly alter aquatic ecosystems, affecting the abundance and availability of aquatic emergent insects upon which many riparian and aerial insectivore bird species depend on (Guo et al., 2023; Lepori, 2022; Wu et al., 2019). The Site C hydroelectric dam on the Peace River in northeastern British Columbia, Canada was under construction from 2015 – 2025, and during this time had the potential to negatively impact the surrounding aquatic ecosystem by disrupting aquatic insect life cycles by altering flow regimes and removing suitable oviposition substrates (Kennedy et al., 2016). In addition, dam-related construction activities may lower water quality through secondary effects of sedimentation, pollution, and changes in temperature and light, further reducing the abundance of LCPUFA-rich aquatic insects (Manning & Sullivan, 2021;

Yan et al., 2024). These ecological changes have the potential to cause cascading effects, ultimately effecting insectivorous birds that rely on these habitats for high-quality, LCPUFA-rich prey.

Building an earthfill hydro dam involves extensive construction activity, primarily upstream of the actual dam site. In the case of Site C, construction that may directly impact aquatic insects extended approximately 60 km upstream. However, dam construction can also unintentionally affect downstream ecosystems. Publicly available construction bulletins from 2021–2023 indicate that some of the most intense activity occurred near Hudson’s Hope within this study’s most upstream region (referred to as the “far” proximity area), including the draining of a large wetland. Several other upstream construction activities likely to affect aquatic emergent insects include increased sedimentation, river diversion, and the formation of a headpond, all of which caused abrupt fluctuations in water levels. In addition, the excavation of approach channels involved the removal of over 700,000 m³ of potentially acid-generating (PAG) bedrock. These disturbances not only effect upstream habitats but also pose risks to downstream environments due to changes in flow patterns and elevated sedimentation. A particular source of concern is a recorded exceedance in March 2023, when water discharged from a sediment pond associated with relocated surplus excavated materials (RSEM) containing PAG materials showed elevated levels of heavy metals. Measured concentrations of cadmium, copper, and zinc surpassed acceptable environmental thresholds (BC Hydro, 2024). Such increases in heavy metals have the potential to harm downstream ecosystems, including aquatic emergent insect populations that are sensitive to water quality changes. Given the scale and geographic extent of upstream construction activities, this study will assess impacts based on both proximity to the dam (near vs. far) and position relative to it (upstream vs. downstream). Categorizing sites in this way may help identify areas that are more vulnerable to significant environmental impacts.

To evaluate how environmental changes affect avian diet quality, researchers often rely on dietary biomarkers. The use of LCPUFAs as dietary biomarkers is a relatively recent advancement (Twining et al., 2016a); however, markers such as stable isotopes have been widely used in ecological studies for decades (Hobson, 1999; Hobson, 2023). Measurements of naturally occurring ratios of stable isotopes in animal tissues can serve as a useful tool for inferring habitat origin and trophic level of consumed prey, as isotopic ratios of carbon ($\delta^{13}\text{C}$), nitrogen ($\delta^{15}\text{N}$),

and hydrogen ($\delta^2\text{H}$) in animal tissues reflect the isotopic signatures of their dietary sources (Finlay et al., 2010; Hopkins et al., 2012). Freshwater and terrestrial food webs tend to differ predictably in $\delta^{13}\text{C}$ values, with aquatic producers typically depleted in $\delta^{13}\text{C}$ compared to terrestrial ones (Doucett et al., 2007; Genier et al., 2021). $\delta^{15}\text{N}$ values can help infer trophic level and differentiate aquatic from terrestrial prey sources with $\delta^{15}\text{N}$ typically becoming enriched at higher trophic levels and terrestrial prey often exhibiting lower $\delta^{15}\text{N}$ values compared to aquatic sources (Jardine et al., 2012). Lastly, terrestrial plants tend to be enriched in $\delta^2\text{H}$ compared to aquatic plants that occur in water due to differential evaporative loss of ^1H (Genier et al., 2022). Aquatic consumers, like insects and the birds that consume them, are therefore expected to have higher $\delta^{15}\text{N}$, and lower $\delta^{13}\text{C}$ and $\delta^2\text{H}$ values than terrestrial consumers. Examining the three isotopes in concert can be a powerful approach for inferring diet and habitat information for consumers (Fry, 2006).

Fatty acids provide a complementary approach to measurements of stable isotopes in understanding dietary sources and quality. High quality LCPUFAs that are essential for vertebrate health include eicosapentaenoic acid (EPA; 20:5n-3), docosahexaenoic acid (DHA; 22:6n-3), and arachidonic acid (ARA; 20:4n-6) (Hixson et al. 2015). EPA and DHA are omega-3 LCPUFAs produced from the omega-3 precursor Alpha-linolenic acid (ALA; 18:3n-3), and ARA is an omega-6 LCPUFA produced from the omega-6 precursor linolenic acid (LA; 18:2n-6; also known as LNA) (Yan et al., 2024., Hixson et al., 2015) (See Figure 2.1). ARA is a necessary fatty acid for organ development and gene expression yet has been known to have pro-inflammatory properties at high levels (Simopoulos, 2011). Therefore, while higher proportions of EPA and DHA in diets are almost certainly beneficial, the higher proportions of ARA in diets are harder to interpret. A low omega-6/omega-3 ratio is thought to have positive benefits, while a high ratio may cause susceptibility to inflammatory responses (Andersson et al., 2015; Isaksson et al., 2017)

Terrestrial vertebrates are generally inefficient at desaturating and elongating ALA and LA to their LCPUFA products (Figure 2.1); therefore, consuming preformed EPA, DHA, and ARA is the easiest way to obtain these high-quality fatty acids (Parrish, 2013). Aquatic ecosystems can synthesize relatively large amounts of EPA and DHA (Hixson et al., 2015) via primary production at the base of freshwater and marine food webs by algal taxa (diatoms, dinoflagellates, cryptophytes) (Brett and Müller-Navarra, 1997; Galloway and Winder, 2015),

and these LCPUFA are progressively consumed and retained at higher trophic levels in the food web (Hixson et al., 2015). While primary producers in terrestrial ecosystems can produce LCPUFA precursors ALA and LA, they do not have the capacity to synthesize EPA or DHA (Sayanova and Napier, 2004). Therefore, aquatic insects that feed on high-quality, LCPUFA-rich sources provide high-quality food for terrestrial consumers living in riparian zones and provide them with much higher levels of EPA and DHA than terrestrial prey (Yan et al., 2024). EPA and DHA are particularly important for birds (Twining et al., 2016a; Twining et al., 2016b; Yan et al., 2024), with studies showing that the number of offspring, survival rate, and growth significantly increase with the consumption of greater amounts of EPA- and DHA-rich food (Yan et al., 2024). Together, these biomarkers can effectively reveal how anthropogenic changes in aquatic ecosystems influence terrestrial food webs and consumer nutrition.

An example of wildlife that have the potential to be negatively impacted by dam construction is Bank Swallows. Bank Swallows (*Riparia riparia*) have undergone one of the most dramatic population declines of any aerial insectivore in Canada. Now listed as Threatened under Canada's federal Species at Risk Act (SARA), their numbers have decreased by an estimated 98% in Canada in the past 50 years (COSEWIC, 2013). Bank Swallows establish colonies in steep, eroding riverbanks, such as those along the Peace River—home to over 60 breeding colonies and approximately 1,700 burrows (Environment and Climate Change Canada, unpub.). During the breeding season, they forage heavily on aquatic emergent insects (Genier et al., 2021, 2022). Because they forage close to their nesting sites (~1 km; Saldanha, 2016), local environmental changes such as dam construction may have immediate impacts on their food availability and nestling nutrition. A reduction of high-quality aquatic prey could therefore have a negative impact on the health, survival, and reproductive success of Bank Swallows.

This study aimed to evaluate the diet composition and quality of Bank Swallows nesting along the Peace River, upstream and downstream from the Site C dam construction. I hypothesized that swallows nesting downstream would experience greater reductions in aquatic emergent insect availability due to cascading effects from lower water quality and reduced habitat from fluctuating water levels. Additionally, I expected that birds nesting closer to the core construction zone would face higher rates of habitat disturbance or loss of aquatic insect emergence sites, resulting in lower diet quality. Specifically, I predicted that (1) values of $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^2\text{H}$ would vary among colonies based on location and proximity to construction,

reflecting a dietary shift from aquatic to terrestrial prey sources, and (2) fatty acid profiles would show reduced concentrations of omega-3 long-chain polyunsaturated fatty acids (EPA and DHA) in individuals nesting nearer to the construction area, and downstream from construction. data collected in this study provide a valuable snapshot of Bank Swallow foraging ecology and population health during an active phase of environmental change associated with the Site C project. These data serve to represent a mid-disturbance baseline that can be used as a critical reference point for evaluating long-term ecological impacts on Bank Swallows as the system continues to shift through the flooding and post-flooding phases.

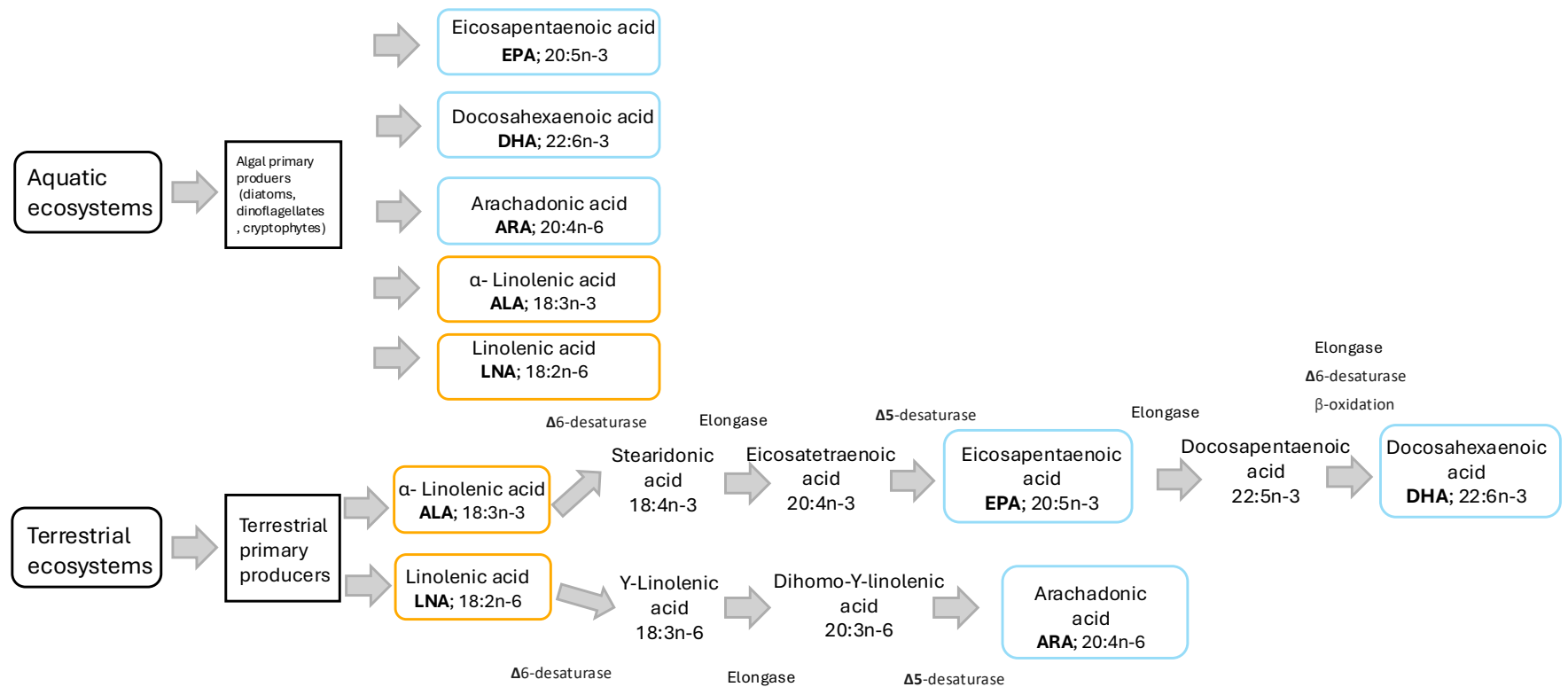


Figure 2.1. Biosynthesis pathways of n-3 and n-6 polyunsaturated fatty acids from aquatic and terrestrial ecosystems. Top pathway: Blue boxes indicate essential LCPUFAs that Bank Swallows acquire exclusively from aquatic sources. Orange boxes denote LCPUFA precursors. Bottom pathway: Blue boxes show essential LCPUFAs that some vertebrates—but not Bank Swallows—can synthesize from α -linolenic acid (ALA) and linoleic acid (LNA) precursor. Information modified from Hixson et al., 2015.

METHODS

Field Methods

Field work was conducted to collect samples that would allow us to assess stable isotopes ($\delta^2\text{H}$, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) and fatty acids (DHA, EPA, ARA, ALA, and LA) in a population of Bank Swallows along the Peace River. To accomplish this, I collected feather and blood samples from both adults and juveniles at breeding colonies from approximately Hudson's Hope ($56^\circ06'51''\text{N}$, $121^\circ46'53''\text{W}$) to the British Columbia–Alberta border ($56^\circ07'27''\text{N}$, $120^\circ03'24''\text{W}$), representing a transect of roughly 60 km above and 65 km below the Site C dam in 2021 and 2023 (Figure 2). Along this 125 km stretch of river, I divided the colonies into two main groups for comparison: 1) upstream vs. downstream of the Site C dam, and 2) near vs. far from the dam. Upstream, "near" colonies were within 30 km of the dam, while "far" colonies were located further upstream. Downstream, "near" colonies were within 35 km, and "far" colonies were located further downstream (Figure 2.2). These categories were chosen based on natural colony groupings and a minimum 10 km gap between "near" and "far" colonies, which reduced the likelihood of overlap in foraging areas. Due to weather, annual variability in the locations of active Bank Swallow breeding colonies, and limited access to some parts of the river in 2023 during ongoing construction, there was variation in the specific sampling sites between years.

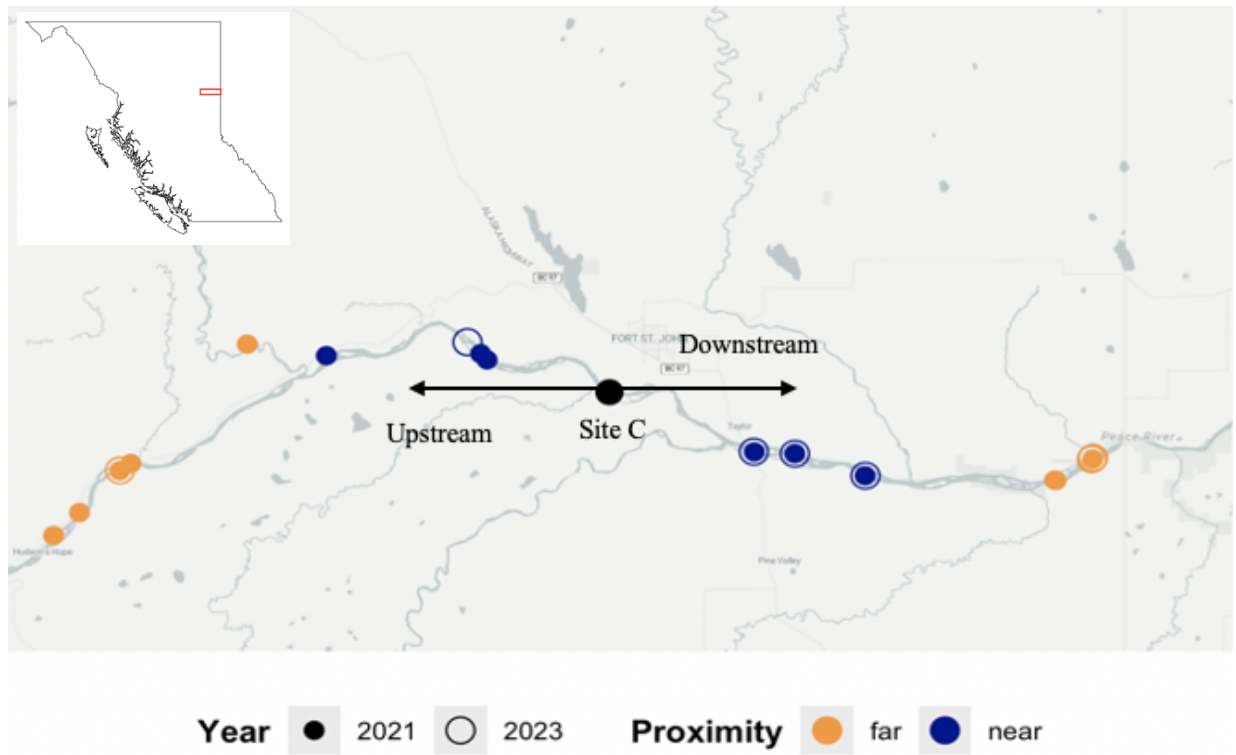


Figure 3.2. Map of study site on the Peace River with sampling locations on either side of the site C dam development. Sampling locations are depicted as solid bullets for 2021 and open circles for 2023; some colonies were sampled in both years. Colours represent colonies “far” from the dam (> 30 km upstream from dam, > 35 km downstream from dam), and “near” to the dam (<30 km upstream from the dam, < 35 km downstream from the dam).

