Mercury Biomagnification in Freshwater Ecosystems of Nova Scotia

By
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ABSTRACT

Mercury (Hg) biomagnifies consistently in aquatic food webs around the world. This can be a human health concern in areas with recreational and subsistence fisheries, as the main biomagnifying agent (methylmercury), is a potent neurotoxin. My objective was to assess mercury biomagnification rates in freshwater ecosystems across Nova Scotia and provide data on potential Hg risk in freshwater based on environmental parameters. Trophic magnification slope factors and intercepts varied significantly among the 21 waterbodies examined (TMS; 0.021 - 0.423). Potential bioavailable Hg in freshwater, calculated using water quality data (chlorophyll-a, phosphorus, total organic carbon, and pH) and percent wetland cover, showed that Hg risk varied across the province.

[December 19, 2022]

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I would like to thank my family and friends for their continuous support throughout the last two years. Thank you to my grandparents, who filled my childhood with hours of fishing and outdoor play, building a basis for a love of field work and appreciation for nature. To my parents, who always encouraged education, curiosity, and hard work. Thank you Aunt Lisa for editing and reviewing help. And finally, to Jacob for your unfailing support and encouragement; and the answer is finally “Yes, my thesis is done”.

Note: This is a manuscript-style thesis; therefore, similar background information is repeated within the three chapters. Chapter 1 includes background information and thesis objectives. Chapter 2 examines mercury biomagnification in Nova Scotia freshwater food webs. Chapter 3 summarizes existing consumption guidelines for fish across Canada, water quality, and risk factors for mercury in fish in Nova Scotia. Citation styles vary by chapter, depending on the journal they will be submitted to.
Mi’kmaq place and species names are provided in brackets in italics following the English or scientific name.

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Chapter 1. Introduction and Objectives

Invasion Biology

A non-native, non-indigenous, or exotic species is one that has been introduced to an area outside of its natural range through human activity (Havel et al., 2015; Young & Larson, 2011). These introductions can occur through unintentional mechanisms, such as a mussel travelling on the hull of a boat, or intentionally, such as planting ornamental flowers. Invasive species are often characterized as non-native species that persist and spread widely in their new environment (Havel et al., 2015; Richardson, 2011). Invasive species can have intense and pervasive ecological or economic impacts on communities and ecosystems and often require management to mitigate negative effects (Strayer, 2010).

The impact of invasive species has been well studied and theorized throughout the last several decades. As species' ranges expand due to anthropogenic effects, researchers around the globe have been studying the impacts or potential impacts of non-native species (Bates et al., 2013; Simberloff et al., 2013). Currently, the dispersal and establishment of invasive species are better understood than their impact, as it is often difficult to quantify the potential impacts of non-native species on an ecosystem (Gallardo et al., 2016; Simberloff et al., 2013). Although some invasive species have little or no detectable effects (Havel et al., 2015), it is common for invasive species to negatively impact the functional components of a community.

The introduction of non-native or invasive species can cause multiple impacts to ecosystems. One such impact is trophic cascades through direct interactions and indirect changes in habitat conditions (Crooks, 2002; Gallardo et al., 2016; Moyle & Light, 1996). These changes can cause shifts in the transfer of energy within food webs (Crooks, 2002), loss of biodiversity and community richness, and extinctions (Bates et al., 2013; DeRoy et al., 2020; Havel et al., 2015). The impacts of invasive species can vary depending on habitat type and trophic position of the invader (Gallardo et al., 2016), but systems with low diversity are more susceptible to invasions and the presence of an invasive species tends to decrease the overall diversity of an ecosystem (Gallardo et al., 2016; Havel et al., 2015; Moyle & Light, 1996). Invasive species have strong and consistent impacts on aquatic systems as shown throughout the literature.

Aquatic systems generally have strong trophic links that can be disrupted by an invasive species, making them an ideal model ecosystem for studying the effects of invasions (Gallardo et al., 2016). Freshwater ecosystems generally have greater biodiversity than marine or terrestrial ecosystems (Dudgeon et al., 2006) and have been deeply impacted by invasive species from a wide range of taxonomic groups (Simberloff et al., 2013; Strayer, 2010). The establishment rates of aquatic invasive species (AIS) are high, and aquatic systems are especially at risk for loss of diversity (Havel et al., 2015), furthering the importance of monitoring the interactions of non-native species in an ecosystem. It is common for multiple invasive species to be present in aquatic systems, especially lakes (Havel et al., 2015), yet the impacts of multiple invaders in one system are poorly studied. Many freshwater ecosystems in Nova Scotia contain two AIS, chain pickerel (*Esox niger*) and smallmouth bass (*Micropterus dolomieu*), but no literature exists on the cumulative impact of these species on native biota.

Fisheries agencies have widely introduced game fish (Havel et al., 2015), including historically in Nova Scotia waterbodies. Smallmouth bass were introduced as a sportfish in 1942 in Nova Scotia (LeBlanc, 2010), which now has a significant recreational fishery throughout the province. Similarly, many anglers enjoy fishing for chain pickerel, increasing the desire to illegally move the species across the province. The introduction of predatory fish can alter community structure through a decrease in the abundance of fish, benthic invertebrates, and zooplankton (Gallardo et al., 2016; Vander Zanden et al., 1999), which can in turn impact water quality such as algae production (Eriksson et al., 2009). This could impact the transfer of contaminants, such as mercury (Hg), as biomagnification and bioaccumulation are impacted by food web structure and environmental parameters at both a landscape and waterbody level. Therefore, the introduction of non-native species could impact mercury concentrations in freshwater ecosystems.

Chain Pickerel

Although the native range of chain pickerel is theorized to be from Maine to Florida along the eastern seaboard (Coffe, 1998; Hoyle & Lake, 2011), their distribution has expanded in the last century. The first official documentation of chain pickerel in Nova Scotia was 1945 – 1949 in four lakes and one brook in Digby County (Gilhen, 1969), but according to locals, they were introduced from the United States in the early 1900s (Livingstone, 1953). Only a decade after their first official record, chain pickerel were documented as "thriving mightily", and a range expansion was predicted for the area (Livingstone, 1953). In the decades following, their spread throughout the province has been facilitated through the illegal movement of live fish and subsequent dispersal within adjoining watersheds (Mitchell et al., 2010).

The spread of invasive chain pickerel throughout Nova Scotia has caused ecosystem changes such as the reduction of species richness and diversity and increased competition for resources with native species (Mitchell et al., 2010). Pickerel are a generalist species (Kanno & Vokoun, 2008) and consume a variety of foods such as fish, invertebrates, amphibians, algae, and plants (Hunter & Rankin, 1939; Mcilwain, 1970). The broad feeding habits of this non-indigenous species suggest they may have trophic adaptability which would allow for greater success establishing in new habitats, thus increasing their spread. The presence of an aggressive invasive species within an established food web can lead to disruptions of native species' role in the food web and energy and chemical transfer.

Stable Isotope Analysis

Stable isotope analysis (SIA) of carbon and nitrogen is a useful tool frequently used in food web ecology to identify trophic relationships (Boecklen et al., 2011; Layman et al., 2012; McCutchan et al., 2003). This analysis determines the ratio of heavy to light isotopes in tissue (Nielsen et al., 2018), which can be used to assess diet, assign trophic positions (Post, 2002), assess patterns of resource acquisition and allocation (Bodey et al., 2011) and characterize niche properties (Boecklen et al., 2011). SIA is a valuable tool for invasive species management as understanding food use and sources allows researchers to identify behavioural patterns that can help in eradicating or managing an invasive population (Bodey et al., 2011).

Although other elements can be used, $\delta^{15}N$ and $\delta^{13}C$ are among the most common stable isotopes used in ecology. SIA is focused on aquatic systems, possibly because these systems have strong trophic links (Gallardo et al., 2016). Within these systems, $\delta^{15}N$ is used to characterize trophic position, as its values increase by 2-5 ‰ (mean of 3.4‰; 1 SD = 1‰) with each trophic level (McCutchan et al., 2003; Post, 2002). $\delta^{15}N$

reflects resource use during tissue turnover, so it can be used as a continuous measure of trophic behaviour (Kidd et al., 1995). $\delta^{13}C$ is used to track dietary sources as either benthic or pelagic in origin (Hecky & Hesslein, 1995; Post 2002), or track nutrient sources as either marine, brackish, or freshwater (Boecklen et al., 2011). SIA provides time and space-integrated insight into trophic relationships and therefore can be used in constructing models of trophic structure (Figure 1) (Layman et al., 2012; Nielsen et al., 2018).

SIA can be used in conjunction with environmental contaminant assessments to allow researchers to fully understand the implications of food web structure and diet on Hg and other trace elements (e.g., Ofukany et al., 2014). This is an important tool for contaminants that bioaccumulate or biomagnify within food webs, such as mercury. Regressing log-transformed Hg concentrations in fish against $\delta^{15}N$ values gives a biomagnification slope value which can be used to assess food web connections and the impact of non-native species over time (e.g., Campbell et al., 2009; Lavoie et al., 2013; Wyn et al., 2010). The equation of this regression slope is the rate at which mercury is biomagnifying in food webs and can be used to identify the risk for mercury contamination in upper trophic levels.