Sample collection

At each colony, I set up 1-2 mist nets in front of each cluster of burrows to catch both juvenile and adult Bank Swallows. I determined the sex and age of each bird based on the presence of a brood patch (adult female), cloacal protuberance (adult male), or yellow gape on bill and/or plumage (feather) characteristics (juvenile); it is not possible to visually determine the sex of juveniles. I collected two R3 rectrices (tail feathers) from each individual, and one was used for stable isotope analysis. Blood samples were collected from the brachial vein of each swallow, with each sample not exceeding 1% of the individual’s body mass up to 140 μ L (one Fisher Scientific microhematocrit capillary tube = 70 μ L). After banding and sample collection, I released the swallows back to their colonies.

Within hours of collection, I centrifuged the blood samples at 6000 rpm for 17 minutes to separate the plasma and buffy coat (i.e., white blood cells/leukocytes, and platelets) from the erythrocytes (red blood cells). I used a Hamilton needle to separate the plasma from the red blood cells, and then transferred the two layers to Eppendorf tubes labelled with the corresponding band numbers. The centrifuged plasma and RBCs were stored frozen at -18 °C or colder until lab analysis.

Sample Processing

To evaluate potential dietary differences in Bank Swallows, I used juvenile tail feathers to measure stable isotope ratios, and adult and juvenile blood plasma to assess LCPUFA percentages. Stable isotope content in feathers reflects the conditions during the period of feather growth as the tissue is inert after fully developed. Therefore, for juveniles, it represents conditions during the 18-29 days of nestling development along the Peace River (Audubon Field Guide, 2025); however, for adults, stable isotope values reflect conditions during the previous winter (Imlay et al., 2017) and would not be informative for this study. Blood plasma is a metabolically active tissue, and in birds, whole blood is replaced much more rapidly than feathers, typically within 3 to 6 days (Pearson et al., 2003). Therefore, LCPUFA analysis on blood plasma will reflect current diet conditions along the Peace River for both juveniles and adults. Sample sizes for each analysis are provided in Table 2.1.

Table 2.1. Summary table of samples collected and analysed for stable isotope and fatty acid analysis in 2021 and 2023 for adult and juvenile Bank Swallows. Adult feathers were not included in analysis.

Age	Year	Stable isotope analysis (feathers)	Fatty acid analysis (blood plasma)
Juvenile	2021	21	14
	2023	61	59
Adult	2021	-	42
	2023	-	21

Stable Isotope Laboratory Methods

To determine feather $\delta^2\text{H}$, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, feather samples were analyzed at the Cornell University Stable Isotope lab (Cornell University, Ithaca, New York, USA). The samples were heated to a minimum of 60°C for at least 30 minutes prior to sample preparation and analyses. Each feather sample was then washed, and small amounts of feather vane were weighed into silver ($\delta^2\text{H}$) or tin ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) cups. Then, samples were analyzed with a Thermo Delta V isotope ratio mass spectrometer (IRMS) interfaced to a NC2500 elemental analyzer (Thermo Fisher Scientific, Waltham, MA, USA).

Accurate stable isotope analysis requires calibration of instrumentation using reference materials with certified $\delta^2\text{H}$, $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$ values. These standards ensure consistency and comparability of isotope ratio measurements. Values were calibrated using three in-house protein standards with known $\delta^2\text{H}$, $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$ values relative to Vienna Standard Mean Ocean Water for $\delta^2\text{H}$, Vienna Pee Dee Belemnite (V-PDB) for $\delta^{13}\text{C}$, and Atmospheric Air for $\delta^{15}\text{N}$. An in-house animal tissue standard was included between every 10 samples, with an analytical precision (1 standard deviation (SD)) of $\pm 2.4\text{‰}$ for $\delta^2\text{H}$, $\pm 0.07\text{‰}$ for $\delta^{13}\text{C}$, and $\pm 0.11\text{‰}$ for $\delta^{15}\text{N}$. Isotope corrections for $\delta^2\text{H}$ were calculated using both the original values of two established standards (Wassenaar and Hobson, Environmental Canada, CBS-Caribou hoof and KHS-Kudu horn) and the updated 2017 recalibrated values. My analysis used data from only the updated 2017 recalibrated values.

LCPUFA Laboratory Methods

To determine the mass percent of DHA, EPA, ALA, LA and ARA in blood plasma samples, LCPUFA analysis was completed at the University of Western Ontario (London, Ontario, Canada). The fatty acid analysis protocol followed techniques revised by Dr. Chris Guglielmo (Genier et al., 2021) based on the protocol by Bligh and Dyer (1959). During lab analysis, blood plasma samples underwent centrifugation and several filtering, evaporation, and resuspension phases with the goal of removing water from the sample. Each sample was also combined with an internal 17:0 standard for comparison during gas chromatography (GC) analysis. The final product of each sample was collected into an insert and placed into GC vials.

On a carousel, GC vials were loaded with a dichloromethane blank and two standards (Supelco® PUFA and 37 components), and samples were analyzed by a GC/flame ionization detector (Agilent Technologies® 6,890 N G1530N, Santa Clara, U.S.A.) equipped with a DB23 column (Agilent Technologies® DB23 122–2,332). The retention times for both standards across all runs were averaged for each fatty acid peak. Each fatty acid peak in every sample chromatograph was manually identified by comparing retention times to the fatty acid library.

Statistical Analyses

All statistical analyses were conducted using the software R (version 4.4.3; R Core Team, 2024) within RStudio (version 2024.09.0+375). I performed all analyses with *dplyr*, *car*, *lmer*, and *tidyr* packages within RStudio and visualized the results with *ggplot2*. Mapping was conducted with *ggmap*.

Stable Isotopes

To determine if there were differences in Bank Swallow diet composition and quality by year, location, proximity, or age group, I first performed a Principal Components Analysis (PCA) on the $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^2\text{H}$ values to provide a single index of diet. The first Principal Component (PC1) accounted for 67% of the variability among the three isotopes, and PC2 only accounted for 24% of the variability (below the threshold of 27.8% from the broken stick model) and therefore was not included in analyses or discussed further in this chapter. Higher values in PC1 indicated diets that include more terrestrial prey (enriched or higher $\delta^2\text{H}$ and $\delta^{13}\text{C}$ values). Details on PCA loadings are provided in Appendix A. Next, I used a linear mixed effects model to evaluate variation in PC1 as the response variable, and year (2021/2023), location (upstream/downstream), and proximity (near/far) as categorical fixed effects. A unique ID for each individual colony was included as a random effect. I assessed model validity by visual inspections of QQ and residual plots. Additionally, I fitted separate linear mixed-effects models for $\delta^2\text{H}$, $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$ using the same fixed and random effects structure. Results of these individual isotope models are presented in Appendix A but are not further discussed here.

LCPUFA

To further assess if Bank Swallow diet composition and quality differed by year, location, proximity, or age group, I evaluated the effects of each independent variable on all five LCPUFAs with a Multivariate Analysis of Variance (MANOVA). MANOVA enables the assessment of the combined fatty acid profile variability across the levels of the predictor variables, considering correlations among the fatty acids. In the MANOVA, the five fatty acids (EPA, DHA, LNA, ALA, and ARA) were included as the response variables, with year, location, proximity, and age group (juvenile/adult) as categorical predictor variables. Next, I assessed mean relative mass percentages of each fatty acid of interest individually using linear mixed effect models (LMMs). Each individual fatty acid was the response variable in each model, and the same categorical predictor variables used in the MANOVA (i.e., age, year, location, and proximity) were included as fixed effects. Lastly, I assessed mean relative mass percentages of each fatty acid of interest in adult and juvenile Bank Swallows separately using LMMs, with each individual fatty acid as the response variable in each model, and year, location, and proximity as fixed effects. Unique colony IDs were also included as a random effect for all LMMs to account for variability in the data that is not captured by the fixed effects. I assessed assumptions of linearity by visual inspections of QQ and residual plots.

RESULTS

Bank Swallow Diet by Stable Isotope Analysis

I did not find any differences in diet (based on the variability of stable isotope values explained by PC1) associated with proximity to the dam ($p = 0.3$, $\beta = -0.21$) or year ($p = 0.16$, $\beta = -0.13$) (Table 2.3). However, differences in PC1 approached significance based on upstream vs downstream locations ($p = 0.06$, $\beta = -0.37$), where downstream nestlings had in general higher PC1 scores and less variability indicating a more consistent diet that is more enriched in $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$.

Changes in Bank Swallow Diet by Fatty Acid Analysis

Assessing overall fatty acids profiles (EPA, DHA, ALA, LA, and ARA mass percents assessed together) revealed significant differences based on location (upstream vs. downstream),

proximity (near vs. far), year (2021 vs. 2023), and age class (adult vs. juvenile) (MANOVA; $P < 0.001$ for all variables) (Table 2.2). These results suggest that the overall composition of Bank Swallow diets varied across spatial gradients, between years, and between age groups

There was considerable variability in the relationships between the LCPUFAs, but visual inspection indicated that high quality LCPUFAs EPA and DHA were higher in 2023 compared to 2021, and higher in juveniles than adults. I found no differences in EPA and DHA based on nesting location, suggesting that the variance among nesting locations was driven by another influence.

Table 2.2. Results from MANOVA assessing fatty acid profiles for five LCPUFAs as a group (EPA, DHA, ALA, LNA, and ARA). Results reveal significant differences in diet profile based on location (upstream vs. downstream), proximity (near vs. far), year (2021 vs. 2023), and age class (adult vs. juvenile)

Variable	DF	Pillai's trace	Approx. F	p-value
Location	1	0.16	5.16	<0.001***
Proximity	1	0.24	8.66	<0.001***
Year	1	0.62	43.19	<0.001***
Age	1	0.29	0.29	<0.001***

I observed differences between mean relative fatty acid percent and year, age, location and proximity, when fatty acids were analyzed individually in linear mixed effects models. The relative mass percentage of the five LCPUFAs was between 46%-470% higher in 2023 compared to 2021 (Table 2A, Figure 2.1). Three LCPUFAs DHA, ARA and ALA indicated dietary differences between juvenile and adult Bank Swallows. The mean mass percentage of DHA and ARA (both indicators of more aquatic prey) were 309% and 113% higher in juveniles ($p < 0.001$, $\beta = 0.60$, and 0.001 , $\beta = 1.32$, respectively), and LA (an indicator of more terrestrial prey) was marginally (0.7%) higher in adults ($p = 0.03$, $\beta = -0.19$) (figure 2.1, Tables 2A, 3A).

Table 2.3. Results from linear mixed effects models comparing stable isotopes and fatty acid biomarkers to location, proximity, year, and, for fatty acids, age. All models included a unique ID for the colony as a random effect.

Response	Explanatory variable	Estimate	SE	p-value	Marginal r^2	Conditional r^2
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<i>Biomarker: stable isotopes</i>						
PC1	Location	-0.37	0.19	0.06	0.22	0.59
	Proximity	-0.21	0.19	0.29		
	Year	-0.13	0.09	0.16		
<i>Biomarker: fatty acids</i>						
EPA	Location	0.09	0.61	0.88	0.42	0.61
	Proximity	1.10	0.59	0.06		
	Year	1.66	0.33	<0.0001***		
	Age	0.48	0.43	0.26		
DHA	Location	0.02	0.16	0.92	0.45	0.52
	Proximity	-0.9	0.15	0.55		
	Year	0.34	0.09	<0.0001***		
	Age	0.60	0.15	<0.0001***		
ARA	Location	-0.78	0.35	0.02*	0.48	0.54
	Proximity	-0.65	0.34	0.05*		
	Year	0.83	0.18	<0.0001***		
	Age	1.32	0.33	<0.0001***		
ALA	Location	-0.14	0.10	0.17	0.21	0.26
	Proximity	0.02	0.09	0.84		
	Year	0.24	0.05	<0.0001***		
	Age	-0.19	0.10	0.07		
LA	Location	-0.14	0.10	0.13	0.23	0.35
	Proximity	0.01	0.09	0.61		
	Year	0.24	0.06	<0.0001***		
	Age	-0.19	0.10	0.03*		
Signif. codes: <0.05*, <0.01**, <0.005***						

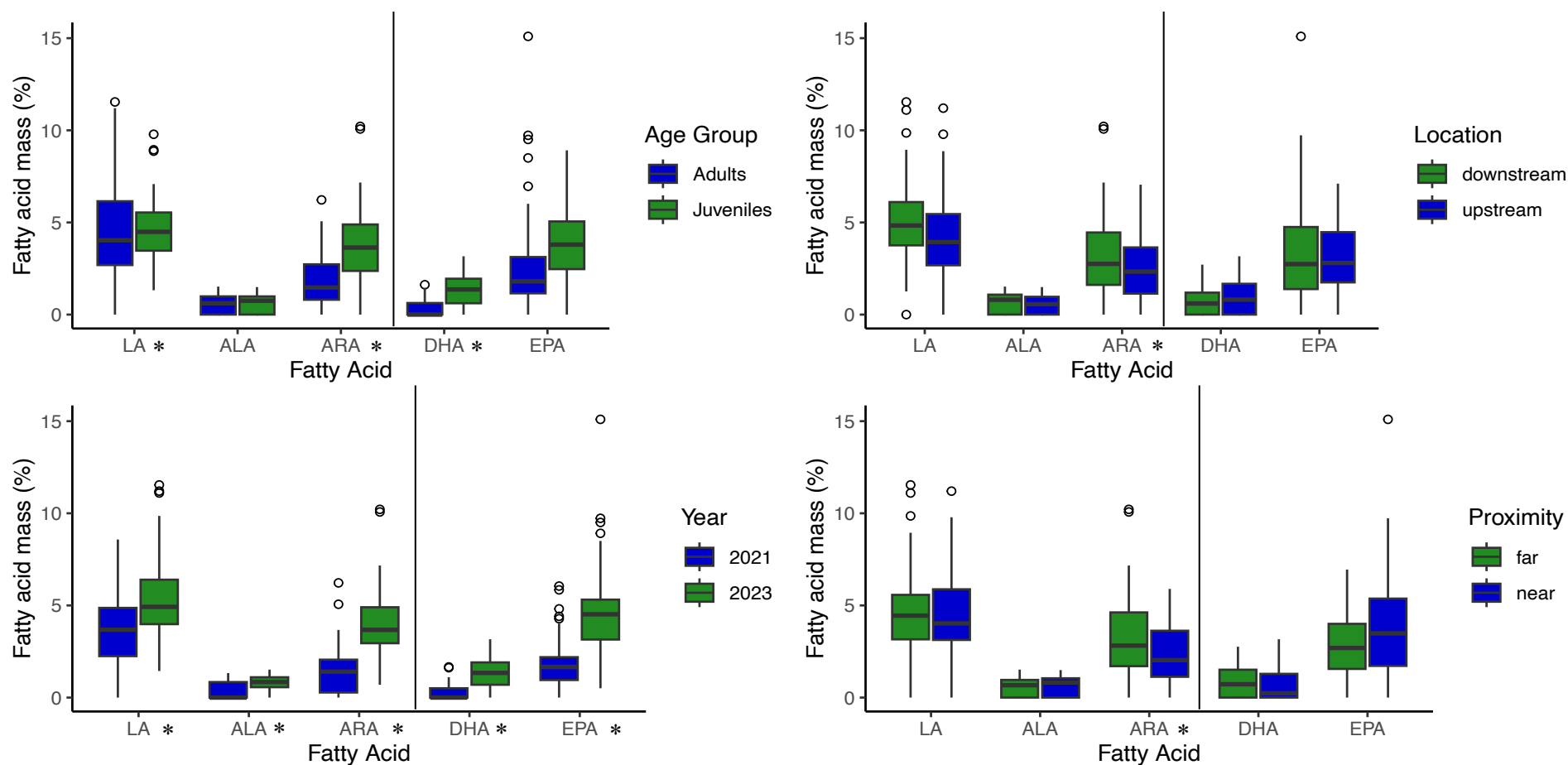


Figure 2.3. Mass % of omega-3 and omega-6 fatty acids analyzed from blood plasma from adult and juvenile Bank Swallows along the Peace River. Top left represents differences in mass % of each fatty acid by age group, top right represents differences in mass % by location, bottom left represents differences in mass % by year, and bottom right represents differences in mass % by proximity. High quality, aquatic based omega-3 fatty acids DHA and EPA are separated by a vertical line in all figures. Asterisks (*) are next to each significant fatty acid in each individual linear mixed effect model.

Table 2.4. Results from linear mixed effects models assessing fatty acid biomarkers to location, proximity and year between adults and juvenile Bank Swallows. All models included a unique ID for the colony as a random effect.

Response	Explanatory variable	Estimate	SE	p-value	Marginal r ²	Conditional r ²
<i>Adults</i>						
EPA	Location	-1.74	1.37	0.20	0.38	0.72
	Proximity	2.08	1.37	0.13		
	Year	1.77	0.68	0.009**		
DHA	Location	-0.08	0.14	0.58	0.28	0.35
	Proximity	-0.26	0.14	0.06		
	Year	0.20	0.07	0.006**		
ARA	Location	-1.13	0.46	0.01**	0.34	0.43
	Proximity	-0.23	0.45	0.61		
	Year	0.62	0.23	0.008		
ALA	Location	0.34	0.16	0.04*	0.30	0.38
	Proximity	-0.006	0.16	0.97		
	Year	0.24	0.08	0.002***		
LA	Location	-1.67	1.03	0.11	0.27	0.43
	Proximity	0.07	1.02	0.95		
	Year	1.25	5.21	0.02*		
<i>Juveniles</i>						
EPA	Location	0.41	1.25	0.75	0.32	0.66
	Proximity	0.90	1.24	0.47		
	Year	1.40	0.65	0.03*		
DHA	Location	0.37	0.26	0.15	0.31	0.36
	Proximity	0.06	0.26	0.79		
	Year	0.06	1.49	0.00003***		
ARA	Location	-0.30	0.78	0.69	0.37	0.51
	Proximity	-1.30	0.78	0.09		
	Year	1.45	0.43	0.0008***		
ALA	Location	0.05	0.17	0.78	0.16	0.24
	Proximity	0.15	0.17	0.37		
	Year	0.22	0.10	0.02*		
LA	Location	0.20	0.68	0.76	0.15	0.28
	Proximity	0.31	0.68	0.63		
	Year	0.76	0.38	0.04*		
Significance codes: <0.05*, <0.01**, <0.005***						

Assessing only the juvenile Bank Swallows revealed no differences in LA, ALA, ARA, EPA or DHA input based on location (upstream vs. downstream) or proximity (Table 2.4), indicating that juvenile Bank Swallows were consuming a similar diet to each other in terms of fatty acid input despite relative rearing location to the Site C dam. Assessing only Bank Swallow adults revealed that fatty acid input did not change based on proximity, however adults nesting downstream from the dam construction had on average higher inputs of both ARA and ALA (Figure 2.2).

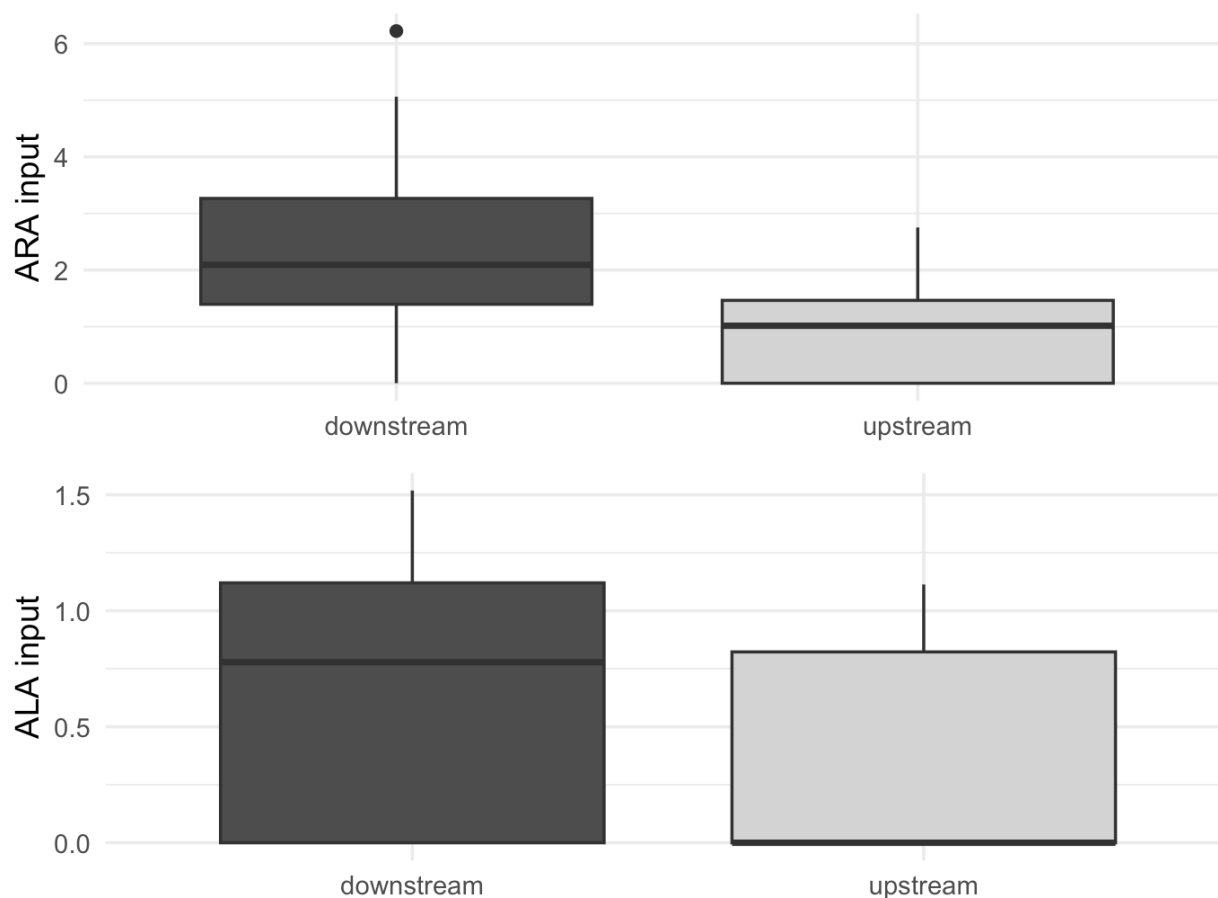


Figure 2.4. Differences in LCPUFA in Adult Bank Swallows based on nesting location. Top: Adult Bank Swallows nesting downstream from Site C have higher Arachidonic acid (ARA) input than adults nesting closer to the dam. Bottom: Adults nesting downstream from Site C have higher Alpha-linolenic acid (ALA) input than adults nesting upstream from the dam.

DISCUSSION

As aerial insectivores, Bank Swallows are highly dependent on the availability and composition of insect prey, making them particularly vulnerable to changes in ecosystem function driven by environmental disturbance. Large scale anthropogenic projects, such as the construction of the Site C dam, have the potential to impact aquatic food webs, ultimately influencing diet quality for consumers. For Bank Swallows, who rely heavily on aquatic insects to provision their offspring, changes to diet may negatively impact offspring growth and survival, putting an additional stressor on a rapidly declining Species at Risk.

This study demonstrates the effectiveness of examining dietary components through LCPUFA analysis, as evaluating stable isotopes alone provided limited resolution of diet differences among juvenile Bank Swallows. At best, the weak, non-significant difference ($p = 0.06$) in PC1 scores between upstream and downstream colonies may suggest a more aquatic based diet among upstream juveniles. This lack of a clear isotopic signal may reflect several limitations. First, the isotopic composition of aquatic and terrestrial insects in this system may overlap, reducing the ability to discriminate between prey types using stable isotope analysis (Evans et al., 2017). Second, isotopes integrate diet over relatively broad time scales, potentially obscuring finer-scale or short-term dietary differences among individuals or sites (Hobson & Clark, 1992). In contrast, LCPUFA profiling provided a more robust assessment of diet in juvenile and adult Bank Swallows. Both the MANOVA, which included all five fatty acids, and individual LMMs for each fatty acid indicated that there were key differences in diet across years, ages, location, and proximity. In particular, fatty acid profiles consistently differed between 2021 and 2023 and between adults and juveniles.

Several factors may explain the differences in LCPUFA levels between years. Because EPA, DHA, ARA, LA, and ALA can all be synthesized within aquatic ecosystems, my results suggest that aquatic input into the swallow diet was lower in 2021 compared to 2023. The environmental drivers behind the higher dietary quality observed in 2023 remain unclear. This finding contradicts my original prediction, as wetland drainage and water diversion, to my knowledge, occurred after 2021, and as such we would expect a lower abundance of aquatic insects in 2023. Previous studies have shown that variables like total phosphorous (Heino, 2008)

and dissolved organic carbon (DOC) concentrations (Johnson & Goedkoop, 2002) impact community structure in lakes and thus lead to differences in LCPUFA abundance. Supporting this, Kesti et al. (2022) found that stoneflies (Order: Plecoptera) and mayflies (Order: Ephemeroptera)—two key aquatic emergent insect groups—were more abundant in lakes with lower phosphorus and lower DOC, conditions that may enhance the availability of high-quality, LCPUFA-rich prey. Although I lack water quality and prey abundance data for this study, it is well established that intensified land use can increase DOC concentrations in watersheds (Shang et al., 2017). It is possible that intense habitat alterations such as the deforestation along the channels would increase phosphorus and DOC levels in a particular year, causing shifts in primary producers and ultimately decreasing the abundance of aquatic emergent insects (Environment & Climate Change Canada, 2010).

Another possible reason for this unexpected result could be due to decreases in only certain taxa of aquatic insects. Recent studies have demonstrated that stream alterations often reduce the abundance of sensitive insect orders such as Ephemeroptera, Plecoptera, and Trichoptera, while promoting disturbance-tolerant taxa such as Diptera (Raitif et al., 2019, Kennedy and Turner., 2011), which may increase under altered conditions. The elevated aquatic input observed in 2023 relative to 2021 may therefore be attributable to a higher emergence of aquatic Diptera, but a lower diversity of overall aquatic insects. Incorporating a prey analysis would have substantially strengthened this study by identifying the specific dietary sources of fatty acids.

While it is unclear why these striking differences in diet from LCPUFAs were also not observed in the stable isotope data, these differences highlight the value of complementary approaches to assessing diet quality. Given the ecological changes that will remain unknown until after the Site C reservoir is completed and studied, it is important to characterize interannual variability in dietary patterns to differentiate between natural variation and changes due to anthropogenic impact. This pre-reservoir data may prove useful to inform long-term monitoring of Bank Swallow diet.

In addition to the marked differences in diet quality between years, I also detected differences in LCPUFA intake between juvenile and adult Bank Swallows. The MANOVA revealed distinct overall LCPUFA profiles between age classes, and linear mixed models confirmed that juveniles consumed higher proportions of DHA and ARA—LCPUFAs derived

from aquatic prey—compared to adults. This pattern suggests that adult Bank Swallows may preferentially provision their offspring with higher-quality, LCPUFA-rich diets than those they consume themselves. Twining et al. (2016, 2018) found that higher dietary DHA increases nestling health and fledging success, and a study on Tree Swallows *Tachycineta bicolor* found parents were highly selective in their choice of insect sizes and insect species they fed nestlings (McCarty & Winkler, 1999). Additionally, a study on blue tits *Cyanistes caeruleus* concluded that parents selectively feed their offspring diets with optimized nutrition, possibly selecting for prey meeting requirements for taurine (Arnold et al, 2007). These findings suggest that the observed dietary differences between age groups in Bank Swallows potentially reflect active parental foraging strategies rather than random variation. However, it remains unclear whether adult Bank Swallows consistently consume lower-quality diets than their young, or a context-dependent response to environmental conditions altered by the dam construction.

Interestingly, and opposed to my initial predictions, there were no differences in LA, ALA, ARA, EPA or DHA input for juvenile Bank Swallows based on location (upstream vs. downstream) or proximity, indicating that juvenile Bank Swallows were consuming similar diets to each other in terms of fatty acid input despite relative nesting location to the Site C dam. The consistency in LCPUFA input in juveniles across locations implies that, regardless of nesting proximity to the Site C dam, juvenile Bank Swallows were able to access similarly high-quality prey via parental feeding. This finding may indicate a buffering effect through adult foraging behavior. The lack of differences in LCPUFA profiles across locations, combined with the weak trends in the stable isotope data suggests limited or inconsistent spatial variation in diet during the study period. Considering both the LCPUFA and stable isotope results, these findings reveal the importance of using multiple dietary tracers to assess diet composition and quality.

Contrary to patterns displayed by juveniles, Bank Swallow adults nesting downstream from the dam construction had higher ARA and ALA in their diets than adults nesting upstream from the dam, indicating nesting location may impact diet quality for adults only. Additionally, many adults nesting near site C had no or close to no DHA input in their diets. Contrary to my findings, a previous study on Tree Swallows found that aquatic insects made up the largest proportion of adult prey (Michelson et al., 2018), and adult diet remained relatively consistent compared to nestling diet throughout the season. My results suggest that juveniles are consuming diet made up of larger proportions of aquatic insects than adults, which furthers my hypothesis

that adults may be selectively feeding their young higher quality diet than they themselves are consuming. These results provide preliminary evidence that adult Bank Swallow diet quality may be impacted by their nesting location in relation to the Site C dam construction, and they may be consuming from a broader range of prey than they feed their young. This flexibility in adult feeding behavior could temporarily mitigate the effects of habitat degradation on reproductive success, but it may come at long-term costs to adult health and population viability.

CONCLUSION

The results from this study emphasize the complex ways in which anthropogenic environmental change can affect wildlife diets. Notably, I observed differences in the diet quality of Bank Swallows nesting near dam construction sites across two sampling years. Surprisingly, 2023 showed a much higher-quality diet compared to 2021, suggesting that diet quality does not always decline uniformly with environmental degradation, but rather is shaped by a variety of complex factors. I found that adult Bank Swallows exhibited location-based differences in diet, with those nesting downstream having a higher proportion of ALA and ARA, suggesting a more aquatic diet. In contrast, juvenile Bank Swallows showed no such differences in diet quality based on nesting location, which may imply that adults are selectively provisioning their young, potentially buffering them against the impacts of habitat degradation. However, further research is needed to confirm this hypothesis. Interestingly, while LCPUFA data revealed several diet differences, stable isotope analysis showed little variation in diet. This discrepancy underscores the challenges of assessing diet in rapidly changing ecosystems. Stable isotope analyses, which reflect diet over a 18-29 day period in juveniles, and LCPUFA blood analyses, which provide a snapshot of diet over approximately three days in both juveniles and adults, offer different temporal insights. This suggests that LCPUFA analysis may provide a more accurate representation of current environmental conditions. Ultimately, these findings reinforce the complexity of understanding diet shifts in the face of environmental change and the need for diverse analytical approaches to fully capture these dynamics.

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CHAPTER 3: ASSESSING TRACE ELEMENTS INCLUDING HEAVY METALS IN BANK SWALLOWS NEAR LARGE SCALE DAM CONSTRUCTION

ABSTRACT

Reservoir formation from hydroelectric dam development is well known to cause negative environmental impacts, including through the accumulation of methylmercury in aquatic food webs. However, dam construction itself often spans many years and involves extensive environmental disturbance in or near waterways. These impacts remain relatively understudied compared to those associated with completed reservoirs. The Site C dam in northeastern British Columbia was under construction from 2015 to 2025, representing a decade-long period during which environmental contamination was possible. In this study, I assessed concentrations of 19 trace elements (Ag, Al, As, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Mo, Ni, Pb, Sb, U, V, Zn) in juvenile Bank Swallows reared upstream and downstream of the dam. While overall methylmercury levels were low, suggesting that riverine alterations had not yet led to increased methylmercury accumulation, I detected elevated concentrations of chromium and lead. Thirteen of the trace elements were present in over 75% of sampled individuals. Significant spatial and temporal effects were observed, with higher concentrations of mercury and lead found both upstream and in the 2023 sampling year. These findings underscore the need for continued monitoring of trace elements, particularly methylmercury, following reservoir filling to evaluate the full toxicological impact of dam construction on wildlife.

INTRODUCTION

Large-scale industrial projects pose a suite of environmental threats to local populations of organisms, including habitat loss, ecological degradation, and environmental contamination and exposure to trace elements including heavy metals. While trace elements are naturally present and widely distributed in the environment (Hejna et al., 2018; Tchounwou et al., 2012), human activities such as mining, industrialization, waste disposal, urbanization, and environmental manipulation have significantly elevated their concentrations in affected areas (Singh et al., 2011; Simsek et al., 2021; Tchounwou et al., 2012). Once introduced into ecosystems, these pollutants can accumulate in biological tissues and persist over time, leading to chronic toxicity in wildlife. As a result, trace elements including heavy metals, are among the most insidious environmental threats across the biosphere (Abbasi et al., 2015; Tchounwou et al., 2012).

Some trace elements (e.g., zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn)) are necessary for biological processes in organisms—for example zinc and copper serve as cofactors for enzymes involved in protein synthesis. However, these essential trace elements may become harmful or toxic when they exceed a threshold level. On the other hand, non-essential trace elements, hereafter referred to as heavy metals, serve no biological role and have negative effects on animals even at low concentrations (Ali & Khan., 2019; Balali-Mood et al., 2021; Khwankitrittikul et al., 2024; Kiran & Sharma., 2022; Singh et al., 2011). While heavy metals are naturally present in ecosystems, human activities can magnify their presence in the environment. These heavy metals are persistent and they bioaccumulate in the food web, moving up from autotroph uptake to consumption at the consumer level (Ali & Khan, 2019; De Luca-Abbot., 2001; Sharma & Agrawal., 2005.).