Mercury

Mercury is an element that occurs both naturally and from anthropogenic sources. Naturally occurring in the Earth’s upper crust, some sources of mercury include volcanoes, geothermal processes, and rock weathering (Falandysz et al., 2020). Atmospheric deposition is one of the most important sources of mercury in water (Swartzendruber & Jaffe, 2012). Sources of atmospheric Hg include the combustion of plant biomass, which could occur through forest, brush, or grassland fires, as well as human use of biofuels (Falandysz et al., 2020). Among the primary anthropogenic sources of Hg is coal-fired plants (Mason et al., 2000; NRC, 2015), which can deposit Hg into ecosystems far from the point source.

Mercury exists as elemental (Hg^0), inorganic (Hg^+ and Hg^{2+}), and organic compounds (Park & Zheng, 2012). This compound is not required in biological functioning, and many forms of it can be highly toxic, such as methylmercury (MeHg) (LeBlanc et al., 2020; Park & Zheng, 2012). MeHg is one of the most toxic mercury compounds created from inorganic mercury (Hong et al., 2012). In aquatic systems, the combination of anaerobic conditions, high microbial activity, and abundances of organic carbon (such as wetland conditions) can allow inorganic Hg to undergo methylation and produce organic Hg compounds such as methylmercury (Figure 2) (O'Driscoll et al., 2005).

Hg bioaccumulates within organisms and biomagnifies in food webs; nearly all mercury bioaccumulated by fish and other aquatic organisms is MeHg (Lavoie et al., 2013; Lehnherr, 2014). Bioaccumulation is the amount of a substance, often a contaminant, accumulated in the tissue of an organism within its lifetime, while biomagnification is the transfer of a substance from lower to higher trophic levels, resulting in elevated concentrations in higher trophic position organisms. The rate of biomagnification is the regression slope of log-transformed Hg concentrations against $\delta^{15}N$ values and is further noted as the Trophic Magnification Slope (TMS). Bioaccumulation and biomagnification rates of mercury in food webs are a human health concern, as MeHg exposure can have neurological or physiological effects.

The main pathway of Hg in humans is fish consumption, and communities practicing traditional marine or freshwater diets are at greater risk of Hg contaminants (Baker et al., 2004; Johansen et al., 2004; Mason et al., 2000). In fish, most of the total mercury (THg) accumulation is MeHg; ranging from 69 – 99% (Bloom, 1992; Grieb et al., 1990; Lavoie et al., 2013). Methylmercury is a neurotoxin that can cause physiological and behavioural effects as well as reduced reproductive success (Evers, 2018). After consumption, MeHg is almost completely absorbed and flows into the blood (Fernandes et al., 2020; Hong et al., 2012). This compound is highly bioavailable, and lipophilic, allowing it to pass through membranes such as the blood-brain barrier and placental barrier (Park & Zheng, 2012). It is theorized that MeHg poisons the heart and blood vessel system, reproductive system, and immune system (Hong et al., 2012). The liver is integral in removing non-essential elements and toxins from the bloodstream, such as Hg, therefore cells in this organ can have elevated levels of contaminants (Campbell et al., 2005). This element is slow to be eliminated from the body, further increasing the risk of bioaccumulation and biomagnification (Bridges & Zalup, 2010; O'Driscoll et al., 2005).

Mercury concentrations within fish are well studied in North America. In 2013, a group of researchers created the Canadian Fish Mercury Database (CFMD), which is the most extensive summary of mercury measurements in freshwater fish within Canada (Depew et al., 2013*a*). Across Canada, Hg in prey fish species exceeds thresholds for impaired health in loons and piscivorous fish (Depew et al., 2013*c*). Elevated total mercury concentrations in fish appears to be caused by THg concentrations in lower trophic levels, suggesting that the processes that affect Hg at the base of the food web are more important than the rates of biomagnification (Wyn et al., 2009). Even in areas where the water has low concentrations of mercury, fish accumulate it at higher rates due to biomagnification (Walkuska et al., 2010).

Elevated Hg or MeHg in fish may be a concern to other wildlife, as well as humans, because it is highly toxic and biomagnifies consistently in food webs around the world (Campbell et al., 2003; Lavoie et al, 2013; Lehnherr, 2014). The rate of mercury transfer within a food web can be measured using Log Hg and $\delta^{15}N$ values (e.g., Depew et al., 2013a; Campbell et al., 2005). This rate is comparable between temperate, tropical, and arctic lakes, suggesting that Hg accumulation in freshwater food webs is independent of climate and species composition (Campbell et al., 2003; Kidd et al., 2003; Lavoie et al., 2013).

Many factors influence Hg within aquatic systems, including both landscape and environmental parameters. Some of the main water chemistry factors include nutrients, pH, and dissolved organic carbon (Chen et al. 2005; Clayden et al., 2013; Driscoll et al. 1995; Essington & Houser, 2003) (Figure 3). Fish community, food web length, and food web structure, including fish body size, are also important in determining aquatic Hg concentrations (Cabana et al. 1994; Eagles-Smith et al., 2018). Wetland area, vegetation cover, land use, and drainage area are also known to influence the rates of Hg methylation and bioavailability in aquatic systems (Chasar et al., 2009; Lavoie et al., 2013; Mattieu et al., 2013; Shanley et al., 2012). The combination of these factors result in varying mercury bioaccumulation and biomagnification rates across waterbodies.

Reservoirs are often created by flooding an area, which can increase THg and MeHg availability in freshwater food webs (Hall et al., 2005; Mailman et al., 2006), as organic matter in soils retains 80-90% of atmospheric Hg deposition (Krabbenhoft et al., 2005). Flooding can increase the amount of organic carbon and microbial activity, as well as create anaerobic conditions, which are correlated with methylation of Hg (Evers et al., 2011; Gilmour & Henry, 1991; O'Driscoll et al., 2005). This increase in available Hg in organic matter and increased methylation result in elevated MeHg in food webs following flooding events. MeHg from lower trophic organisms biomagnifies in the food web, therefore, invertebrates feeding on decomposing plant tissues could be a vector for MeHg to the fish community (Hall & St. Louis, 2004), in which MeHg could persist for many years. Aquatic emergent insects from sites with elevated Hg can also act as biovectors to neighbouring aquatic or terrestrial habitats (Speir et al., 2014), which could increase the risk of MeHg in areas surrounding reservoirs. Nova Scotia has approximately 155 dams on lakes and rivers (NSPI, 2022*b*), which could increase the availability of MeHg in freshwater systems across the province.

Mercury concentrations are correlated with trophic position, being highest in piscivorous species and increasing in concentrations with age and size (Depew et al., 2013*a*; Gandhi et al., 2014; Haines, 1997; Neumann & Ward, 1999; Wyn et al., 2009). Recreational fish or sportfish, which are generally top predators such as chain pickerel or smallmouth bass, are likely to have elevated concentrations of Hg which is concerning for human health. Hg levels in fish can warrant a notice for fishers as it can be dangerous for human consumption (Haines, 1997).

Food web length is an important factor in freshwater Hg concentrations, and the addition of non-native species can alter the food web structure, which in turn can change the Hg concentrations in fish (Southward Hogan et al., 2007). Lakes with longer food webs and slow-growing fish tend to have elevated Hg in the top predators (Cabana et al., 1994). Shifts in diet due to the addition or removal of a species can create pathways for contaminant transfer (Bowles et al., 2001; Eagles-Smith et al., 2008; Southward Hogan et al., 2007). Nova Scotia food webs are predicted to shift in both species' composition and contaminant transfer with the addition of invasive chain pickerel (Figure 4).

Predicting mercury concentrations in fish communities is a potentially cost-effective way to expand Hg datasets in areas with limited resources. To assess mercury concentrations in freshwater ecosystems, researchers have used predictor variables, such as fish length, water pH, and percent wetland of watersheds (Qian et al., 2001; Shanley et al., 2012), or used existing Hg data to develop estimates for Hg risk exposure to fish and wildlife (Depew et al., 2013*c*). Predictive models are often complex, with confounding variables, but can provide information on mercury risk at various levels of precision.

Nova Scotia may be of particular concern for mercury accumulation in freshwater ecosystems. Depew et al. (2013*c*) examined mercury concentrations in freshwater fish across Canada and found that Southeastern Canada has the highest calculated risk for Hg across the country. Further studies have shown that Southwest Nova Scotia [*Kesputkwit*] is a biological hotspot for Hg concentrations and was found to have some of the highest levels of Hg in fish in North America (Evers et al., 2007; Kamman et al., 2005; Wyn et al., 2010). This could be due to an abundance of wetlands, water chemistry, eutrophication processes, gold mine tailings, or atmospheric deposition of Hg in the area (e.g., Evers, 2007; Wyn et al., 2010; LeBlanc et al., 2020). Southwest NS has naturally acidic waterbodies, which could contribute to the bioaccumulation of Hg (Wyn et al., 2009).

In Nova Scotia, anthropogenic Hg sources include atmospheric emissions, legacy reservoirs, and household items. Data show that Hg from abandoned gold mine sites is bioaccumulating in fish (LeBlanc et al., 2020). Other mercury sources in Nova Scotia may include Nova Scotia power plants (NSPI, 2022*a*), gas- or diesel-powered vehicles (Won et al., 2007), and legacy reservoirs including chemical generation from the pulp and paper industry (Dillon Consulting Limited, 2019). These sources, combined with naturally occurring Hg and methylation, increase the risk of Hg bioaccumulation in freshwater ecosystems.