Due to their high degree of toxicity, lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg) rank among the non-essential trace elements of greatest concern. These heavy metals are not necessary for biological processes, and lead, mercury and cadmium are known to bioaccumulate in the body (Collin et al., 2022; Das et al., 2023; Harding et al., 2018). Further, mercury is known to biomagnify as it moves up the food chain in aquatic ecosystems (Ackerman et al., 2016; Brasso & Cristol, 2008; Eagles-Smith et al., 2016.; Kozak et al., 2021; Ma et al 2018), ultimately inducing effects such as organ damage and reproductive failure, even at lower

levels of exposure. Mercury levels are elevated in areas with extensive water management, such as reservoirs, where microbial processes convert inorganic mercury in sediments and soils to bioavailable methylmercury (MeHg) (Alberts et al., 2013; Dumont et al., 1988; Gerrard & St. Louis, 2001; Kardynal et al., 2020). Bioaccumulation of MeHg poses significant risks to wildlife, including birds, by transferring through the food chain and affecting reproductive success and overall health (Cristol et al., 2008; Speir et al., 2014). Similarly, elevated concentrations of cadmium (Cd) can suppress egg production, impair growth, and cause mortality in wildlife (Balali-Mood et al., 2021; Eisler, 1985; Khwankitrittikul et al., 2024). Introduced mainly through wastewater discharges or urban industrial activities, high Cd concentrations often occur close to point sources of contaminated waste. Chromium (Cr) enters the environment through natural weathering and industrial discharge, and exists in two forms: relatively immobile trivalent chromium (Cr(III)) that is essential in small amounts, and the highly toxic hexavalent chromium (Cr(VI)) (Outridge & Scheuhammer, 2022; Prasad et al., 2021) that is a potent environmental hazard, with significant health risks to both wildlife and humans. The highly toxic and persistent heavy metal lead (Pb) is another contaminant that poses serious threats to wildlife, particularly birds, by impairing immune, nervous, and reproductive systems, and causing neurological damage (Swarup & Patra, 2004; Vallverdu-Coll et al., 2019).

Hydroelectric dam construction and reservoir creation are one way that trace elements, including heavy metals, can become more prevalent in the environment (Guo et al., 2023; Muller et al., 2008; Rosenberg et al., 1997). Along the Peace River in northeastern British Columbia, Canada a 9,330-hectare hydroelectric dam and reservoir dubbed “Site C” broke ground in 2015 and was finally completed in 2025. This 10-year project has the potential to introduce pollutants into the natural environment (Guo et al., 2023; Muller et al., 2008). Based on publicly available construction bulletins from 2021-2023, I suspected that the mechanisms of pollutant introduction for this project include but are not limited to: recorded increased sedimentation levels, river diversion and headpond formation upstream—both of which contributed to abrupt fluctuations in water levels—as well as the excavation of approach channels where over 700,000 m³ of potentially acid generating (PAG) bedrock was excavated. Additionally, riparian and shoreline vegetation removal, dam trench excavation, and on-site concrete production (BC Hydro, 2025). Notably, in March of 2023 an exceedance was measured in water discharged from a PAG-containing relocated surplus excavated materials area (RSEM) sediment pond to the Peace River

(BC Hydro, 2024). This included a confirmed exceedance of acceptable environmental thresholds of total cadmium, copper and zinc.

Because trace elements introduced from large industrial sites like Site C are hazardous to terrestrial and aquatic ecosystems (Guo et al., 2023; Muller et al., 2008; Singh et al., 2011; Tchounwou et al 2012), it is critical to assess the level of exposure for vulnerable and at-risk species that could result from this landscape transformation. Elevated levels of mercury, cadmium, chromium, and lead are of particular concern for species foraging in contaminated aquatic habitats. The bioaccumulation of these trace elements can lead to neurological impairment, endocrine disruption, and reduced reproductive success (Ackerman et al., 2016; Ali et al., 2019; Balali-Mood et al., 2021; Brasso et al., 2008; Eagle-Smith et al., 2016; Gerrard & St. Louis, 2001). Nesting birds that forage on emerging insects in streambeds may be especially vulnerable, as pollutants accumulate in sediments and ingested by birds can then bioaccumulate and subsequently be transferred to their eggs and offspring. For example, high dietary methylmercury exposure can decrease reproductive success of birds by 35–50%, and can affect cognitive function, immune response, and flight performance, contributing to population declines (Ackerman et al., 2016; Brasso et al., 2007; Seewagen, 2020). Assessing trace element levels in birds may thus have broader applications for their use as effective biomonitors of environmental contamination (Spears et al., 2008).

Bank Swallows *Riparia riparia* are a Threatened species of aerial insectivores in Canada under the federal Species at Risk Act (SARA), and since 1970 have declined in Canada by an estimated 98% (COSEWIC, 2013). Bank Swallows are currently still declining at a rate of -4.9% per year across North America (Sauer et al., 2017), the second greatest decline of all aerial insectivores behind Black Swifts *Cypseloides niger* (Sauer et al., 2017). The Peace River where the Site C dam is located supports one of the largest populations of Bank Swallows in British Columbia, Canada (Howie, 2015). The species decline, combined with their suitability for studying contaminants, makes them an ideal subject for examining the potential environmental effects of dam construction and its impact on wildlife.

I examined heavy metal signatures from Bank Swallow feathers to evaluate the accumulation of trace elements and heavy metals present in the environment surrounding the Site C construction. Feathers are formed during a bird's growth period and are directly linked to blood circulation. Therefore, they serve as an effective medium for assessing exposure to trace

elements, including heavy metals (Yao et al. 2023). Measurements of various heavy metals in feathers are a reliable indicator of the level of exposure to metals during the time of feather growth in Passeriformes (Aziz et al., 2021; Dauwe et al., 2000; Durkalec et al., 2022; Dmowski and Golimowski, 1993; Iemmi et al., 2021; Innangi et al., 2019; Janeydeh et al., 2016; Markowski et al., 2013), raptors (Gruz et al., 2019), columbids (Asgari et al., 2024), and waterbirds in the Ciconiidae, Threskiornithidae, and Anatidae Families (Varagiya et al., 2021). Adult Bank Swallows moult and regrow their feathers during their migration and non-breeding seasons, so trace element concentrations in adult feathers are representative of these environments (Imlay et al., 2018). In contrast, juvenile Bank Swallow feathers are grown in the burrow on the natal grounds and are representative of conditions on the Peace River, including around Site C.

To assess the potential extent of environmental pollution associated with the Site C development, I assessed concentrations of 19 trace elements (Ag, Al, As, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Mo, Ni, Pb, Sb, U, V, Zn) in Bank Swallow feathers. My primary focus was on the presence of mercury, lead, chromium, and cadmium, as these metals are expected to be present in the environment at elevated levels and are known to pose toxicological risks to avian species. I predict that trace element concentrations will vary with location and proximity to the dam, with juveniles nesting downstream likely accumulating higher concentrations of trace elements and heavy metals. To assess spatial patterns of contamination, feather samples were collected from sites at varying distances both upstream and downstream of Site C. This sampling design allows us to compare trace element concentrations relative to their position along the Peace River, upstream from Site C and downstream from Site C. Most recorded construction occurred at the main Site C construction site and further landscape disturbances (i.e., deforestation, wetland draining, headpond formation) occurred upstream. I also predict that trace element concentrations will differ between juvenile and adult Bank Swallows, reflecting age-related variation in exposure. This comparison will provide insights into temporal patterns of metal accumulation and potential differences in contaminant exposure between overwintering sites and nesting habitats along the Peace River near the Site C development

While many studies have investigated heavy metal accumulation in relation to mining, agricultural, urban, or landfill sites (Abbasi et al., 2015; Asgari et al., 2024; Durkalec et al.,

2022, Eagles-Smith et al., 2022; Simsek et al., 2016; Swarup & Patra, 2005), studies of heavy metal accumulation near dam sites is limited, besides mercury (Guao et al., 2023; Muller et al., 2008). Research about heavy metal accumulation in aerial insectivores is also limited, with no research available specifically on Bank Swallows. To my knowledge, this is the first study that investigates trace element and heavy metal accumulation in Bank Swallows in relation to large-scale dam construction.

METHODS

Field Methods

The goal of my field work was to collect body samples that would allow us to assess 19 trace elements in a population of Bank Swallows nesting along the Peace River. To accomplish this, I collected feather and blood samples from both adults and juveniles at breeding colonies from approximately Hudson's Hope (56°06'51"N, 121°46'53"W) to the British Columbia–Alberta border (56°07'27"N, 120°03'24"W), (Figure 3.1).

At each colony, I set up 1-2 mist nets in front of each cluster of identified nesting burrows to catch both juvenile and adult Bank Swallows. I determined the sex and age of each adult bird based on the presence of a brood patch (females) or cloacal protuberance (males). Juveniles were identified by a yellow gape on bill and/or plumage characteristics; it is not possible to visually determine their sex. I collected two rectrices or tail feathers (R3) from each individual, and one was used for heavy metal content analysis (the other feather was used for stable isotope analysis, Chapter 2). After banding and sample collection, I released the swallows back to their colonies.

Along the stretch of river that comprised the study area, I divided the colonies where sampling occurred into two main groups for comparison: 1) Upstream vs. Downstream of the Site C dam, and 2) Near vs. Far from the dam. Upstream, "near" colonies were within 30 km of the dam, while "far" colonies were located beyond that. Downstream, "near" colonies were within 35 km, and "far" colonies were located further out (Figure 3). These categories were chosen based on natural colony groupings while maintaining a minimum 10 km-gap between "near" and "far" colonies—this approach reduces the likelihood of overlap in foraging areas, as Bank Swallows typically forage within 1 km of their burrows (Saldanha 2016).

Due to weather, annual variability in the locations of active breeding colonies, limited access to some parts of the river in 2023 as a result of ongoing construction for Site C, there was variation in the specific sampling sites between years. Among the 188 total feather samples analyzed for this study, there were between 5-40 feather samples for each category of interest (Table 3.1). One colony was part of an active construction zone in an artificial berm established to support the construction work and was next to a containment pond; all other colonies were natural in banks of the Peace River.

Table 3.2. Summary of sampling categories for each Bank Swallow feather collected and analyzed for heavy metals. A total of 188 feathers was analyzed from the Peace River (British Columbia, Canada) breeding colonies. Feathers are categorized twice to capture both location and proximity.

Sampling Year		2021		2023		
Bird Age Class		Adults	Juveniles	Adults	Juveniles	Total
Colony Location	Upstream	29	22	8	40	99
	Downstream	38	5	22	24	89
	Total	67	27	30	64	188
Colony Proximity	Close to dam	35	5	10	24	74
	Far from dam	33	22	19	40	114
	Total	68	27	29	64	188

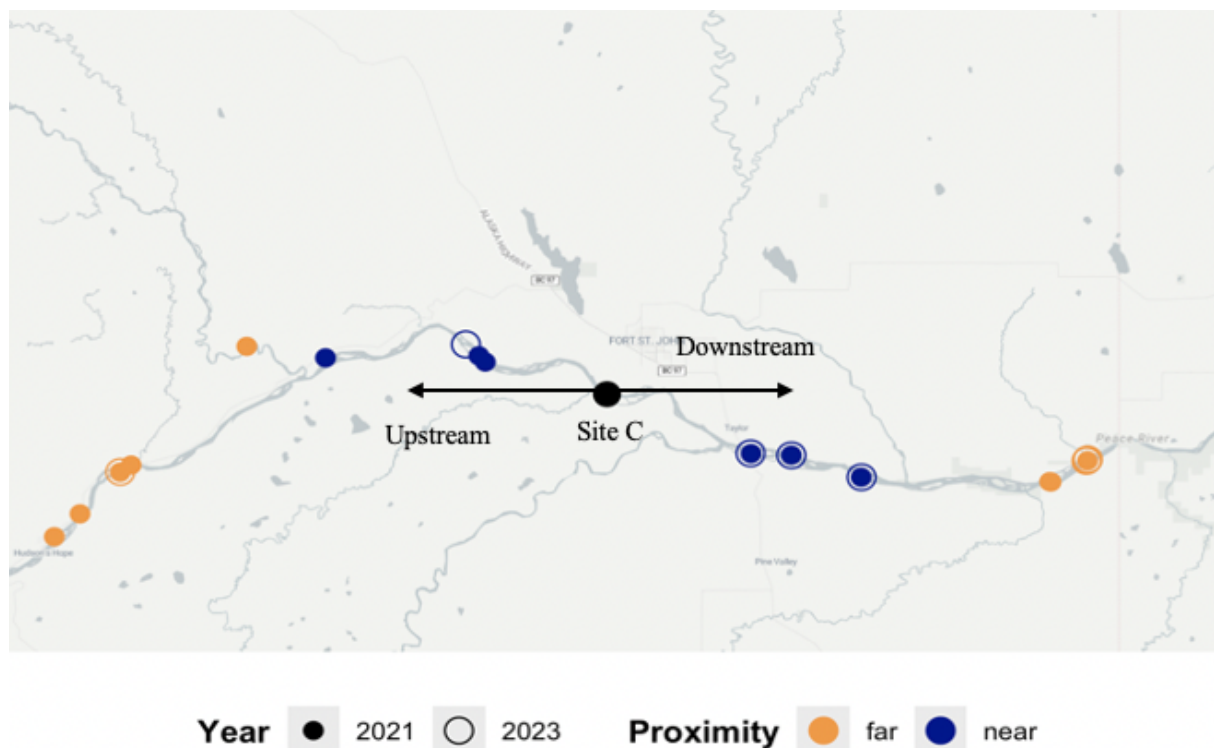


Figure 3.1. Map of study site on the Peace River with sampling locations on either side of the Site C dam development. Sampling locations are depicted as solid bullets for 2021 and open circles for 2023; some colonies were sampled in both years. Colours represent colonies “far” from the dam (> 30 km upstream from the dam, > 35 km downstream from the dam), and “near” to the dam (<30 km upstream from the dam, < 35 km downstream from the dam).

Laboratory Methods

“Heavy metal” is a broad term that traditionally describes a group of naturally occurring metallic elements of high molecular weight and density compared to water (Fisher & Gupta., 2024). This term has been used interchangeably with “trace element” in the past, however many trace elements do not possess the typical chemical properties of heavy metals making the definition of “heavy metals” somewhat undefined.

The trace elements chosen for assessment in this study (Table 3.2) include some that are both non-essential trace elements and heavy metals (e.g., Ag, Pb, etc.), and others that are only non-essential trace elements (e.g. V). Not all heavy metals exhibit the same toxicological profiles; some elements such as aluminum (Al) and antimony (Sb) typically require prolonged

and elevated exposure to elicit physiological effects. For this reason, my assessments of "heavy metals" are focused on non-essential trace elements that can cause physiological impacts at low concentrations (As, Cd, Cr, Hg, Pb, Ni). All other elements will be assessed as trace elements with the assumption they may cause physiological impacts at high concentrations or chronic conditions. This approach allows for meaningful comparisons between elements with similar toxicological profiles, rather than conflating elements like Pb and Al, which differ significantly in their physiological impact thresholds.

Table 3.2. Classification of 19 trace elements assessed in this study based on their biological role and chemical characteristics. Elements are categorized as essential, non-essential, or heavy metals. Some elements fall into multiple categories (e.g., heavy metals that are also non-essential).

Trace element	Abbreviation	Essential trace element	Non-essential trace element	Heavy metal
Silver	Ag		✓	✓
Aluminum	Al		✓	✓
Arsenic	As		✓	
Barium	Ba		✓	✓
Cadmium	Cd		✓	✓
Cobalt	Co	✓		
Chromium*	Cr	✓	✓	✓
Copper	Cu	✓		
Iron	Fe	✓		
Mercury	Hg		✓	✓
Magnesium	Mg	✓		
Manganese	Mn	✓		
Molybdenum	Mo	✓		

Nickel	Ni	✓	✓
Lead	Pb	✓	✓
Antimony	Sb	✓	
Uranium	U	✓	
Vanadium	V	✓	
Zinc	Zn	✓	

* Cr(III) is essential but relatively immobile, Cr(VI) is highly toxic. ICP-MS cannot differentiate between the two different oxidation states. Erring on the side of caution for the sake of this study, we are considering Cr concentrations to be Cr(VI).

Sample Preparation

I weighed the 188 R3 feather samples using an analytical balance, and then rinsed each sample in a 2% nitric acid (HNO₃) solution with a purity ranging from 68% to 70% from Millipore Sigma Canada Ltd. (Oakville, Ontario, Canada) diluted with high-purity water with a conductivity exceeding 18 MΩ cm⁻¹ generated using a Milli-Q purification system (Millipore, Billerica, MA) to remove any contaminants that may have been present on the feather surface. Next, I transferred each sample into Teflon microwave digestion vessels. The samples underwent digestion using 4 mL of concentrated nitric acid (HNO₃) using the Multiwave Go digestion system (Anton Paar, USA INC.) by ramping the temperature incrementally to 200°C over 20 minutes, followed by a 10-minute incubation period at 200°C. Post digestion, I allowed the samples to cool to room temperature before transferring them to 50 mL Falcon tubes. I then diluted the samples with 10 mL of 2% nitric acid before filtration. Lastly, the resulting filtrate was diluted to 50 mL with 2% nitric acid. This preparation protocol ensured uniform treatment of all samples and minimized potential sources of variability.