The use of chain pickerel as a recreational species in Nova Scotia is concerning due to high levels of mercury previously documented within the province. The concentrations of mercury within these fish could pose a risk to anglers if they are consuming fish from areas at higher risk of Hg contamination or in large amounts. Understanding the risks and Hg levels in fish within Nova Scotia could help to inform scientific, governmental, and community groups on safe consumption levels regarding Hg.

There is currently limited data for mercury in freshwater fish in Nova Scotia. This is concerning because of the province's designation as a biological Hg hotspot. Some work has been done to assess the potential mercury bioaccumulation of freshwater fish in historical gold mines tailings; however, chain pickerel was often not included or underrepresented (LeBlanc & Halfyard, 2010). This invasive species is likely to have higher concentrations of Hg due to its high trophic level and piscivorous nature. Most of the existing work in Nova Scotia on mercury biomagnification and freshwater fish is limited to Kejimkujik National Park and occurred before the introduction of invasive species to the area (e.g., Wyn et al., 2009; Wyn et al., 2010).

Fish Consumption Recommendations

Fish with elevated contaminants can lead to consumption advisories or recommendations. Advisories are often notices to reduce or avoid consumption of fish in high-risk areas, while recommendations are often suggested serving sizes and frequency of consumption. These recommendations are often focused on two categories: the sensitive population (children under 12 years of age, those who are pregnant, women of childbearing years, and sometimes frequent fish consumers) and the general public (all individuals over the age of 12). These definitions can vary by jurisdiction but are usually outlined in the recommendation guide. Consumption guidelines are often calculated based on the World Health Organization's safe consumption levels.

The Provisional Tolerable Daily Intake (pTDI) is the amount of a substance that can be consumed daily over the course of a lifetime without negatively impacting the consumers' health (Health Canada, 1995). The World Health Organization (WHO) developed guidelines for the pTDI value of mercury that are used by many governments in developing consumption recommendations for fish. For adults of the general population, the pTDI is 0.71µg THg or 0.47µg MeHg per kilogram of body weight per day (µg/kg bw/day) (WHO, 1972). After additional research on MeHg on fetal and infant brain development, the Joint WHO/FAO Expert Committee on Food Additive (JECFA) recommended for sensitive populations, the tolerable weekly intake for MeHg is 1.6 µg/kg bw/week (0.23 µg MeHg/kg bw/day) (WHO, 2003).

Canada has federal guidelines for the safe consumption of Hg and MeHg and has several regulations surrounding this. The Bureau of Chemical Safety in Canada agrees with the WHO’s level for safe consumption and uses 0.47 µg MeHg/kg bw/day as the pTDI value for the general population (Health Canada, 2007). Health Canada developed a pTDI for sensitive populations of 0.2 µg MeHg/kg bw/day (Health Canada, 2007), which concurs with the JECFA value of 0.23 µg MeHg/kg bw/day. For the commercial sale of fish in Canada, Health Canada Guidelines for the maximum total mercury (THg) is 0.5 ppm for most fish, while some piscivorous fish species (i.e., shark, tuna, swordfish, and escolar) have a limit of 1.0 ppm (Health Canada, 2020). The Canadian Food Inspection Agency (CFIA) regularly tests commercial fish and shellfish to ensure they do not violate Canadian standards (Health Canada, 2019).

Most Canadian provinces and territories have fish consumption advisories or recommendations based on mercury risk. These guidelines are often calculated using Health Canada’s pTDI values; however, the scale at which recommendations are implemented varies across the nation. Nunavut is the only Canadian region with no existing advisories or recommendations, despite elevated risk due to traditional diets incorporating large amounts of fish (Priest & Usher, 2004). Many provinces and territories have general guidelines on portion sizes, fish size classes, and the respective frequency at which they can be safely consumed. Ontario and Quebec are leading the nation with comprehensive guidelines, focused on specific waterbodies. These provinces have interactive online maps allowing users to select waterbodies and see a list of recommended fish sizes and portions that can be safely consumed.

Nova Scotia has two sets of consumption advisories and recommendations for certain fish in the province: one published in the angler's handbook and a more detailed recommendation guide published on the Government of Nova Scotia webpage. However, these recommendations are designated province-wide, despite the many factors influencing mercury bioaccumulation in freshwater systems. Mercury concentrations can vary between waterbodies, and care should be taken when developing consumption recommendations for fish. Nova Scotia's guide recommends that the general population should not consume more than two meals per week of chain pickerel under 35cm, while fish exceeding 35 cm should be limited to two servings per month (Table 1).

The two study lakes from the 2020/2021 field seasons are in Lunenburg County, Nova Scotia, in the LaHave River [*Pijinuiskaq*] Watershed (Figure 5). Wentzells Lake is a fluvial lake, with two main branches of the LaHave River entering the lake and one outflow. The lake has distinct vegetation and morphology: some sections of the lake are shallow and densely vegetated with *Pontederia cordata* (pickerel weed), other areas have gradual increases in water depth with *Nymphaea* species (water lily) and *Potamogeton* species (pondweed), while another section has steep increases in depth, sparsely vegetated with rush species and has little bottom habitat. The deepest part of this lake is approximately 12 m. Sherbrooke Lake is the largest waterbody in the LaHave watershed and covers 16.94 km^2 (Coastal Action, 2018). Sherbrooke River is the largest inlet stream of the 14 inlets, while the North Branch is the only outlet stream. The deepest part of the lake is approximately 20 m. Sherbrooke Lake is one of two lakes in Nova Scotia known to have a population of lake trout (*Salvelinus namaycush*). Both study lakes contain AIS chain pickerel and smallmouth bass.

Data from 2013 – 2015 were from 15 freshwater lakes across Nova Scotia, ranging from Blacketts Lake in Cape Breton to Second Lake near Yarmouth in southern Nova Scotia (Figure 5), and was conducted in collaboration with Nova Scotia Fisheries & Aquaculture (Campbell, 2014*a*; Campbell, 2014*b*). Many of these lakes contained chain pickerel and/or smallmouth bass.

Thesis objectives

The primary objective of this thesis is to examine mercury biomagnification of freshwater food webs in Nova Scotia and its relationship to consumption guidelines for fish. Here I provide framework and background information on predicting mercury risk in fish across Nova Scotia. Previously limited studies have examined the relationship of contaminant transfer within invasive chain pickerel or sportfish in Nova Scotia; here we provide a variety of food web data, many including invasive chain pickerel and smallmouth bass. Using water quality data and other environmental parameters, we provide a coarse-scale risk prediction for mercury in fish in Nova Scotia. Assessing mercury biomagnification rates and predicting Hg risk in fish communities can contribute to a more precise evaluation of public health concerns in relation to consuming freshwater fish in Nova Scotia.

Chapter 1. Figures

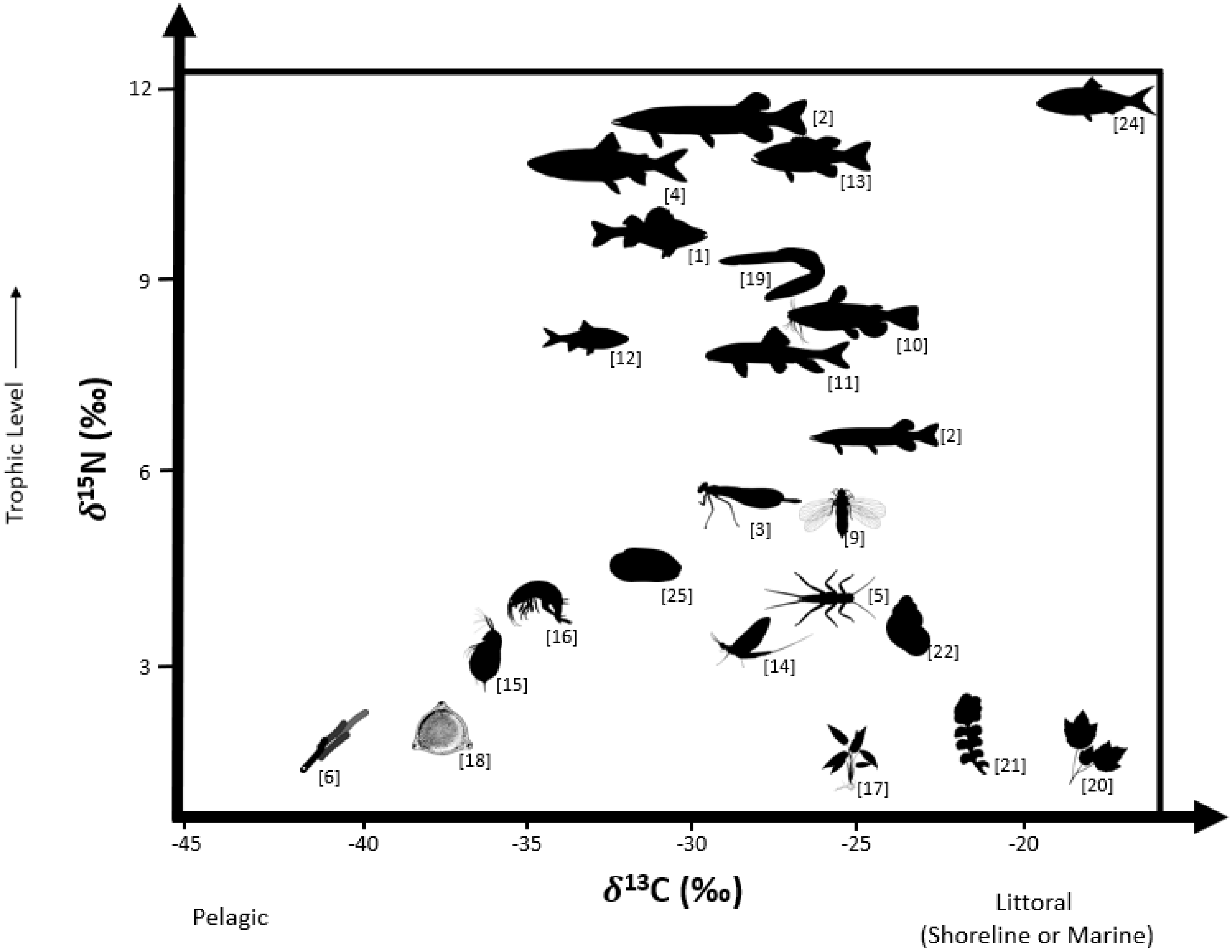


Figure 1. Conceptual model of freshwater food webs in Nova Scotia constructed using stable isotopes δ15N and δ13C. Species names and image references outlined in appendix A.

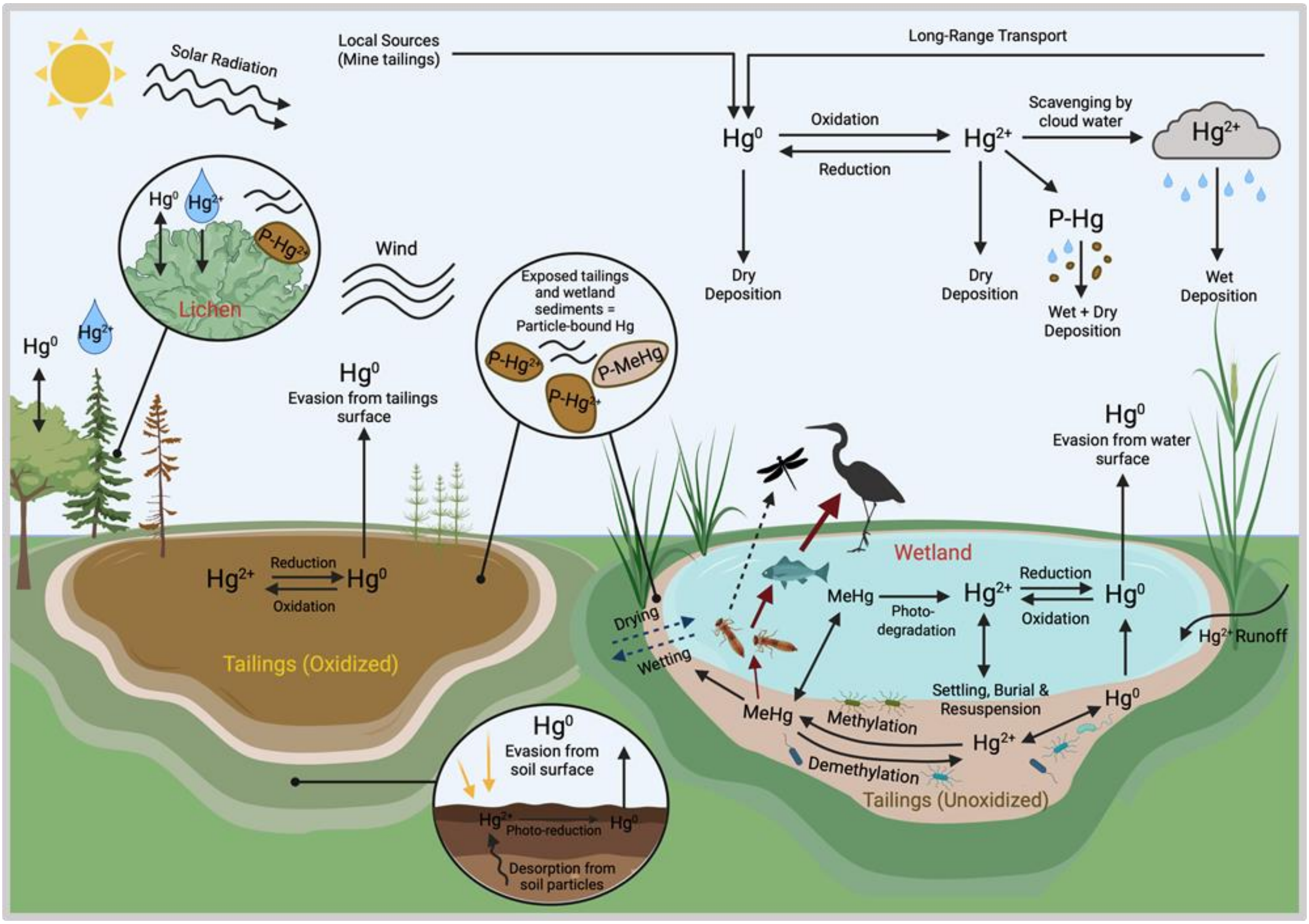


Figure 2. Mercury cycling diagram by Michael Smith, Saint Mary’s University. Image created in Biorender.

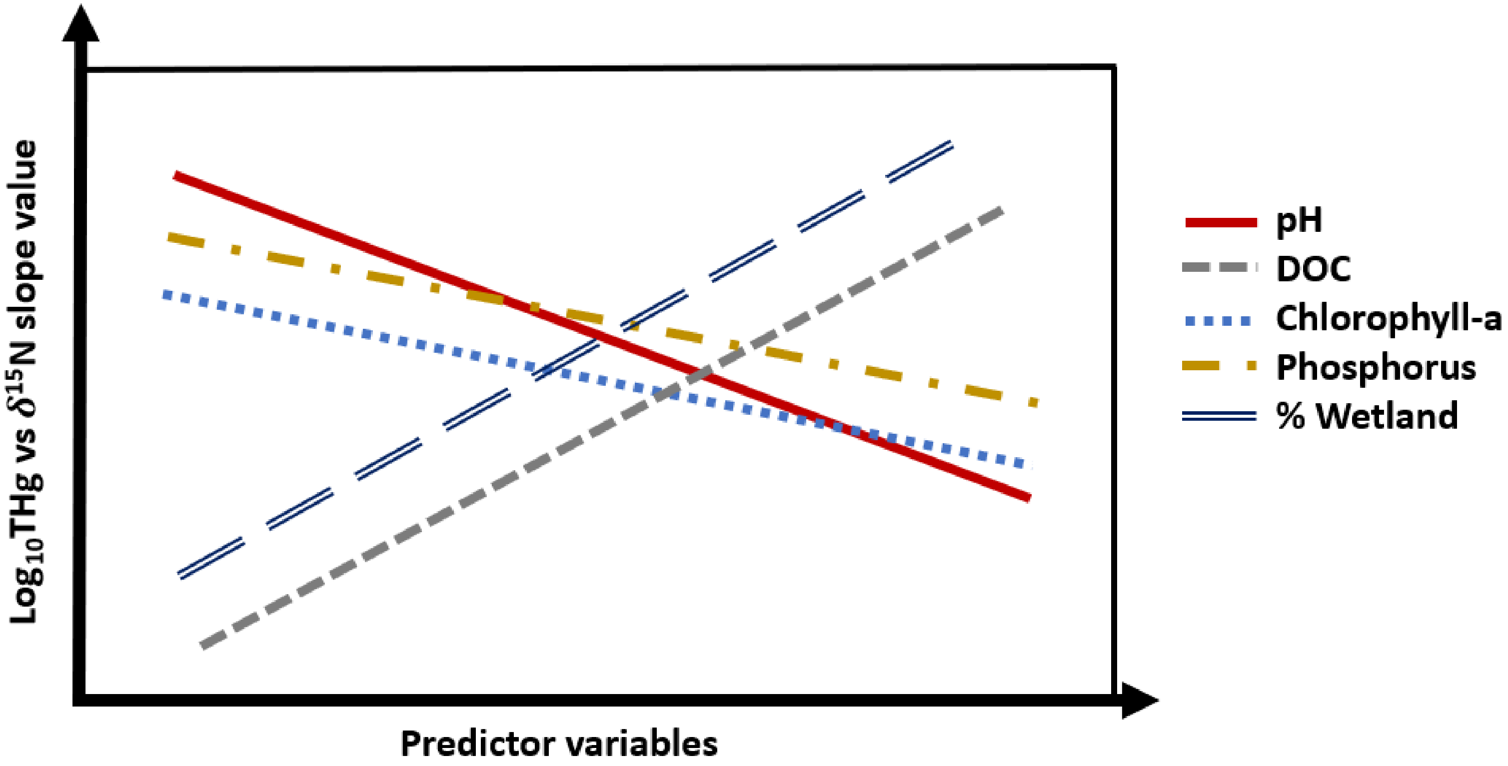


Figure 3. A conceptual model showing the relationship between trophic magnification slope (regression of Log$_{10}$ THg vs δ^{15}N values) and different water quality parameters. (DOC = Dissolved Organic Carbon).