Instrumentation

I measured heavy metal concentrations of each sample using the Agilent 7900 single quadrupole ICP-MS, operated in both He and H₂ modes and controlled by the Mass Hunter Workstation software developed by Agilent Technologies. Sample uptake was performed by the

Agilent SPS4 autosampler. This sample introduction system included: a peristaltic pump, a concentric Micro Mist nebulizer, a Scott-type quartz double-pass spray chamber, a standard quartz ICP torch equipped with a 2.5 mm inner diameter injector, an Ni-plated sampler and skimmer cones, and an x-Lens ion lens. Operating parameters were established based on the FDA Elemental Analysis Manual (EAM) method 4.7, with necessary adjustments as detailed in Table 9B (Appendix B). To ensure precision and accuracy, I optimized the operating parameters of the ICP-MS during the startup procedures. Internal standard calibration was employed to determine the concentration of each trace element of interest. A multi-element stock solution, including the internal standard mix, and environmental calibration standard procured from Agilent Technologies Inc. (Mississauga, ON) was introduced online to correct for instrumental drift.

Method Validation

Calibration standards were prepared by diluting the environmental calibration mix (Agilent Technologies, Inc.) with reagent water containing 2% HNO₃ and 0.5% Analytical reagent-grade hydrochloric acid (HCl) with a purity of 37% sourced from Millipore Sigma Canada Ltd. (Oakville, Ontario, Canada).

Five concentration levels of each trace element, ranging between 0.1 and 100 µg/L, were analyzed to assess the linearity of the method. Calibration curves were generated using the Agilent Mass Hunter software and confirmed within ±10% error using a mid-range standard (i.e., 10 µg/L for trace metals) derived from a separate stock solution. A mid-range calibration standard was analyzed as a sample at regular intervals during analysis (i.e., every 7 samples) to monitor instrumental drift, which was maintained within ± 20% of the initial measurement. Additionally, an instrument blank sample (reagent water) and method blank were analyzed regularly to identify sample carry-over and cross-contamination, respectively. Failure to meet performance limits necessitated instrument recalibration or reoptimization.

To obtain precise measurements for each trace element, digested samples were analyzed using ICP-MS, with each sample run through the instrument three times for accuracy. I applied Pearson's R correlation analysis to assess the consistency of measurements across the three runs, with the runs themselves as the explanatory variables and the measurements as the response. All

trace elements returned a P -value < 0.001 , except selenium (Se) (see Table A8-appendix) — that indicated that results of the three runs for each metal were highly correlated, i.e. that consistency was statistically significant. That is to say, the measurements across the runs are reliable and consistent. In contrast, selenium returned a P -value > 0.001 , suggesting that the three runs were not statistically consistent. For this reason, selenium was excluded from the analysis below. A mean value for all other heavy metals for each individual bird was thereafter determined and used in subsequent analyses.

Replicate Samples

In recent years the use of feathers to measure heavy metals and Hg exposure has been criticized, partly due to the possibility of high variation in accumulation of contaminants within and among feathers from the same bird (Low et al. 2019; Peterson et al. 2019; Whitney and Cristol 2017). However, the use of feathers for assessing accumulated contaminants is still popular because it is a relatively non-invasive and non-destructive way to assess accumulation in bird individuals and populations. To address the possibility of high intra-individual variation, I assessed two R3 feathers from eight Bank Swallows to compare the similarity of values. Each sample was prepared and run through ICP-MS following identical protocols. I compared results for R3 feathers of the same bird using a Wilcoxon rank-sum test (table A7). I found that 19 of the 20 element pairs (all except Mg) returned p -values > 0.05 , showing that trace element concentrations among feathers from the same individual provided statistically similar values.

Statistical Analyses

All statistical analyses were conducted using the software R (version 4.4.3; R Core Team, 2024), using the packages *dplyr*, *car*, and *tidyr* within RStudio (version 2024.09.0+375). Figures were generated using *ggplot2* and *ggmap*. I performed post-hoc tests to ensure that the assumptions of MANOVA and GLM described below were met.

Trace Element Accumulation Around Site C

The goal of these analyses was to assess the distribution of trace elements along the Peace River, and determine if trace element burden on juvenile Bank Swallows depends on

proximity or location in reference to Site C. I also intended to assess whether non-essential heavy metals of concern, i.e., chromium (Cr), lead (Pb), mercury (Hg), and cadmium (Cd), were present and accumulating in the population.

First, I conducted two Multivariate Analyses of Variance (or MANOVA) on juvenile feather data: one test to assess trace element differences, and one to assess more toxic heavy metal element differences. adult feather data were omitted from this analysis since adult feathers are grown on the non-breeding grounds and would not be representative of trace element concentrations around Site C. Data were log-transformed to satisfy the assumptions of normality for the MANOVA. The first MANOVA assessed 12 trace elements of low concern (Mg, Al, V, Mn, Fe, Co, Mo, Cu, Zn, Ag, Sb, Ba) as the response with proximity (near, far), location (upstream, downstream) and year (2021, 2023) as categorical predictor variables. The second MANOVA assessed six “non-essential” trace elements (Cr, As, Ni, Cd, Pb and Hg) as the response with proximity, location, and year as predictor variables. MANOVA enables the assessment of the overall pattern of accumulation of multiple heavy metals as dependent variables simultaneously, while accounting for their potential correlations. Selenium (Se) was removed from this analysis due to the lack of consistent replication among each run. Each statistical test was run twice, once including outlier values that were identified by visual inspection, and once without; Table (3B-6B Appendix B) presents the results for the MANOVA with/without the outliers. Significant differences for MANOVA tests were determined at a 95% confidence level ($\alpha = 0.05$).

Second, I ran general linear models (GLMs) on juvenile feather data to evaluate how predictor variables influenced concentrations of the four specific heavy metals (Hg, Pb, Cd, and Cr). Each GLM assessed the concentration of a heavy metal as the response with proximity, location and year as the predictor variables. GLMs allow for analysis of each heavy metal separately, to test hypotheses about the accumulation of each metal independently, while accounting for the effects of other variables. To address the fact, I conducted multiple comparisons and reduce the risk of Type I errors, I applied Bonferroni correction, adjusting the significance threshold to a 98.75% confidence level ($\alpha \leq 0.0125$).

Trace Element Accumulation Between Site C and Non-Breeding Grounds

The goal of my secondary analysis was to determine whether trace element concentrations differ between juvenile and adult Bank Swallows, reflecting potential differences in contaminant exposure between overwintering sites and nesting habitats along the Peace River near the Site C development. To address this, I performed similar analyses as described above.

I conducted two MANOVAs to compare the accumulation of heavy metals between adults and juveniles. Again, the response variables were either the 13 trace elements of lesser concern and the six non-essential trace elements with an age variable (adult, juvenile) as the response. Sex was removed as a factor in this analysis as it was not significant in my preliminary analysis. This comparison was used as a proxy to determine if there are differences in accumulation between the Peace River around Site C (juvenile feathers) and on non-breeding grounds (adult feathers). Similarly to the first MANOVAs, each statistical test was run twice, once with outlier values and once without (Table x). Significant differences for MANOVA tests were determined at a 95 % confidence level ($\alpha \leq 0.05$). Consistent with the above analyses, individual GLM models were run for mercury, lead, cadmium, and chromium to compare the differences between adults and juveniles.

RESULTS

Trace Element Accumulation Around Site C

Initial exploratory analysis revealed that 13 of the 19 trace elements studied, including Mg, Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, Ba, Pb, and Hg, were present in detectable amounts in the feathers of over 75% of the juvenile Bank Swallows sampled around Site C (Table 1B). Eleven of these trace elements (Mg, Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ba, Hg) were present in over 90% of juveniles. Of these heavy metals, Mg, Al, Mn, Fe, Co, and Cu are essential, Ba is essential in trace amounts, and Cr, Pb, Ni, and Hg are non-essential heavy metals (Figure 3.2). Trace elements that were detected in less than 50% of the juveniles include V, As, Mo, Ag, Sb, and U.

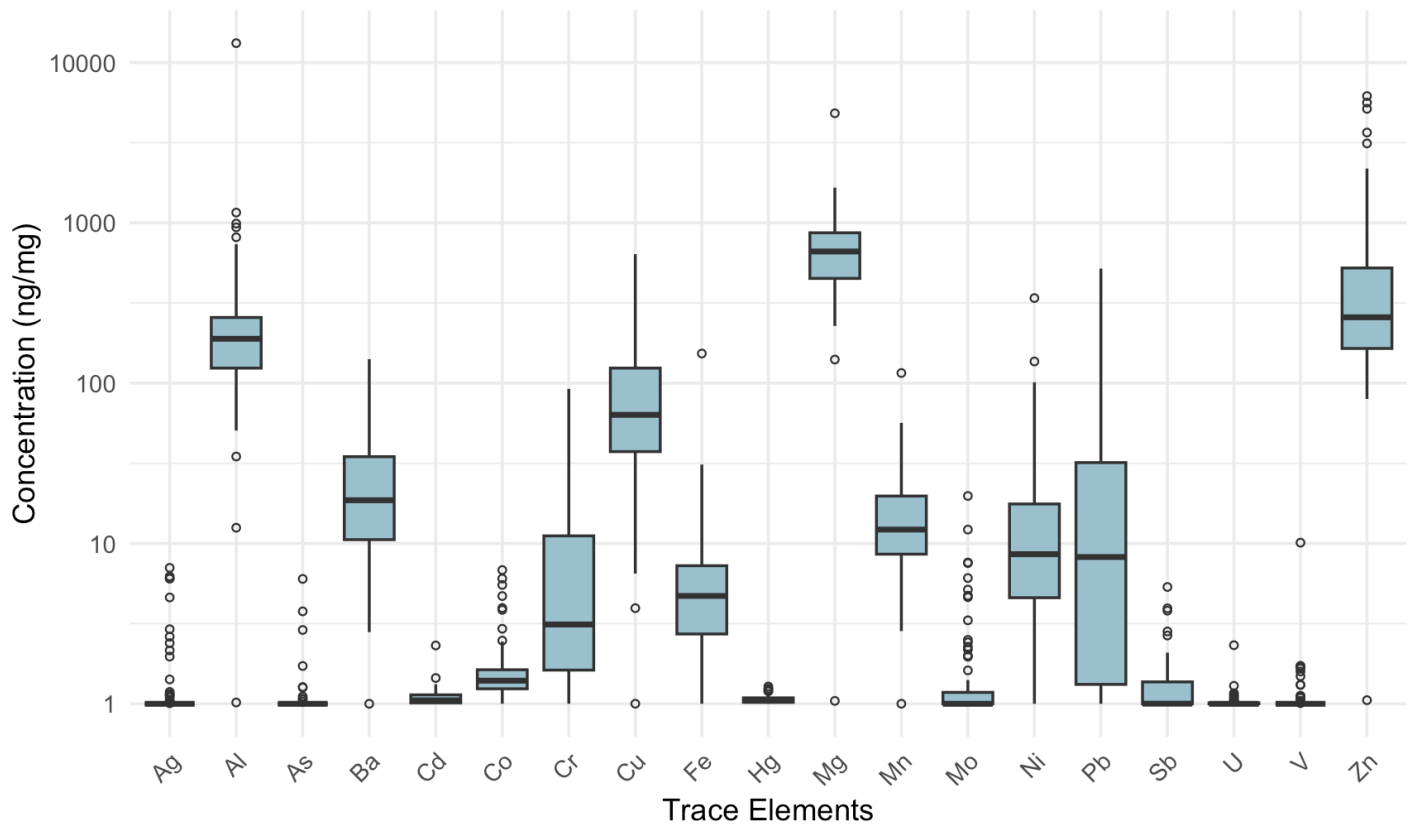


Figure 3.2. Concentration of trace elements in feathers collected during the 2021 and 2023 breeding season from juvenile Bank Swallows along the Peace River (British Columbia, Canada) surrounding Site C. Data displayed with a log transformed axis.

Considering overall concentrations of samples representative of Site C (juveniles), trace elements reached a maximum value of 13,196 ng/mg for Al and a minimum of 0.000,0003 ng/mg for Cd. Some individuals showed concentrations of 0 ng/mg for Ag, As, Cd, Cr, Mo, Ni, Pb, Sb, U & V, indicating that levels were non-detectable. In general, the mean concentrations of each metal in juveniles decreased by the following pattern: $Mg > Zn > Al > Cu > Pb > Ba > Ni > Mn > Cr > Fe > Mo > Sb > Cd > Hg > Ag > U > V > As$.

Table 3.3. Summary statistics for presence of trace elements in feathers of 87 juvenile Bank Swallows sampled in nesting colonies along the Peace River. Values are reported as number of total, observations (N), and observation removed because they were non-detectable, i.e., 0 ng/mg, during analysis (N_{rm}), mean, standard error of the mean (SEM), minimum (min) and maximum(max).

N	Mean	SEM	Min	Max
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	(N _{rm})				
Ag	87	0.380	0.13	0	6.05
	(67)	1.660	0.47	0.009	6.05
Al	87	393.26	150.6	0.02	13196.3
	(0)				
As	87	0.128	0.07	0	5.01
	(77)	1.120	0.52	0.03	5.01
Ba	87	24.752	2.43	<0.001	140.1
	(0)				
Cd	87	0.097	0.017	0	1.31
	(8)	0.107	0.018	<0.001	1.31
Co	87	0.700	0.06	<0.001	5.83
Cr	87	10.361	1.905	0	91.08
	(6)	11.120	2.01	0.001	91.08
Cu	87	97.400	11.06	0.001	636.39
	(0)				
Fe	87	6.583	1.77	<0.001	151.97
	(0)				
Hg	87	0.064	0.006	<0.001	0.28
	(0)				
Mg	87	726.791	58.23	0.043	4817.8
	(0)				
Mn	87	16.333	1.68	<0.001	114.67
	(0)				
Mo	87	0.852	0.28	0	19.03
	(61)	2.831	0.84	0.015	19.03
Ni	87	18.48	4.39	0	338.30
	(1)	18.69	4.44	<0.001	338.30
Pb	87	42.27	9.47	0	517.3
	(18)	53.29	11.58	0.005	517.3

Sb	87	0.33	0.07	0	4.35
	(43)	0.64	0.13	0.002	4.35
Se	87	5.09	0.46	0	26.69
	(10)	5.76	0.46	<0.001	26.69
U	87	0.03	0.016	0	1.32
	(55)	0.08	0.042	<0.001	1.32
V	87	0.16	0.10	0	9.12
	(70)	0.83	0.52	0.01	9.12
Zn	87	687.3	122.8	0.05	6174.8
	(0)				

Trace Elements of Low Concern

Among the concentrations of 12 trace elements (Mg, Al, V, Mn, Fe, Co, Mo, Cu, Zn, Ag, Sb, Ba) occurring in the feathers of juvenile Bank Swallows, I found significant differences between feathers sampled upstream versus downstream of the Site C dam (MANOVA: $F = 2.95$, $p = 0.002$) and those sampled in 2021 compared to 2023 ($F = 2.49$, $p = 0.008$). There were no differences in concentrations based on proximity to the Site C dam. Seven trace elements (Al, Ba, Co, Cu, Fe, Mg, Mn) had detectable concentrations in at least 75% of juveniles, of which five (Al, Co, Cu, Fe, Mn) had a mean concentration at least 10% higher upstream compared to downstream, but no elements had a mean concentration at least 10% higher downstream. Similarly, six trace elements (Al, Co, Cu, Fe, Mg, Mn) had a mean concentration at least 10% higher in 2021 and none had a mean concentration higher in 2023.

Non-Essential Heavy Metals

I found significant differences in the concentrations of six non-essential heavy metals (Cr, As, Ni, Cd, Pb and Hg) year (MANOVA: $F = 2.37$, $p = 0.03$) and differences approaching significance between feathers sampled upstream and downstream from the Site C dam (MANOVA: $F = 2.05$, $p = 0.06$), but not based on proximity. Among the six metals included in this analysis, Cd, Cr, Ni and Hg had detectable concentrations in at least 75% of juveniles. Cd,

Cr, and Hg had a mean concentration at least 10% higher downstream compared to upstream, and Ni and Pb had a mean concentration at least 10% higher upstream compared to downstream. Concentrations of Cr and Hg were at least 10% higher in 2023 compared to 2021.