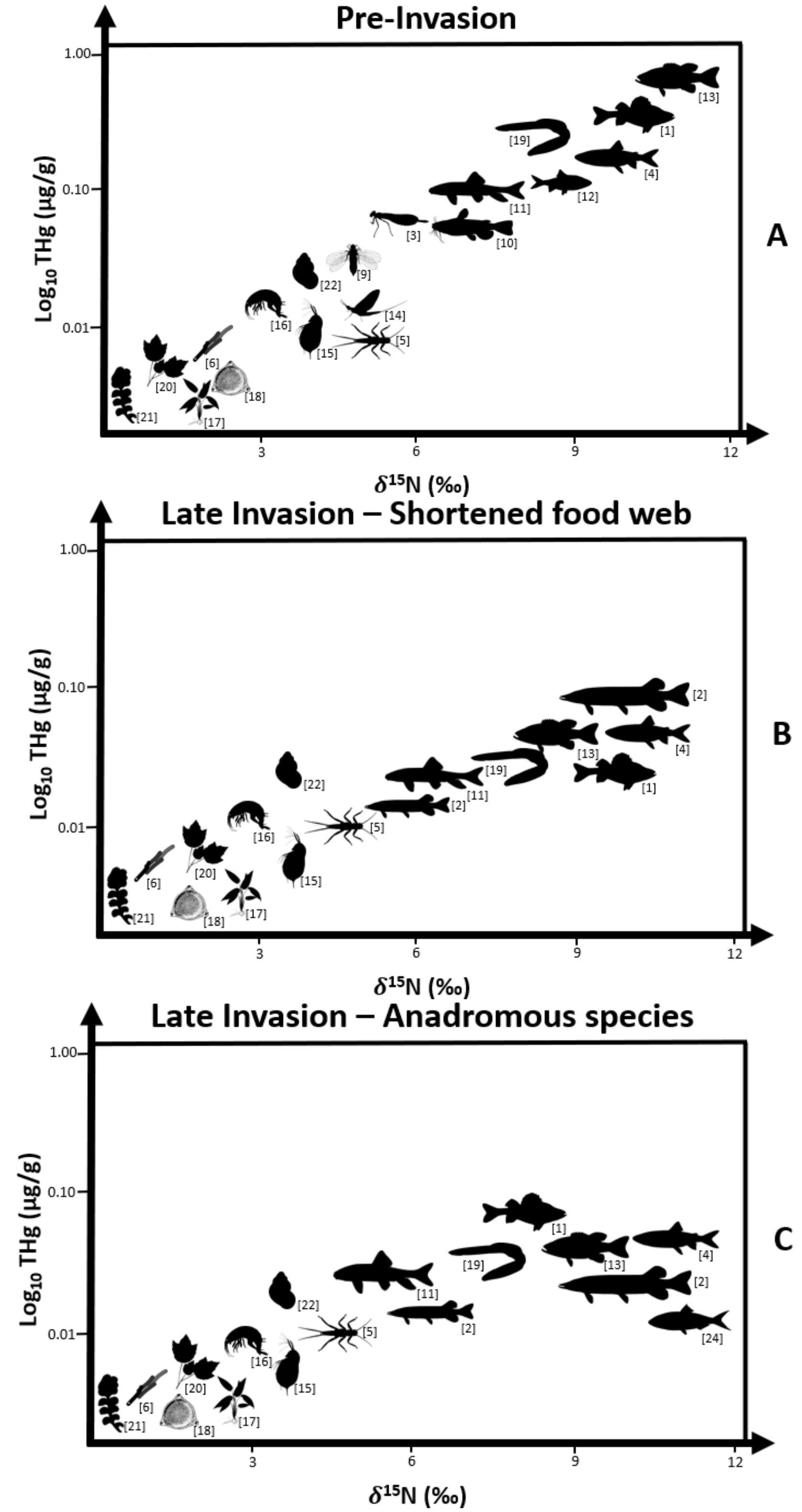


Figure 4. Conceptual models showing the potential mercury biomagnification in Nova Scotia food webs pre-invasion of chain pickerel (A), late invasion with the removal of species (B), and late invasion with the addition of anadromous species (C). Species names and image references outlined in appendix A.

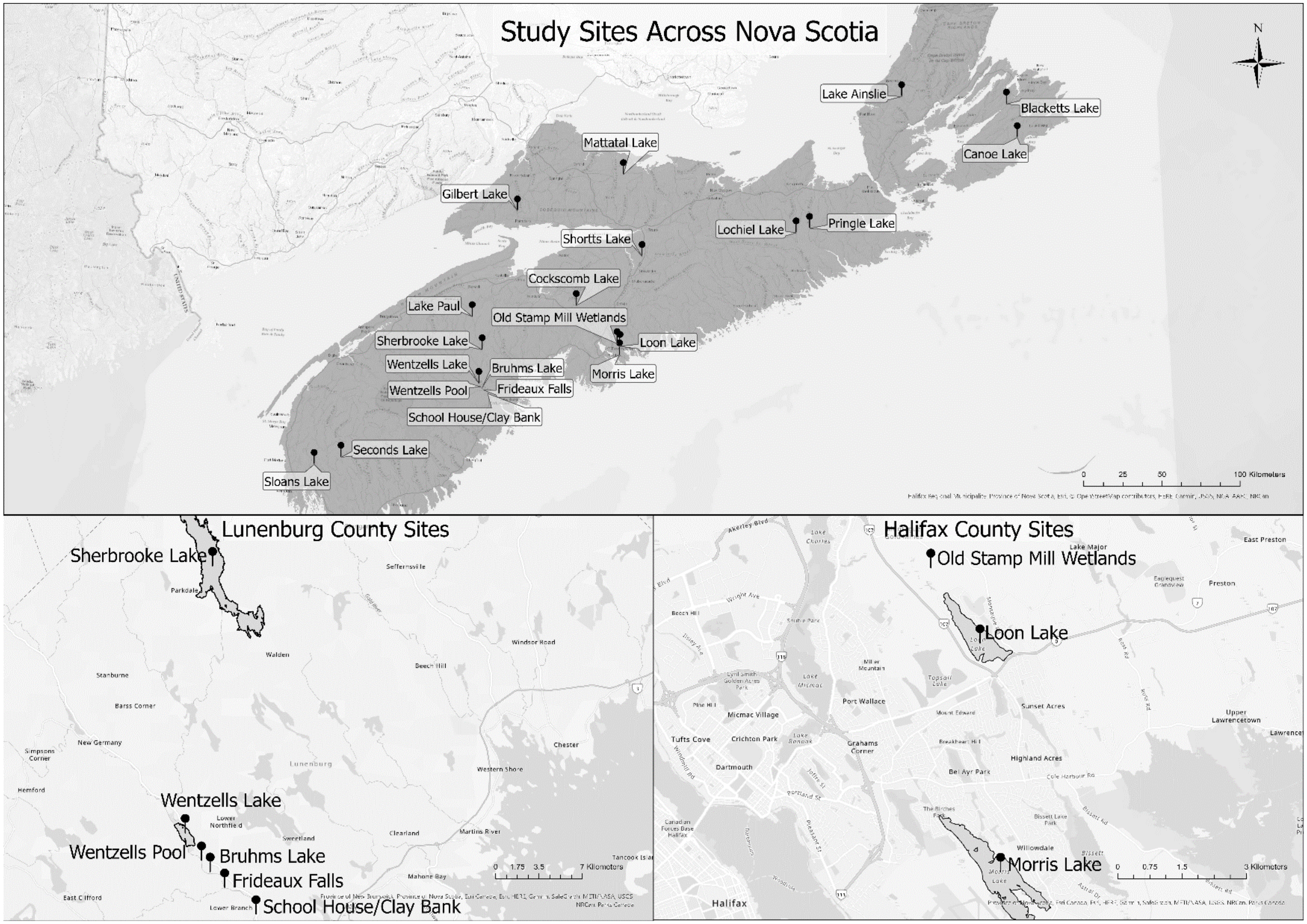
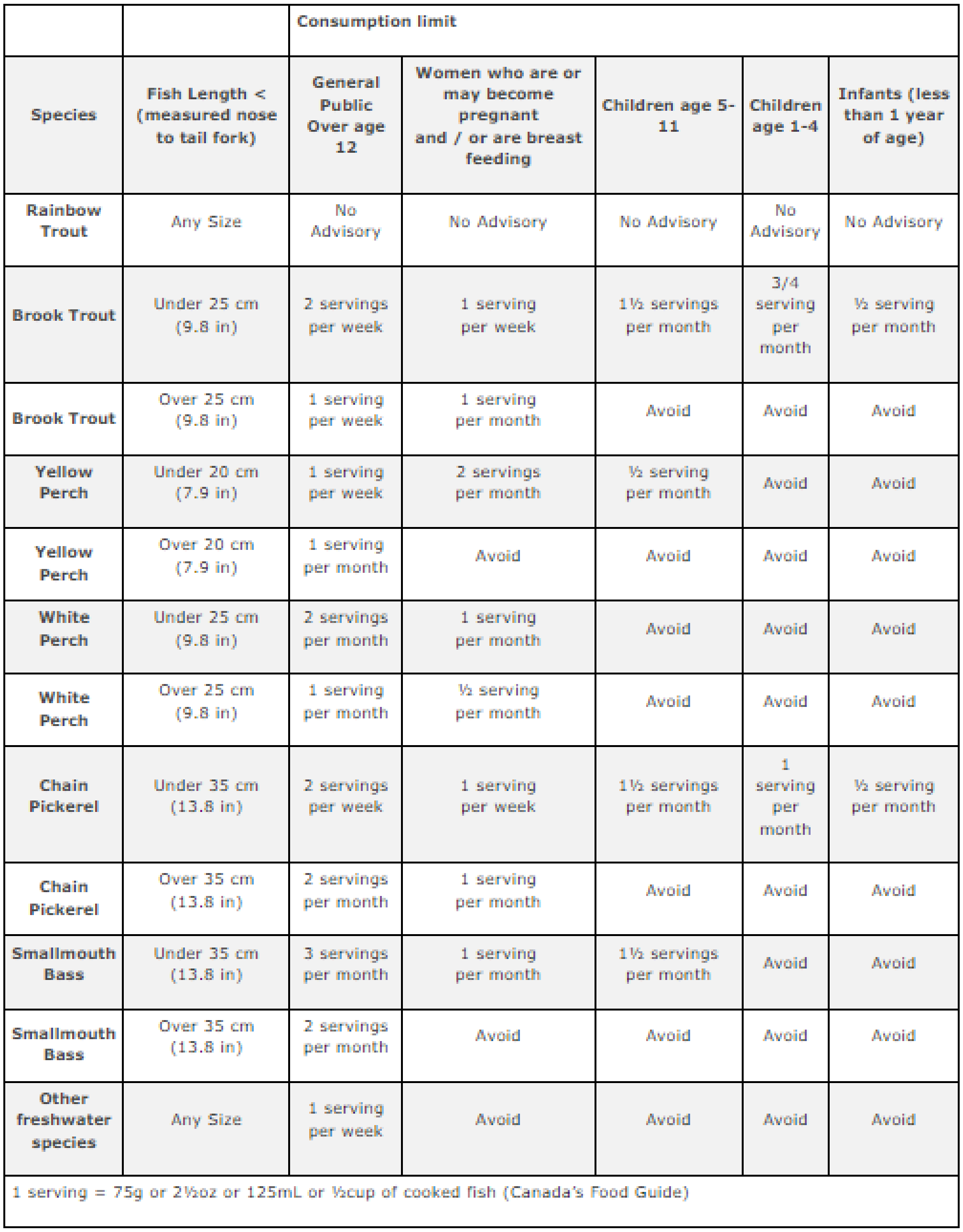


Figure 5. 21 study sites across Nova Scotia.

Chapter 1. Tables

Table 1. Nova Scotia fish consumption guidelines, available from https://novascotia.ca/nse/fish-consumption-advisory.asp (accessed June 23, 2022).



		Consumption limit				
Species	**Fish Length < (measured nose to tail fork)**	**General Public Over age 12**	**Women who are or may become pregnant and / or are breast feeding**	**Children age 5-11**	**Children age 1-4**	**Infants (less than 1 year of age)**
Rainbow Trout	Any Size	No Advisory	No Advisory	No Advisory	No Advisory	No Advisory
Brook Trout	Under 25 cm (9.8 in)	2 servings per week	1 serving per week	1½ servings per month	3/4 serving per month	½ serving per month
Brook Trout	Over 25 cm (9.8 in)	1 serving per week	1 serving per month	Avoid	Avoid	Avoid
Yellow Perch	Under 20 cm (7.9 in)	1 serving per week	2 servings per month	½ serving per month	Avoid	Avoid
Yellow Perch	Over 20 cm (7.9 in)	1 serving per month	Avoid	Avoid	Avoid	Avoid
White Perch	Under 25 cm (9.8 in)	2 servings per month	1 serving per month	Avoid	Avoid	Avoid
White Perch	Over 25 cm (9.8 in)	1 serving per month	½ serving per month	Avoid	Avoid	Avoid
Chain Pickerel	Under 35 cm (13.8 in)	2 servings per week	1 serving per week	1½ servings per month	1 serving per month	½ serving per month
Chain Pickerel	Over 35 cm (13.8 in)	2 servings per month	1 serving per month	Avoid	Avoid	Avoid
Smallmouth Bass	Under 35 cm (13.8 in)	3 servings per month	1 serving per month	1½ servings per month	Avoid	Avoid
Smallmouth Bass	Over 35 cm (13.8 in)	2 servings per month	Avoid	Avoid	Avoid	Avoid
Other freshwater species	Any Size	1 serving per week	Avoid	Avoid	Avoid	Avoid

1 serving = 75g or 2½oz or 125mL or ½cup of cooked fish (Canada's Food Guide)

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Chapter 1. Appendix A.

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Chapter 2. Mercury Biomagnification in Freshwater Food Webs of Nova Scotia.

ABSTRACT

Mercury (Hg), specifically methylmercury (MeHg), biomagnifies consistently in aquatic food webs across the globe. The objective of this study was to examine mercury biomagnification rates across 21 freshwater food webs in Nova Scotia, Canada. Many of the food webs in this study contain invasive species smallmouth bass (*Micropterus dolomieu*) and/or chain pickerel (*Esox niger*). Using stable isotopes carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) and mercury concentrations in muscle tissue of fish and invertebrates, we were able to characterize food webs and biomagnification rates across the province. Mercury concentrations ranged across species and location, while trophic magnification slope factors and intercepts varied significantly among lakes (TMS; 0.021 - 0.423). Food webs standardized to a common primary consumer, Eastern elliptio (*Elliptio complanata*) [*U'jipenekey Elliptio*] mussels, had similar structures, suggesting this is not the main influencing factor for Hg biomagnification rates across the province. Key water quality parameters varied across the study sites. Aluminum and iron were positively correlated with the TMS, while calcium, dissolved oxygen, and secchi depth were negatively correlated to the TMS.

INTRODUCTION

Mercury (Hg) is a wide-spread element that occurs both naturally and as an environmental contaminant. Atmospheric deposition from both natural and anthropogenic sources is one of the most important sources of mercury in water (Swartzendruber & Jaffe, 2012). Naturally occurring sources include volcanoes, geothermal processes, and rock weathering (Falandysz et al., 2020). Atmospheric Hg sources can include the combustion of plant biomass, which could occur through forest, brush, or grassland fires, as well as human use of biofuels (Falandysz et al., 2020). Coal-fired plants are among the primary anthropogenic Hg sources (Mason et al., 2000; NRC, 2015), which can deposit Hg into ecosystems far from the point source.

Mercury in the environment exists as elemental (Hg^0), inorganic (Hg^{2+}), and various organic compounds (Park & Zheng, 2012). Mercury compounds are not required in biological functioning and many forms, especially methylmercury (MeHg), can be highly toxic (LeBlanc et al., 2020; Park & Zheng, 2012). In aquatic systems, the combination of anaerobic conditions, high microbial activity, and abundances of organic carbon (such as wetland conditions) can allow inorganic Hg to undergo methylation and produce organic Hg compounds such as MeHg (O'Driscoll et al., 2005). MeHg then bioaccumulates within organisms; nearly all mercury bioaccumulated by fish and other aquatic organisms is MeHg (Lavoie et al., 2013; Lehnherr, 2014). MeHg biomagnifies consistently in food webs, with concentrations of Hg tending to be highest in top predators such as white perch (*Morone americana*), chain pickerel (*Esox niger*), and smallmouth bass (*Micropterus dolomieu*).

Stable isotope analysis (SIA) of nitrogen ($\delta^{15}N$) can be used in conjunction with trace element concentrations in muscle tissue, allowing researchers to determine the trophic transfer of elements within aquatic food webs. These analyses can allow researchers to fully understand the implications of food web structure and diet on Hg and other trace elements (e.g., Ofukany et al., 2014). This is an important tool for contaminants that bioaccumulate or biomagnify within food webs, such as mercury. Regressing log-transformed Hg concentrations in fish against $\delta^{15}N$ values gives a biomagnification slope value which can be used to assess food web connections and the impact of non-native species over time (e.g., Campbell et al., 2009; Lavoie et al., 2013; Wyn et al., 2010). The equation of this regression slope is the rate at which mercury is biomagnifying in food webs, and can be used to identify the risk for mercury contamination in upper trophic levels.

Mercury concentrations vary in freshwater ecosystems across the globe and are influenced by key physiochemical and environmental factors. At a landscape level, watershed or lake size, wetland area, and connectivity are known to influence the amount of Hg available for methylation and uptake into aquatic food webs (Bodaly et al., 1993; Cabana et al., 1994; Kidd et al., 1995). At a waterbody level, some of the factors influencing Hg biomagnification rates include dissolved organic carbon, annual precipitation, lake alkalinity, nutrient availability, and dissolved organic matter (Kamman et al., 2005; Kidd et al., 2003; Mattieu et al., 2013; O’Driscoll et al., 1995).

Southeastern Canada has been identified as high risk for mercury compared to the rest of the country (e.g., Depew et al., 2013*c*). Studies on mercury in freshwater fish in Nova Scotia have previously been concentrated within Kejimkujik National Park and Historic Site (KNPHS) (e.g., Evers et al., 2007; Clayden et al., 2013; Evers & Clair, 2005; Nocera & Taylor, 1998; Wyn et al., 2009), with limited studies in other areas of the province. The focus on KNPHS is likely because studies have shown that Southwest Nova Scotia [*Kesputkwit* district] is a biological hotspot for Hg concentrations, with some of the highest levels of Hg in fish in North America (Evers et al., 2007; Kamman et al., 2005; Wyn et al., 2010). However, parameters that affect Hg bioaccumulation vary across the province, so examining the rate of accumulation could lead to a better understanding of mercury transfer in the food webs.

This study examines carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotopes and Hg concentrations in detritus, invertebrates, and fish at 21 freshwater sites across Nova Scotia.