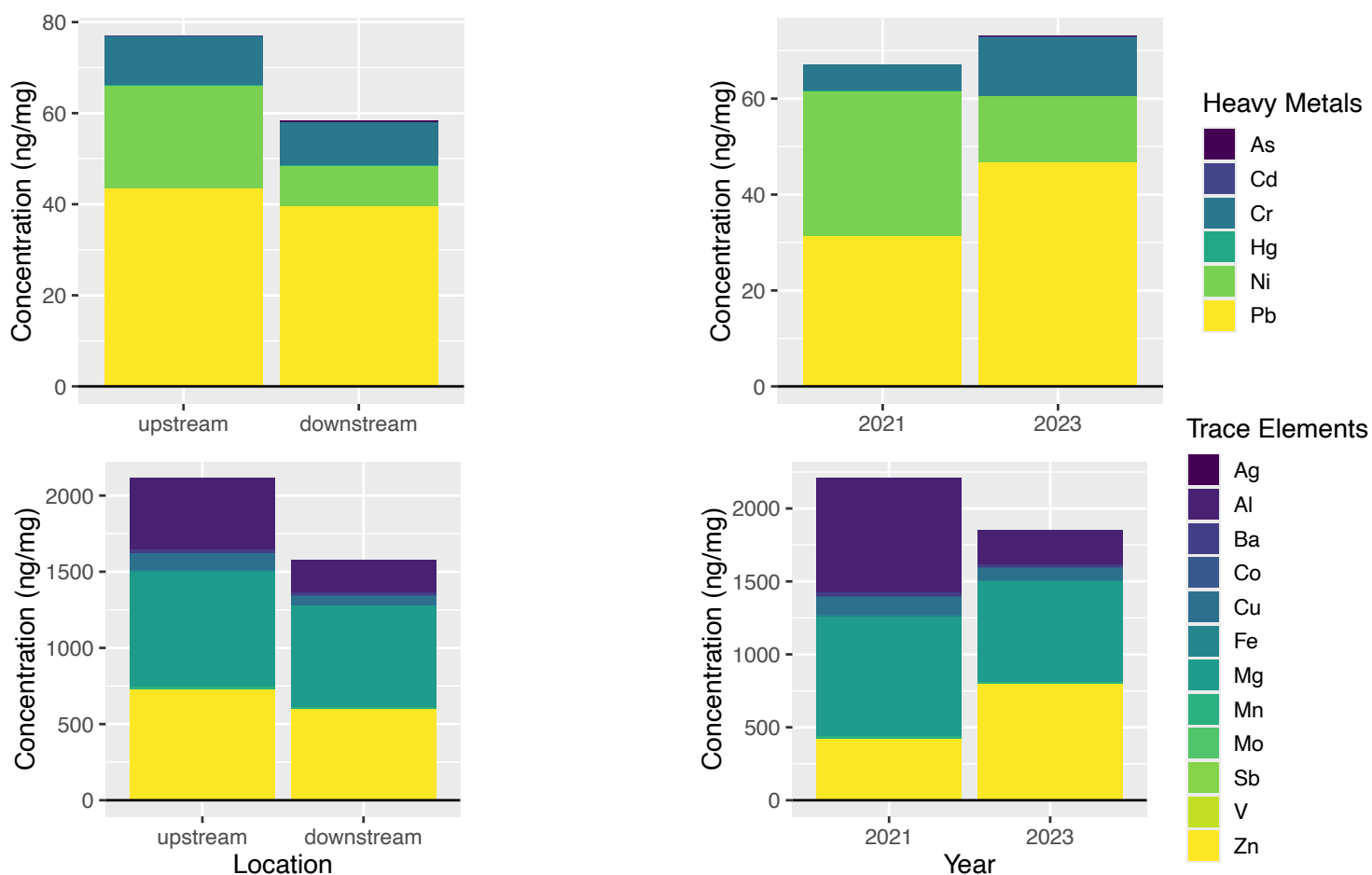


Figure 3.3. Stacked boxplots showing the explanatory variables that significantly impacted trace element distribution. Left column displays differences among locations. Right column displays differences by year. Top row displays non-essential heavy metals and bottom row displays trace elements of low concern including essential trace elements; these groups were analyzed in separate MANOVAs. Data is displayed as non-log transformed raw data.

Among the four trace elements of concern (Cr, Pb, Cd, and Hg) measured in juvenile feathers, I found significant differences for only Cr and Pb in relation to colony location and year (Table 4). Therefore, I focus my presentation of the results on these trace elements. Cr ($F = 7.23$, $p = 0.008$) and Pb ($F = 9.84$, $p = 0.002$) were present in higher concentrations upstream from the Site C construction. Higher concentrations of Cr ($F = 8.58$, $p = 0.004$) and Pb ($F = 10.2$, $p = 0.002$) were also observed at Site C in 2023 compared to 2021. Lastly, Cr ($F = 7.19$, $p = 0.009$) and Pb ($F = 4.93$, $p = 0.03$) both were present in higher concentrations further from the dam construction (Figure 3.2). After Bonferroni correction ($\alpha = 0.0125$), levels of Cr and Pb were significantly different between colony locations, and between years, but only Cr was significant when comparing proximity.

Table 3.4. Results from 16 general linear models (GLMs) comparing concentrations of four trace elements of concern (Pb, Hg, Cd, and Cr) in juvenile Bank Swallow feathers based on location and proximity to the Site C dam in two sampling years.

Variable	Trace element	$\beta \pm SE$	F	p*
Above vs below	Cr	1.13 ± 0.43	7.23	0.008
	Pb	1.44 ± 0.46	9.84	0.002
	Hg	-0.03 ± 0.21	2.88	0.09
	Cd	0.58 ± 0.36	2.50	0.11
Year	Cr	-1.1 ± 0.42	8.58	0.004
	Pb	0.76 ± 0.23	10.20	0.002
	Hg	-0.02 ± 0.11	0.03	0.87
	Cd	-0.30 ± 0.19	2.57	0.11
Proximity	Cr	-1.1 ± 0.41	7.19	0.009
	Pb	-1.00 ± 0.45	4.93	<i>0.03</i>
	Hg	-0.39 ± 0.21	3.36	0.07
	Cd	-0.41 ± 0.35	1.33	0.25

* Bolded p-values are significant at $\alpha = 0.05$ and 0.0125 (Bonferroni correction) and italicized p-values are only significant at $\alpha = 0.05$

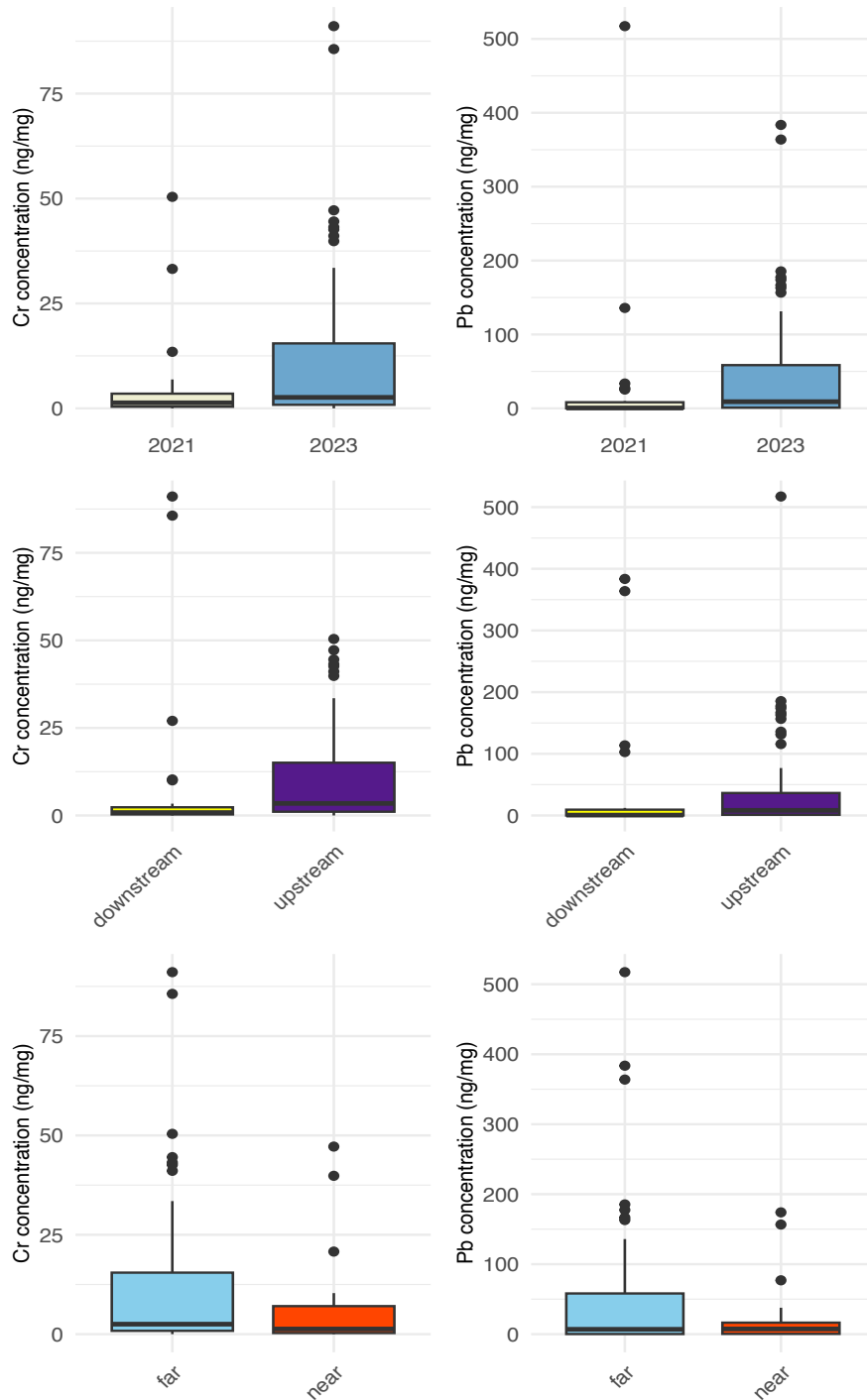


Figure 3.4. Top row: Concentrations of Cr and Pb in juvenile Bank Swallows along the Peace River near Site C for years 2021 and 2023. Higher concentrations of Cr and Pb were found in 2023 compared to 2021. **Middle row:** Concentrations of Cr and Pb in Bank Swallows along the Peace River in nesting locations upstream from Site C and downstream from Site C. Bank Swallows nesting upstream had higher average concentrations of Pb and Cr than downstream. **Bottom row:** Concentrations of Cr and Pb in the Peace River Bank Swallow population with respect to proximity to the Site C construction. Results suggest that there were higher concentrations of Cr and Pb in the colonies that nested further away from the construction, than

the population that nested closer to the Site C construction. Error bars represent the smallest and largest values within 1.5 x IQR from Q1 and Q3. Outliers beyond this range are individual points.

Trace Element Accumulation Between Site C and Non-Breeding Grounds

The same thirteen trace elements that were detectable in the feathers of over 75% of juveniles including Mg, Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, Ba, Pb, and Hg, were also detectable in at least 75% of adult Bank Swallows. Similarly, eleven of the trace elements that were found in detectable amounts in more than 90% of the juvenile samples (Mg, Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ba, Hg) were also found in over 90% of adult samples. Notably, Cr was present in over 90% of juveniles but not adults, while Cd was present in over 90% of adults but not juveniles.

I found differences in the concentration of trace elements and heavy metals in the feathers of juvenile versus adult birds. Adults and juveniles differed in their trace element of low concern composition (MANOVA: ($F = 3.67$, $p < 0.001$), as well as their total non-essential (or heavy metal) composition ($F = 2.90$, $p = 0.008$). Among the four trace elements of concern (Pb, Hg, Cd, and Cr), adult feathers had higher concentrations of Hg ($F = 4.89$, $p = 0.028$) and Cd ($F = 6.99$, $p = 0.009$) (Figure 3.6), however I found no differences in the concentration of Pb ($F = 1.56$, $p = 0.21$) or Cr ($F = 1.57$, $p = 0.211$).

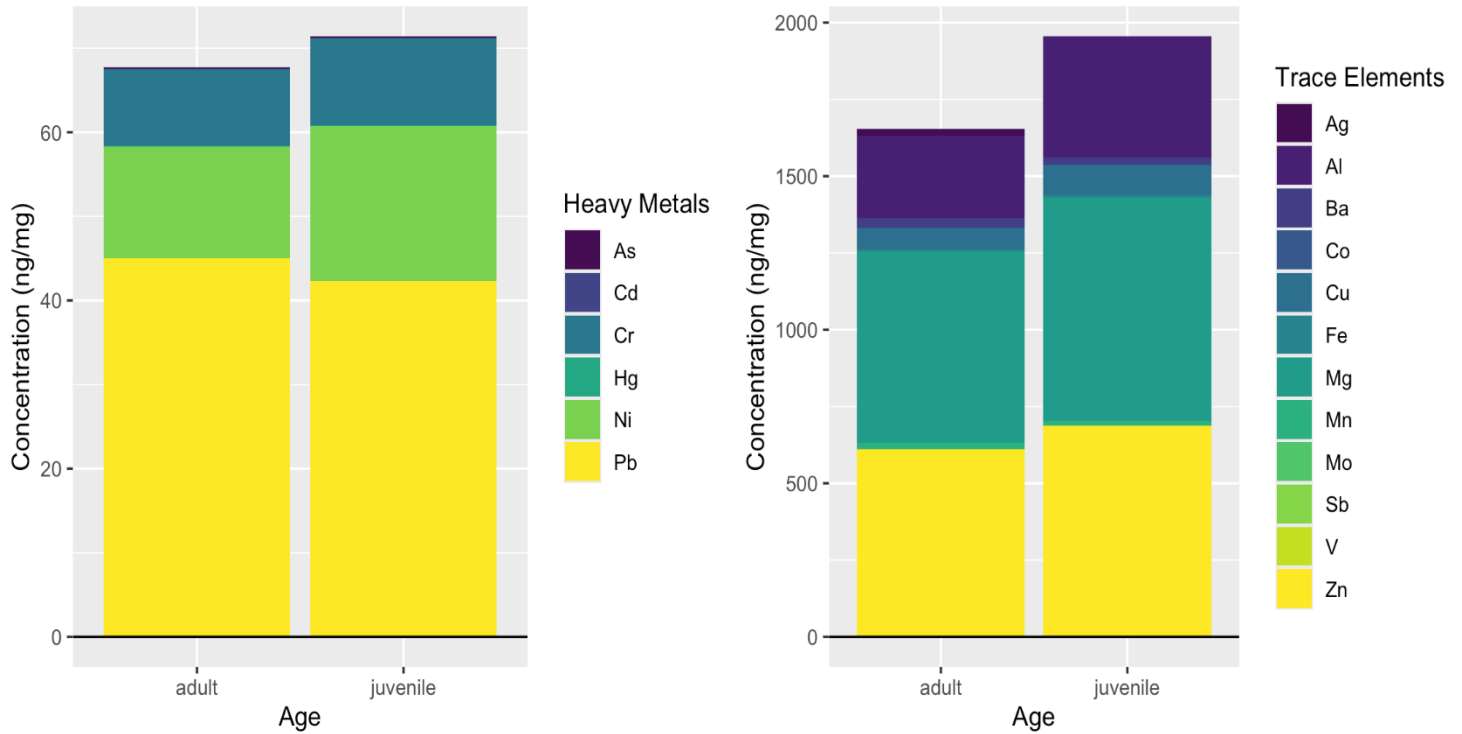


Figure 3.5. Average concentrations of trace elements of low concern (left) and heavy metals (right) between feathers collected from juvenile and adult Bank Swallows. Results indicate that juveniles carried higher burdens of both low concern trace elements, and of non-essential trace elements.

Table 3.5. Results from generalized linear models (GLMs) comparing concentrations of four trace elements of concern (Pb, Hg, Cd, and Cr) between juvenile and adult Bank Swallow feathers.

Trace element	$\beta \pm \text{SE}$	F	p
Cr	0.40 ± 0.29	2.26	0.13
Pb	0.57 ± 0.34	2.92	0.09
Hg	-0.41 ± 0.16	6.25	0.01
Cd	-0.60 ± 0.22	6.99	0.009

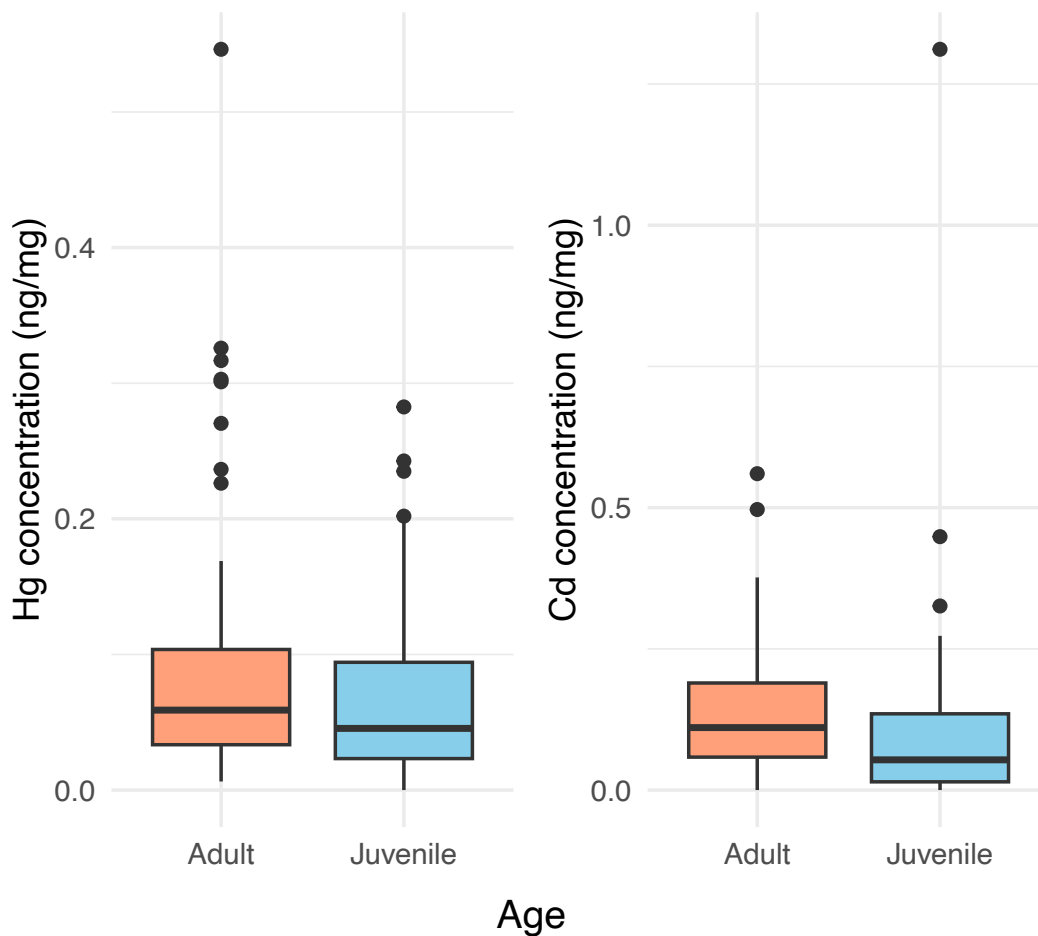


Figure 3.6. Concentration of Hg and Cd in juvenile and adult Bank Swallows. Results indicate that adult Bank Swallow feathers molted during the non-breeding period have a higher average concentration of Hg and Cd compared to juvenile Bank Swallow feathers grown on around the Peace River.

DISCUSSION

Nearly all of the 19 trace elements analyzed were detected in > 75% of feather samples collected from juveniles nesting around site C. Among the elements with high potential for physiological harm Cd, Cr, and Hg, had detectible concentrations in at least 90% of juveniles and Pb was had detectible concentrations in 79% of juveniles. As a group, non-essential heavy metals (Cr, Cd, Hg, Pb, As, Ni) were found in higher concentrations upstream from the dam construction, and in 2023. Trace elements that are only harmful at high concentrations were also found in higher concentrations upstream from the dam construction. One colony sampled upstream in 2023 was a colony in an active construction zone, possibly contributing to the higher contaminant loads overall seen upstream. These differences suggest that the trace element pattern of nestling feathers may reflect local environmental concentrations of trace elements, likely influenced by changes associated with dam construction. Differences in metal burdens in feathers based on nesting location is consistent with previous studies on Barn Swallows where differences in trace element profiles of feathers from different colonies was found (Costanzo et al., 2023).

To fully understand the health consequences of trace element accumulation, it is important to define the concentrations above which each trace element induces sub-toxic behavioral or reproductive effects (Burger & Gochfeld, 2000). I summarized the available information on thresholds for the 19 trace elements in my study in Table 3.6. While some studies define threshold values for wildlife in internal tissues, such as liver or kidney (Adams et al., 2002; Custer et al., 1986; Khwankitrittikul et al., 2024; Rattner et al., 2005; Zaccaroni et al., 2003), a low number of studies set thresholds for feather concentrations, and most of these studies have been conducted on seabirds or raptors (Khwankitrittikul et al., 2024). In addition, many of the elements included in my study (Al, Cr, Fe, Se, Co, Ni, Cu, Ag) have little, outdated, or no previous research regarding toxic thresholds.

While previously reported thresholds (Table 3.6) are not a direct comparison or meant to be used as exact guidelines for Bank Swallow feathers, only lead (Pb) appears to possibly be near any toxicity threshold. Minimum Pb concentrations in raptor feathers associated with some degree of effect ranged from 2.5-9.9 mg/kg (Dauwe et al., 2003) and 2.10 ± 1.57 mg/kg (Khwankitrittikul et al., 2024). I found a mean Pb concentration of 42.3 ng/mg with a maximum

concentration of 517 ng/mg, which is considerably higher than the previous studies. Reported feather Pb toxicity thresholds in literature varies greatly, but it is possible that lead concentrations found in the Peace River Bank Swallows may lead to harmful effects. This may be of particular concern for birds nesting upstream, and in 2023, that had significantly higher concentrations of lead in their feathers, compared to downstream nesting birds and those in 2021.

The concentrations of other trace elements, including heavy metals, in this study are likely currently below any toxicity thresholds that would cause immediate physiological harm. Further, the trace element concentrations in juvenile Bank Swallows are comparable to previous avian trace element studies. For example, arsenic (As) concentrations are usually lower than 1 µg/g in unpolluted sites, and lower than 10 µg/g in polluted sites (Sanchez-Virosta, 2015). The mean As content in juvenile Bank Swallows was 0.12 ng/mg with a maximum concentration reported as 5.01 ng/mg which is below both reported average concentrations. The mean cadmium (Cd) content obtained in the feathers (0.09 ng/mg) was within the range obtained in other raptors studied in Belgium (0.06–0.33 mg/kg) (Dauwe et al., 2003), while in the common buzzard *Buteo buteo* the result was 0.09 ± 0.03 mg/kg (Gruz et al., 2019). The mean content of manganese (Mn) in feathers obtained here (16.33 ng/mg) is like that published by Adout et al., (2007), who found a concentration of 10.8 ± 16.1 mg/kg in sparrows and crows, and by Dauwe et al., who found concentrations of 11.1–15.3 mg/kg in raptors. The mean iron (Fe) content in American Kestrel *Falco sparverius* feathers (223.714 ± 319.090 mg/kg) obtained by Rodreiguez-Alvarez et al. (2022) is similar to that obtained by Dauwe et al. in raptors (44–328 mg/kg). Both studies are generally higher than Fe concentrations found in Bank Swallows (6.58 ng/mg), although some Bank Swallows did exhibit concentrations as high as 151.97. The mean chromium (Cr) content in feathers obtained by Rodreiguez-Alvarez et al (0.823 ± 2.620 mg/kg), and in another study on raptors (Horai et al., 2003) (0.44–3.56 mg/kg) are both lower than my concentrations found in Bank Swallow feathers (10.36 ng/mg), however there is no data on whether these concentrations are high enough to cause negative physiological effects.

Total mercury (THg) concentrations are likely below established toxicity thresholds (Table 3.6), however definitive conclusions regarding potential physiological effects in birds nesting at Site C remain uncertain. Small birds like swallows have shown to be more sensitive to Hg (Fuchsman et al., 2017) and studies on Tree Swallows (Longcore et al., 2007) report that egg

Hg concentrations as low as 0.6-1.0 mg/kg may lead to adverse reproductive effects. This paired with my results suggests a need for a more thorough Hg investigation in this population once the Site C reservoir has been completed. Regarding the other metals analyzed (Mg, Al, Co, V, Cu, Zn, Se, Ag, Sb Mo, and Ba), few authors explore feather analysis of these trace elements. Overall, the wide range in reported toxicity values for all elements, paired with the lack of data in general on certain metals indicates that more laboratory research is needed to determine the tissue levels (including in feathers) that are associated with adverse effect in birds.

Non-essential trace elements Cr and Pb were found at higher concentrations in 2023 compared to 2021. This was expected as construction for the Site C dam was further along in progress at this point. While non-essential trace element concentrations were below toxicity thresholds in 2023, the increase in individual element concentrations over time could indicate that heavy metal concentrations in the environment could continue to rise as construction continues and the reservoir is filled. Hg may be of particular concern due to the flooding of organic-rich soils and vegetation, which promotes microbial activity—particularly by sulfate-reducing bacteria—that convert inorganic mercury into its more toxic and bioavailable form, MeHg.

Overall, juvenile feathers exhibited higher concentrations of all trace elements compared to adult feathers, yet adult feathers had higher concentrations of specifically harmful Hg and Cd. However, these differences remain difficult to disentangle because adult and juvenile feathers represent different environments in this study, and I do not know where the migrating adult Bank Swallows were feeding during the time of feather formation. A possible reason for these differences could be attributed to the differences in volume or type of food ingested between the two age groups. Indeed, adult birds tend to have higher food intake due to the increased energy requirements needed for reproductive activity compared to juvenile birds and are thus potentially more exposed to food-borne contaminants (Janaydeh et al. 2018). No significant differences were found in the levels of trace elements or heavy metals in the feathers between adult male and female samples.

Table 3.6. Average concentration of juvenile Bank Swallow feathers collected along the Peace River compared to known thresholds of trace element toxicity with blood, tissue, feather, and dietary measures.

Element	Mean concentrati on in juvenile feathers (ng/mg) (ppb)	Blood	Feather	Dietary	Study	Species
		Equivalent concentration of lowest observed effects				
Mg	726.8 57.2	No data available		1500 ppm	Harland et al., 1976	Japanese Quail
Al	393.3 26.8					
V	0.16 0.02			25 µg/g dw in kidney	38-2650 ppm	Rattner et al., 2005
Cr	10.4 0.84	18 µg/g dw in liver			Custer et al. ,1986	Common Tern
Mn	16.33 1.6			5 mg/kg	Al-Zubaidy & Mohammad. , 2012	7-12 day old Chicks
Fe	6.6 0.47			200 ppm	McGhee et al., 1965	Poultry Chicks
Co	0.7 (0.06)	No data available				
Ni	18.48 1.31	10 µg/g dw in the kidney and 3 µg/g dw in the liver		≥300 µg/g	Outridge & Scheuhamm er, 1993	Mallard
Cu	97.4 6.7	No data available				
Zn	687.3 56.1	300- 1200 ppm ¹ (other studies say Zn thresholds do not exist)	1200 ppm ²		¹ Gasaway and Buss (1972); ² Khwankitrit tikul at al. (2024)	¹ Mallard Duck ² 37 species including 4 insectivore species
As	0.12 0.01			72 µg/g	Albert et al., 2008	Zebra finch

Se	5.09 0.38	21–31 mg/kg dry wt			Adams et al., 2002	Mallard
Mo	0.85 0.06			>1200 mg/kg	Stafford et al., 2016	Northern bobwhite
Ag	0.38 0.7					
Cd	0.097 0.01	¹ 0.17 mg/kg in liver	² 2 ppm ³ 0.1 to 2 µg/g		Zaccaroni et al., 2003, ² Khwankitrit tikul at al. (2024) ³ Burger & Gochfeld, 2000	¹ Little Owl, ² 37 species including 4 insectivore species ³ Various Seabird species
Sb	0.33 0.02			0.05 mg/kg/ day	Sample & Arenal, 2015	mammals
Ba	24.7 2.45			200-450 mg barium/kg/d ay as barium chloride	Agency for Toxic Substances and Disease Registry (2008)	Lab Rats
Pb	42.3 0.83	¹ 2 mg/kg dw in liver ⁴ 4 µg/g		²⁴ ppm ³ 2.51 mg/kg	¹ Pain et al , 1995. ² Khwankitrit tikul at al. (2024) ³ Dauwe et al. ⁴ Burger & Gochfeld, 2000	¹ 16 Raptor species ² 37 species including 4 insectivore species ³ Raptor species ⁴ Various Seabird species
Hg (THg)	0.06	¹ 0.2 ng/mg ² 3 mg/kg ³ 0.7 mg/kg ⁴ 5 µg/g			¹ Custer et al. (2000); ² Longcore et al. 2007 ³ King et al. 1991 ⁴ Burger & Gochfeld, 2000	¹ Lesser Scaup, ² Tree Swallow, ³ Forster’s tern ⁴ Various seabird species

While I have focused my analysis based on the potential for trace element accumulation due to construction of the Site C dam, there are other potential sources of environmental contamination in this region presenting limitations to conclusions I am able to draw in this study. There are two pre-existing hydroelectric facilities upstream from the Site C dam (W.A.C Bennett Dam and Peace Canyon Dam), that may be contributing to the higher concentrations of trace elements particularly further from the Site C upstream of the construction. Additionally, previous studies suggest that elements Al, Cd, Cr, Co, Fe, Ni, and Pb in feathers are unlikely to be a consequence of the blood connection during their growth, and more likely a result of direct atmospheric deposition of contaminants (Dauwe et al, 2003, Rodreiguez-Alvarez et al, 2021). Taking this into account, it is possible that the concentrations of these elements are due to external atmospheric pollution. Interestingly these elements in my study were predominantly found in higher concentrations in 2023, which could be indicative of higher atmospheric pollution of the project in this year. Wildfire intensity in British Columbia was the highest on record in 2023, with more than double the area affected than in the next highest year (2023: 2.8 million hectares vs 2018: 1.4 million hectares; [goc.bc.ca](https://www.goc.bc.ca), 2024.). If these trace elements were released into the atmosphere from the fires, then I speculate that this may have contributed to the higher concentrations observed in 2023.

CONCLUSION

This study provided several insights into trace elements accumulation in feathers for a declining bird species that thus far has not been studied. An extensive dataset of 19 trace elements in Bank Swallows feathers of 188 specimens in two different years provides new data to the limited information available on aerial insectivore environmental trace element toxicity. Data for this study were collected during the construction of the Site C dam, when the reservoir had not yet been filled. Results from individual elemental analyses in this study indicate that trace element concentrations may increase over time, and further research after the dam has been completed may provide more clear insights on environmental contamination.

This study provided a comprehensive analysis of 19 trace elements in the environment, allowing us to identify patterns of overall trace element accumulation. Notably, examining individual elements in isolation yielded different insights than analyses that considered multiple

elements collectively. For example, while adult Bank Swallows exhibited higher concentrations of mercury (Hg) and cadmium (Cd), juveniles demonstrated greater overall accumulation of several heavy metals. These findings underscore the importance of considering cumulative toxicity and highlight the need for careful selection of trace elements in the design and interpretation of toxicity studies. Overall, the lack of data on certain trace elements indicates that more research is needed to determine the tissue thresholds (including in feathers) that are associated with adverse effect in birds. However, comparing the results from this study to other field studies suggest that elevated levels of Pb and Cr may be present in the tissues of juvenile Bank Swallows due to the site C dam development. In particular, birds nesting upstream from site C had the highest concentrations of these elements, as well as birds nesting in 2023.

Bank Swallows are experiencing a significant population decline, estimated at -4.9% per year across North America (Sauer et al., 2017), making it critical to understand the underlying drivers of this trend for effective conservation. Hydropower development has a long legacy in Canada and continues to expand, involving both new constructions and major upgrades to existing infrastructure (Ministry of Energy, 2025). Flood control (dams) is cited as a potential contributor to the species decline due to habitat loss, however there is also a pressing need to investigate the specific impacts of flood control projects in real time. This proactive approach helps fill existing knowledge gaps and enables a more timely assessment of how large-scale hydroelectric developments may influence Bank Swallow populations. Early and targeted research into these interactions is essential to inform management and mitigation strategies and support the conservation of this declining aerial insectivore.

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CHAPTER 4: CONCLUSION

The goal of this research project was twofold: 1) to assess diet quality in Bank Swallows nesting along the Peace River, both upstream and downstream of the Site C dam construction, and 2) to evaluate the presence of trace elements including heavy metals in their feathers to establish possible contamination concerns from the dam construction. Given the well-established link between high quality prey availability and aerial insectivore decline (reviewed in Chapter 2), examining how dam construction may influence diet quality helps address knowledge gaps regarding the ecological impacts of hydropower development on this species.

Analysis of LCPUFAs revealed that juvenile Bank Swallows consistently consumed a higher-quality diet than adults. Diet quality also varied significantly between the two years of data collection, though the underlying drivers of these yearly differences are likely influenced by various complex variables. In addition, trace element analysis (Chapter 3) showed that Bank Swallow juveniles reared along the Peace River near Site C exhibited high detectable levels of lead and cadmium, suggesting environmental contamination from the large-scale construction. While concentrations of other trace elements were low, 13 of the 20 elements analyzed including Mg, Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, Ba, Pb, and Hg were present in the feathers of over 75% of juvenile swallows sampled in the vicinity of Site C. This finding indicates that even in the early “pre-reservoir” phase of development, trace elements and potentially toxic metals remain prevalent in the environment.

Some unexpected results emerged from this study but still contribute meaningfully to our understanding of potential environmental impacts of dam construction. Notably, mercury levels in Bank Swallow tissues were not elevated in the population. This is a tentatively positive finding, as it suggests that riverine modifications associated with dam construction such as headpond formation and flow alterations may not be currently driving methylmercury accumulation in this system. Most other elemental concentrations also fell within non-concerning ranges. Apart from chromium and lead, which exhibited statistically significant differences by year and nesting location, there were relatively few significant findings regarding the rest of the elements tested for in this study. Although the results may not be statistically significant, they are ecologically encouraging, indicating that Bank Swallows near the dam site are not presently

experiencing excessive harmful exposure of multiple contaminants through their diet. The consistency in juvenile diet quality across nesting locations (upstream vs. downstream, near vs. far from construction) suggests that proximity to the dam has not resulted in immediate dietary stress for this threatened species. However, general differences in adult diet quality by location likely points to an overall decline in food quality within the system. These findings should be interpreted with caution, as the long-term ecological and physiological effects of dam construction on this species may not yet be fully apparent. It is abundantly clear even from this short-term study that the need for continued monitoring of the Bank Swallow population is required in this region post reservoir completion.