METHODS

Sample Collections

Samples were collected from a total of 21 sites across Nova Scotia from 2013-2015 and 2020-2021 (Campbell, 2014*a*; Campbell, 2014*b*; Kickbush, 2015; Stevens, 2014) (Figure 1, Table 1). The 2013-2015 samples include 454 organisms from 15 freshwater lakes, most of which had chain pickerel and/or smallmouth bass across Nova Scotia, ranging from Blacketts Lake in Cape Breton to Second Lake near Yarmouth in southern Nova Scotia. Sampling was conducted in collaboration with Nova Scotia Fisheries & Aquaculture (Campbell, 2014*a*; Campbell, 2014*b*). The 2020-2021 systems include two lakes in the LaHave River [*Pijinuiskaq*] Watershed, Wentzells, and Sherbrooke Lakes, and were sampled as part of a Bluenose Coastal Action Foundation (Coastal Action) program (MacLeod, 2022). Zooplankton, macro invertebrates, and fish were collected from Wentzells and Sherbrooke Lakes; macro invertebrates and fish were collected from the 15 lakes sampled in 2013-2015. The LaHave River Salmon Association collected a total of 40 chain pickerel during the 2020 field season from four sites across the LaHave River. In 2021, a total of 12 fish and 31 invertebrates across eight orders were captured from Sherbrooke Lake, while 43 fish and 18 invertebrates across six orders were captured from Wentzells Lake.

Water quality parameters were collected in the 2021 field season using a YSI sonde. The Nova Scotia provincial database also used similar methodologies – YSI and laboratory testing (Bureau Veritas and QEII).

For detritus sampling, leaf litter was collected near the shoreline of each study site. These samples were placed in scintillation vials and frozen until further analyses.

Zooplankton were collected using a 12" diameter tow net. Samples were collected for mercury analysis, stable isotope analysis, and taxonomic identification. Once collected, samples were strained through 243 µm and 54 µm mesh sizes and split into three sub-samples for analyses and identification. Formalin-preserved whole zooplankton were identified to species level by Lynne Witty at IdentaZoop (Ontario, Canada).

Invertebrates were collected using a Canadian Aquatic Biomonitoring Network (CABIN) kicknet. Roughly following the CABIN protocol, one person “kicked” up the bottom of the lake along the shoreline of each lake for 3-minute increments, while the other followed behind with the CABIN net, collecting debris (Environment Canada, 2012). After 3 minutes, the contents of the CABIN net were placed in a white container to easily remove invertebrates. The mesh was rinsed 3-5 times using lake water and a squeeze bottle and taken to the laboratory. Whole invertebrates were identified to the lowest possible classification in the field, placed in labeled glass scintillation vials, and transported on ice. In the lab, invertebrates were identified to the lowest taxonomic class possible using a microscope and identification keys, rinsed with distilled water, and then frozen for further processing. The order Ephemeroptera was the most abundant for Sherbrooke Lake, while Odonata was the most abundant for Wentzells Lake. Odonata was the most abundant order found in chain pickerel stomach contents (6/21 stomachs contained Odonata, while 11 were empty, 2 contained fish, 2 contained detritus, and 1 contained unidentified vertebrae).

Fish from the 2020 field season were provided by the LaHave River Salmon Association anglers. This volunteer group conducted scientific angling surveys and chain pickerel removal derbies across the LaHave River in 2020.

In the 2013-2015 and 2021 field seasons, native and invasive fish were caught using gill nets deployed for 30-minute intervals or overnight (depending on the lake and presence of endangered species), fyke nets, fish traps, down rigging, as well as scientific angling with artificial lures. Chain pickerel and smallmouth bass were targeted using scientific angling, as it allows for the capture of larger fish that would likely be targeted and consumed by anglers. Excess fish caught were released back into the lake, except for invasive chain pickerel and smallmouth bass which cannot be returned under NS regulations and were euthanized and properly disposed of.

Tissue Preparation and Analyses

To preserve samples, the fish and invertebrates were kept on ice during sampling and placed in a freezer upon returning to the lab. Skin-free fillets were prepared from each fish. A full fillet was taken from lethally sampled fish, and skin was removed from muscle tissue. Macroinvertebrates were processed whole, while zooplankton were processed as composite samples by site. All samples were weighed to collect wet weight (ww) data. The samples were dried at ~60ºC for 24-48 hours using an industrial drying oven at the Kejimukujik National Park and Historic Site laboratory and weighed again to collect dry weight (dw) data. Dried samples were ground to a fine, homogenous powder using a Retsch MM400 mixing mill with clean lab protocols. Procedures to avoid cross-contamination of samples were used throughout these processes, including thoroughly cleaning equipment between samples and sites, and processing samples from least expected contamination to most contamination per site. Ground samples with sufficient mass for both analyses were split into two sets for mercury and stable isotope analyses: one remained at Saint Mary's University (SMU) for Hg analysis, while the second vial was sent to the Stable Isotopes in Nature Laboratory (SINlab) at the University of New Brunswick for stable isotope analysis. Invertebrates with limited sample mass were pooled by location and genus and as processed as composite samples from sites when necessary.

Samples were sent to the SINLab at the University of New Brunswick, Fredericton, New Brunswick. For SIA, SINlab uses Continuous Flow-Isotope Ratio Mass Spectrometry (CF-IRMS) to measure the isotope ratios. For quality control, SINLab normalizes isotope values in animal tissues using secondary standards USGS61, BLS, and MLS; and for plant materials, they use CMS, SPS, SPL, and EPS.

Total mercury (THg) was analyzed using a Direct Mercury Analyzer (DMA) 80.3 in a clean-room laboratory at Saint Mary's University using trace-metal protocols. Samples were run in cleaned quartz sample boats. Trace-element protocols were followed to ensure no cross-contamination of samples. Each analysis run included multiple blanks, a series of liquid mercury standards (0, 5, 10, and 20 ppm) as well as three certified reference materials (CRM), to ensure calibration accuracy. The CRMs used were Tort3, Dorm4, and Dolt5. Three to five blanks were run every 10 samples and between sites to prevent contamination carry-over and to check accuracy duplicate samples were run every 20 samples. All mercury data is presented as THg ppm of dry weight unless otherwise stated.

Data analyses

Log_{10} transformations of Hg removed heterogeneity of variance prior to statistical analysis. Simple linear regressions using log_{10} mercury concentrations in tissue vs. $\delta^{15}N$ gave trophic magnification slopes (TMS) for food webs. TMS were compared among lakes using ANCOVA with $log_{10}Hg$ as the dependent variable and $\delta^{15}N$ as the covariate. Maps were created using ArcGIS Pro version 3.0.2. Statistical analyses were performed using RStudio version 4.1.2 and R version 3.0 (R Core Team, 2021). The correlation matrix was created using the Corrplot package (Wei & Simko, 2021) in RStudio. Other figures were created using package ggplot 2 in RStudio (Wickham, 2016).

Data Transformations

Commercial guidelines for mercury in fish are given in wet weight mg/kg fish tissue. To compare results from Nova Scotia food webs, this was transformed to dry weight using the average moisture content of fish (79.39 % ± 8.23%) from LaHave River Watershed.

Eastern elliptio (*Elliptio complanata*; Family Unionidae) [*U'jipenekey Elliptio*], a common filter-feeding mussel, was used to standardize the $\delta^{15}N$ values of the eight food webs containing samples for this species. The trophic position of fish was calculated using Cabana and Rassmussen's (1996) approach, assuming a trophic fractionation rate of 3.4‰:

$[(\delta^{15}N_{sample} - \delta^{15}N_{unionidae})/3.4] + 2$

Where $\delta^{15}N_{unionidae}$ is the average $\delta^{15}N$ of Eastern elliptio for that lake.

RESULTS

Food Webs

Food web structure was similar across the eight Nova Scotian lakes with Eastern elliptio mussels (Figure 2). As expected, there was a continual increase in $\delta^{15}N$ values, and corresponding trophic position increased consistently from detritus to top predators. Eastern elliptio were consistent across food webs in both $\delta^{13}C$ sources (-32.4‰ – -27.9‰) and trophic positions (TP 1.81 – 2.86). Fish were at similar trophic positions in standardized food webs (TP 2.36 – 4.22 SD 0.36), and individuals of the same species generally exhibited similar trophic positions and carbon sources.

Across all lakes, $\delta^{15}N$ was lowest in detritus, Ephemeroptera and Unionida. $\delta^{15}N$ was highest in piscivorous fish in families Esocidae and Centrarchidae (4.65 – 15.53‰).

Water Quality

Water quality parameters were available for 13 of the lakes sampled for Hg and SIA. All lakes had pH data, which ranged from 5.78 – 7.8 (Table 3). Based on the 13 lake water quality data, aluminum and iron were positively correlated with the TMS, while calcium, dissolved oxygen, and secchi depth were negatively correlated with the TMS (Figure 3).

Mercury

Mercury ranged over several orders of magnitude across species, from 0.043 mg/kg in the detritus from Sherbrooke Lake to 10.57 mg/kg in a white perch from Gilbert Lake. Piscivorous fish had elevated mercury, with 21.1% (83/394) of all sampled fish having mercury concentrations greater than 2.33 mg/kg (dry muscle tissue). Hg was positively correlated with fish length in all waterbodies except Wentzells Lake, which had a neutral correlation (p = 0.5464) (Figure 4; Table 4). Mercury concentrations in chain pickerel varied by waterbody, from an average of 0.46 mg/kg (± 0.24 SD) in Morris Lake to 3.31mg/kg (± 1.69 SD) in Seconds Lake (Figure 5).