Limitations of Research and Directions for Future Study

Assessing toxicological impacts on a species is inherently complex, and identifying specific sources of contamination within an ecosystem often involves a degree of uncertainty. In this study, my evaluation of environmental contamination related to the Site C dam was based on an assumption that the trace element and heavy metal concentrations found in Bank Swallow feathers reflected local exposure. I assumed that the birds were primarily consuming prey captured near their nesting sites and that any contaminants present in those prey items were due to environmental changes associated with dam construction. However, I do not know the exact sources of contamination. Site C is downstream from two other dams and reservoirs constructed on the Peace River, and agriculture and other land use practices are prominent near the Peace River. The ability to confirm the source of contamination would have been greatly strengthened by direct analysis of prey items.

My results regarding bird diet quality and bird heavy metal exposure are further conflated by the fact that higher quality prey (i.e., aquatic emergent insects) may be more likely to carry higher trace element burdens in this scenario, due to their aquatic nature. This may create a trade-off scenario where the aquatic system provides both nutritional benefits and toxicological risks to aerial insectivores. For example, birds consuming aquatic emergent prey with high DHA and EPA may also be consuming prey with higher mercury or lead. Future studies assessing the trace element and fatty acid composition of aquatic emergent and terrestrial insects in this ecological system could help clarify both the nutritional value and contaminant burdens of Bank Swallow

diets in this habitat. Above all else, this study confirmed the complexities of studying habitat change effects on a species. Particularly in the case of impacts on birds from dam construction, this topic is relatively understudied, so my conclusions are drawn from very little background literature, or literature primarily on reservoirs. This study has highlighted the importance of further research regarding dam development impacts on wildlife.

Management Implications

Bank Swallows are listed as a Threatened species in Schedule 1 of the Species at Risk Act in Canada with complex and unclear species-level, regional, and local drivers contributing to overall decline (Environment and Climate Change Canada, 2022). The most likely primary threat to Bank Swallow is the broad-scale ecosystem modifications resulting in less abundant invertebrate prey (Environment and Climate Change Canada, 2022). This study provides preliminary evidence that aquatic emergent insect populations are likely impacted by dam construction, thus impacting diet quality for Bank Swallows. This study also suggests that despite typical environmental regulations, toxic heavy metals like cadmium and lead can still enter ecosystems, ultimately affecting the health and well-being of wildlife in the habitat. Further studies on this dam post inundation are required to confirm that reservoirs further impact the availability of aquatic emergent insects, and to confirm the status of methylmercury in the habitat.

According to the Environment and Climate Change Canada Species at Risk Act (2022), it is unknown if sufficient nesting habitat in natural settings remains to support the recovery of this species, and it's suspected that hydrological regimes likely result in a net loss of natural nesting habitat. It is also apparent that mitigating threats to Bank Swallows is highly challenging as ecosystem modifications largely arise from market forces effecting land use policies. As BC grows in population, so does too energy demand, and likely in the form of increased hydro energy. Electricity demand in BC is projected to rise by 15% in the next 5 years (Ministry of Energy, 2025), which would require adding to or upgrading the existing network of more than 15,000 dams across Canada (Canadian Dam Association, 2025). Given that hydroelectric development inevitably will continue and that Bank Swallows rely on habitats directly affected by damming, it is essential to conduct further research on the Peace River system and other

regions. Such studies are necessary to identify the specific threats to the species, inform legislative protections, and guide mitigation strategies to avoid the loss of critical habitats.

The strongest means of protecting Bank Swallows and all other wildlife in Canada lies in the development and implementation of robust legislation and guidelines at the federal, provincial, and municipal levels. Currently, these guidelines vary but are often informed by the federal Species at Risk Act (SARA), provincial conservation strategies, and municipal bylaws addressing habitat protection and land use. These guidelines have traditionally been informed by colonial perspectives. What continues to be overlooked, however, are the practices and lived experiences of Indigenous peoples, who have long maintained reciprocal relationships with the land and nonhuman relatives (Hernandez, 2022). Indigenous voices are too often excluded from environmental decision-making, despite being the original stewards of these ecosystems. Ensuring the protection of Species at Risk requires not only environmental research methods and refined policy, but also genuine collaboration with Indigenous communities (Government of Canada, 2020; Turcotte et al., 2021). While no single study or single policy can offer comprehensive solutions, the integration of diverse knowledge systems and sustained interdisciplinary research, represents the most promising path toward lasting environmental protections.

This research thesis serves as a preliminary case study examining the impacts of dam construction on Bank Swallows. While hydropower is indeed a cleaner alternative to fossil fuels, its development must still be pursued with environmental responsibility and respect for the ecosystems and communities it affects. Large-scale hydroelectric projects that disrupt critical habitats for fish, migratory birds, and native vegetation, while simultaneously degrading water quality and impeding traditional land use by local First Nations are not a truly sustainable alternative. A sustainable renewable energy future in Canada will require integrative approaches where western environmental science, Indigenous knowledge, and long-term ecological monitoring work in collaboration to guide projects that create minimal harm to ecosystems, wildlife, and surrounding communities.

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APPENDIX A

Table 1A. PCA loadings for stable isotopes of Carbon, Nitrogen and Hydrogen, indicating how much each isotope contributes to each principal component. PC1 loadings are all positive and similar in magnitude, suggesting PC1 represents an overall gradient of enrichment across all 3 isotopes.

	PC1	PC2	PC3
Carbon	0.6117590	-0.4107184	0.7299907
Nitrogen	0.4758437	0.8737966	-0.6760631
Hydrogen	0.6319206	-0.2603649	-0.1002608

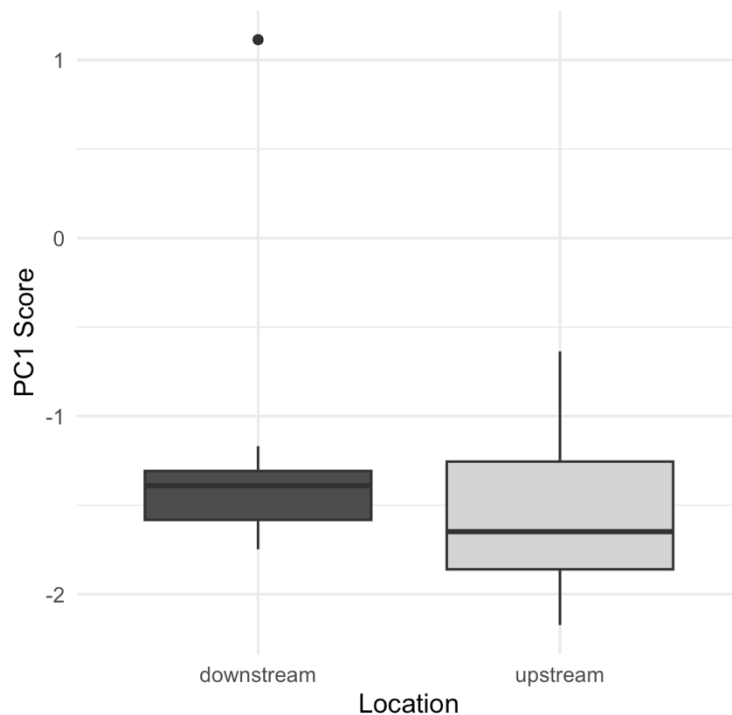


Figure 1A. Comparison of PC1 scores between upstream and downstream nesting locations in juvenile Bank Swallows. Results indicate birds nesting downstream higher PC1 scores and less variability. Higher PC1 scores may indicate a diet with more terrestrial input.

Table 2A. Mean mass percentage (averaged across all individuals) for each long chain poly-unsaturated fatty acid (LCPUFA): Docosahexaenoic acid (DHA), Eicosapentaenoic acid (EPA), Arachidonic acid (ARA), Alpha-linolenic acid (ALA), and Linoleic acid (LA), in each year.

Fatty Acid	2021	2023	% difference
DHA	0.23 ± 0.42	1.32 ± 0.83	473
EPA	1.78 ± 1.33	4.55 ± 2.24	155
ARA	1.48 ± 1.27	4.02 ± 1.75	171
ALA	0.39 ± 0.46	0.78 ± 0.45	94.6
LA	3.67 ± 1.90	5.35 ± 2.12	45.8

Table 3A. Mean mass percentage (averaged across all individuals) of long chain poly-unsaturated fatty acids (LCPUFA): Docosahexaenoic acid (DHA), Eicosapentaenoic acid (EPA), Arachidonic acid (ARA), Alpha-linolenic acid (ALA), and Linoleic acid (LA), between adults and juveniles

Fatty Acid	Adult mean	Juvenile Mean	% difference
DHA	0.31 ± 0.45	1.27 ± 0.88	309
EPA	2.61 ± 2.64	3.85 ± 1.79	47.7
ARA	1.78 ± 1.43	3.80 ± 1.97	113
ALA	0.57 ± 0.50	0.62 ± 0.49	7.85
LA	4.55 ± 2.63	4.55 ± 1.66	0.02

Table 4A. Mean mass percentage (averaged across only adults) for each long chain poly-unsaturated fatty acids (LCPUFA): Docosahexaenoic acid (DHA), Eicosapentaenoic acid (EPA), Arachidonic acid (ARA), Alpha-linolenic acid (ALA), and Linoleic acid (LA), by nesting location

Fatty Acid	Downstream mean	Upstream Mean	% difference
DHA	0.39±0.49	0.16±0.35	0.345
EPA	2.97±3.05	1.96±1.54	1.54
ARA	2.27±1.47	0.94±0.84	0.84
ALA	0.71±0.49	0.35±0.42	0.42
LA	5.22±2.58	3.38±2.33	2.33

APPENDIX B

Table 1B. The proportion (%) of juvenile and adult Bank Swallow feathers sampled on the Peace River with detectable concentration (> 0 ng/mg) of the 19 trace elements analyzed. Values in juvenile and adult feathers represent conditions on the breeding grounds and non-breeding grounds, respectively.

Trace element	Juveniles (%)	Adults (%)
Mg	100	100
Al	100	100
V	19.5	48.9
Cr	93.1	83.3
Mn	100	100
Fe	100	100
Co	100	100
Ni	98.9	100
Cu	100	100
Zn	100	100
As	11.5	12.5
Se	88.5	83.3
Mo	29.9	17.7
Ag	22.9	20.8
Cd	90.8	97.9
Sb	50.6	32.3
Ba	100	100
Pb	79.3	76
Hg	100	100

Table 2B. MANOVA results comparing sex differences in trace element accumulation for adult bank swallows. No sex differences were found and thus sex was not considered in analysis.

model	DF	Pillai's trace	Approx. F	p-value
heavymetalcols ~ sex	1	0.2	1.27	0.23
Signif. codes: <0.05*, <0.01**, <0.005***				

Table 3B. MANOVA results for 13 trace elements of low concern with/without outliers for juvenile feathers around site C. Results indicate no differences between datasets with outliers included vs outliers removed.

model		Variable	DF	Pillai's trace	Approx. F	p-value
All data	Heavymetalcols ~	UpDown	1	0.21	3.09	0.0003***
	UpDown +	Proximity	1	0.10	1.42	0.14
	Proximity + year	Year	1	0.24	3.81	0.000001***
Outliers removed	Heavymetalcols ~	UpDown	1	0.21	3.07	0.0003***
	UpDown +	Proximity	1	0.11	1.4	0.13
	Proximity + year	Year	1	0.24	3.76	0.000001***
Signif. codes: <0.05*, <0.01**, <0.005***						

Table 4B. MANOVA results for 6 non-essential trace elements with/without outliers for juvenile feathers around Site C. Results indicate no statistical differences between datasets with outliers included vs outliers removed.

model		Variable	DF	Pillai's trace	Approx. F	p-value
All data	Heavymetalcols ~	UpDown	1	0.06	1.89	0.08
	UpDown +	Proximity	1	0.07	2.35	0.03*
	Proximity + year	Year	1	0.06	1.72	0.0
Outliers removed	Heavymetalcols ~	UpDown	1	0.06	1.90	0.08
	UpDown +	Proximity	1	0.07	2.2	0.04*
	Proximity + year	Year	1	0.06	1.7	0.12

Signif. codes: <0.05*, <0.01**, <0.005***

Table 5B. MANOVA results for 13 trace elements of low concern with/without outliers comparing adults and juveniles. Results indicate no statistical differences between datasets with outliers included vs outliers removed.

model		DF	Pillai's trace	Approx. F	p-value
All data	Heavymetalcols ~	1	0.23	3.67	0.00002***
	Agegroup				
Outliers removed	Heavymetalcols ~	1	0.23	3.67	0.00002***
	Agegroup				

Signif. codes: <0.05*, <0.01**, <0.005***

Table 6B. MANOVA results for 6 non-essential trace elements with/without outliers comparing adults and juveniles. Results indicate no statistical differences between datasets with outliers included vs outliers removed.

	model	DF	Pillai's trace	Approx. F	<i>p</i> -value
All data	Heavymetalcols ~ Agegroup	1	0.09	2.9	<i>0.008**</i>
Outliers removed	Heavymetalcols ~ Agegroup	1	0.09	3.0	<i>0.009**</i>
Signif. codes: <0.05*, <0.01**, <0.005***					

Table 7B. Results from 20 Wilcoxon rank-sum tests comparing elemental values between feather pairs of 8 birds. Antimony displayed statistically significant differences and was thus removed from the analysis.

Element	V	p-value	Bon-ferroni p-value
Mg	34	0.02	0.0025
Al	26	0.31	0.0025
V	16	0.79	0.0025
Cr	20	0.84	0.0025
Mn	23	0.55	0.0025
Fe	26	0.31	0.0025
Co	13	0.55	0.0025
Ni	21	0.74	0.0025
Cu	29	0.15	0.0025
Zn	26	0.31	0.0025
As	1	1	0.0025
Se	9	0.25	0.0025
Mo	3	0.37	0.0025
Ag	3	0.37	0.0025
Cd	26	0.31	0.0025
Sb	19	0.09	0.0025
Ba	27	0.25	0.0025
Pb	18	1	0.0025
U	8	0.36	0.0025
Hg	26	0.052	0.0025

Table 8B. Pearson's r values for each heavy metal, indicating the correlation of each of the 3 ICP-MS runs. Significant values indicate a high degree of similarity between runs, and non-significant values (bolded) indicate a low degree of similarity between runs.

Element	1v2 Pearson's r	p-value	2v3 Pearson's r	p-value	1v3 Pearson's r	p-value	Mean (ng/mg)	SD (ng/mg)
Mg	0.87	<0.001	0.887	<0.001	0.873	<0.001	0.88	0.01
Al	0.986	<0.001	0.988	<0.001	0.985	<0.001	0.98	0.001
V	0.825	<0.001	0.748	<0.001	0.412	<0.001	0.66	0.22
Cr	0.97	<0.001	0.922	<0.001	0.941	<0.001	0.94	0.02
Mn	0.881	<0.001	0.89	<0.001	0.909	<0.001	0.89	0.01
Fe	0.967	<0.001	0.979	<0.001	0.966	<0.001	0.97	0.007
Co	0.897	<0.001	0.906	<0.001	0.943	<0.001	0.92	0.02
Ni	0.979	<0.001	0.971	<0.001	0.979	<0.001	0.97	0.004
Cu	0.865	<0.001	0.879	<0.001	0.86	<0.001	0.87	0.01
Zn	0.969	<0.001	0.929	<0.001	0.946	<0.001	0.95	0.02
As	0.713	<0.001	0.957	<0.001	0.642	<0.001	0.77	0.17
Se	0.075	0.303	0.231	0.001	-0.036	0.625	0.09	0.13
Mo	0.909	<0.001	0.95	<0.001	0.9	<0.001	0.92	0.46
Ag	0.999	<0.001	0.999	<0.001	0.999	<0.001	0.99	0
Cd	0.925	<0.001	0.929	<0.001	0.97	<0.001	0.94	0.02
Sb	0.872	<0.001	0.81	<0.001	0.746	<0.001	0.81	0.06
Ba	0.99	<0.001	0.99	<0.001	0.988	<0.001	0.99	0.001
Hg	0.731	<0.001	0.473	<0.001	0.738	<0.001	0.65	0.15
Tl	0.97	<0.001	0.981	<0.001	0.988	<0.001	0.98	0.01
Pb	0.92	<0.001	0.908	<0.001	0.855	<0.001	0.89	0.03

Table 9B. ICP-MS instrumental parameters used for analysis of 20 trace elements in Bank Swallow feather samples

Instrument	Instrumental Parameter	Setting
Inductively Coupled Plasma Mass Spectrometry	Nebulizer	MicroMist
	Spray chamber	Quartz, double pass
	RF power (W)	1550
	Ar flow rate (L/min)	15
	Auxiliary gas flow rate (L/min)	0.9
	Nebulizer gas flow rate (L/min)	1.0
	Sample uptake rate (rps)	0.1
	Number of replicates	3
	Integration time (s)	0.3-1.0
	Autosampler	SPS 4
	Probe depth (mm)	150