There was variation in Hg bioaccumulation between waterbodies, shown in the trophic magnification slopes (TMS; 0.021 - 0.423) where factors and intercepts varied significantly among lakes (0.021 - 0.423; p<0.001) (Table 2, Figure 6). Shortts Lake was the only lake with a negative TMS but only occurred with the analysis including anadromous species alewife (*Alosa pseudoharengus*) [*Kaspelaw*]. TMS values changed when alewife were included in the analysis compared to the analysis of exclusively freshwater species (Table 2).

DISCUSSION

Food Webs

Food web structures were similar across the eight lakes standardized using eastern elliptio mussels. One aspect of interest is that chain pickerel, smallmouth bass, and white perch consistently share overlapping ranges of δ^{15}N and δ^{13}C values. This suggests that the non-indigenous fish species are competing with native white perch for similar resources in each lake.

Stable isotope analysis is a useful tool, but it does have some limitations. SIA works best in systems that have existing isotopic parameters calculated from laboratory and field data (Boecklen et al., 2011; Post, 2002). There can also be variation in isotopic values, making it challenging to assess the data. For carbon and nitrogen, variation in trophic shift can be caused by differences in diet, sample preparation (McCutchan et al., 2003), biochemical nitrogenous waste, taxonomic classes, and environment (Vanderklift

& Ponsard, 2003). The study sites did not have existing isotopic parameters; however, to reduce variation in stable isotope data, samples within each system were collected at the same time.

Water Quality

Water quality varied across lakes by several magnitudes of order. In the Nova Scotia water quality database, pH ranged from 3.40 to 9.79, a tremendous range, and for our study lakes, pH had the greatest range of all the water quality parameters, from 5.78 to 7.8. pH is known to be significantly correlated with Hg in fish (Essington & Houser, 2003; Grieb et al., 1990; Jardine et al., 2013). Chlorophyll-a concentrations, also known to influence mercury in food webs (Pickhardt et al., 2002), varied across the lakes from 0.89 to 7.3 µg/L. These water quality variables are known to influence the availability of mercury for methylation and bioaccumulation in aquatic food webs; therefore, significant variation within these parameters across sites could influence the TMS values and Hg bioaccumulation.

Mercury

Nova Scotia, particularly Southwest Nova Scotia, is known as a biological hotspot for mercury concentrations. This also pertains to bioaccumulation in freshwater fish, as Southwest Nova Scotia was found to have some of the highest levels of Hg in fish in North America (Evers et al., 2007; Kamman et al. 2005). Mercury concentrations are correlated with trophic position, being highest in piscivorous species and increasing in concentrations with age and size (Depew et al., 2013; Gandhi et al., 2014; Haines, 1997; Neumann & Ward, 1999; Wyn et al., 2009). Top predators, such as chain pickerel and smallmouth bass, are more likeot to have elevated Hg concentrations than lower trophic position species, which was consistent with our findings. Trophic position was an indicator of mercury concentration, as it increased with $\delta^{15}N$ values within each waterbody, and Hg levels were consistently elevated across the study lakes.

Health Canada Guidelines for the maximum total mercury in retail fish is 0.5 ppm for most fish, while some piscivorous fish species have a limit of 1.0 ppm (Health Canada, 2020). This value is based on the wet weight of muscle tissue, so with an average moisture content of 79.39 % ± 8.23% for fish in the LaHave, the Health Canada Guidelines are equivalent to approximately 2.3ppm; 21.1% of fish in this study exceeded those guidelines. This has some implications for human health, as mercury is a neurotoxic chemical (Hong et al., 2012; WHO, 1990). Hg in fish can be more than 90% MeHg (Bloom, 1992), which can be a human health concern if fish is regularly consumed (Campbell et al., 2003; Pirkle et al., 2016). Hg concentrations in 21% of fish in this study surpassing commercial guidelines is a potential concern for anglers across Nova Scotia who consume fish they catch.

Mercury concentration ranged across both species and location; however, similarity in food webs across the province indicates another variable is influencing mercury biomagnification rates. These differences could be from water chemistry, as mercury concentrations tend to be higher in more acidic waterbodies (Burgess & Meyer, 2008; Chen et al. 2005; Grieb et al., 1990). Another variable is the abundance of wetlands. A variety of factors in wetlands, including low pH, high DOC, and an abundance of microorganisms that methylate Hg at high rates can increase the availability of MeHg for uptake into the food web (Miskimmin et al., 1991; St. Louis et al., 1994;

Thomas et al., 2020). Water quality varied across the lakes, which could provide one explanation for the variation in biomagnification rates.

Fish size is often correlated with mercury concentrations (Bowles et al., 2001; Kamman et al., 2005), which could be the result of water chemistry (Thomas et al., 2020) or available nutrients; however, sometimes there can be a negative or neutral correlation of size and Hg. Chain pickerel total length was positively correlated with mercury concentrations in all food webs, except for Wentzells Lake. This neutral correlation could be due to growth dilution. Growth dilution is when an organism of high trophic position has lower Hg concentrations than expected. This occurs when rapid growth reduces Hg concentrations because the gain in biomass is greater relative to the gain of Hg in tissue (Karimi et al., 2007). Rapid growth from high-quality food can decrease the accumulation and transfer of Hg in freshwater food webs (Karimi et al., 2007). There were more chain pickerel sampled from Wentzells Lake than any other food web, which could account for the variation in these data.

Anadromous species, such as alewife, can change freshwater food webs by adding marine isotopic signatures and low mercury concentrations. MeHg availability significantly increases from marine to freshwater sites and tends to be highest in lakes (Evers & Clair, 2005). Anadromous fish also tend to grow faster than resident freshwater-only fish, resulting in lower Hg due to growth dilution (Swanson & Kidd, 2010). Therefore, predator dependence on anadromous species could introduce lower MeHg values to food webs. Top predators in freshwater food webs have previously been shown to have lower Hg concentrations when anadromous species are present (Swanson & Kidd, 2010), which was consistent with our findings. Across Nova Scotia, trophic magnification slopes were lower when alewife were included in the analysis. In Wentzells Lake, although invertebrates are the dominant food item of smallmouth bass and chain pickerel, they also consume alewife during their migration from May to June (MacLeod, 2020). Anadromous species could cause lower biomagnification and bioaccumulation rates in Nova Scotian freshwater food webs.

In this study, only 21 chain pickerel were examined for stomach contents, as fillets from the other chain pickerel were donated from the LaHave River Salmon Association (LRSA). Stomach contents were not included in the LRSA donated samples, as the other parts of the fish were given to different research groups. Of these, 28% of chain pickerel stomachs contained Odonata species, which was the most frequently consumed food item. It has been documented that chain pickerel frequently consume dragonfly nymphs (Raney, 1942; Warner, 1973), which could negatively impact their populations. There are limited studies on the impact of chain pickerel on Odonata species. Uptake of mercury at the base of the food web is important for determining mercury concentrations in top predators (Wyn et al., 2009), therefore the reliance on Odonata would have influenced the mercury concentrations in chain pickerel.

Nova Scotia has two common aquatic invasive species which were present in many of the study lakes: smallmouth bass and chain pickerel. Smallmouth bass were introduced as a sportfish in Nova Scotia in 1942 (LeBlanc, 2010), and now have a significant recreational fishery throughout the province. Chain pickerel were illegally introduced to Digby County in 1945 (Gilhen, 1969), and have since spread across the province through the illegal movement of live fish and subsequent dispersal within adjoining watersheds (Mitchell et al., 2010). These two piscivorous species are now present throughout Nova Scotia and may be influencing Hg concentrations in food webs.

The introduction of predatory fish can alter community structure through a decrease in the abundance of fish, benthic invertebrates, and zooplankton (Gallardo et al., 2016; Vander Zanen et al., 1999), which can in turn influence water quality such as algae production (Eriksson et al., 2009). This could impact the transfer of contaminants, such as Hg, as biomagnification and bioaccumulation are impacted by food web structure and water quality parameters. The presence and time since the introduction of invasive smallmouth bass and chain pickerel may affect the risk of Hg in fish within that waterbody. In this study, there were no significant differences in Hg concentrations or TMS values of food webs with invasive species versus food webs with only native species. Although further research is needed to investigate these relationships within Nova Scotia waterbodies.

Limitations

The global COVID-19 pandemic created significant delays for the start of the 2021 fieldwork season which had a cascading effect on logistics throughout the remaining field season. This resulted in the bulk of the sampling occurring during the warmer months of July. This impacted the lake sampling processes as well as the success of the invertebrate sampling efforts. The combination of these delays led us to include the historic 15 lake data from previous studies. Not all lakes were included in the final analyses, due to limited data availability. Lake Ainslie was excluded due to limited species for Hg data.

Conclusions

In conclusion, we have shown that mercury biomagnification and bioaccumulation rates vary across Nova Scotia, despite similar food web structures. Further research should examine the underlying causes of these differences. Mercury concentrations in freshwater fish could be a concern for human health, as Nova Scotia has a large recreational fishery. Investigating the causes of Hg biomagnification could further increase knowledge of mercury risk to humans within the province.

Chapter 2. Figures

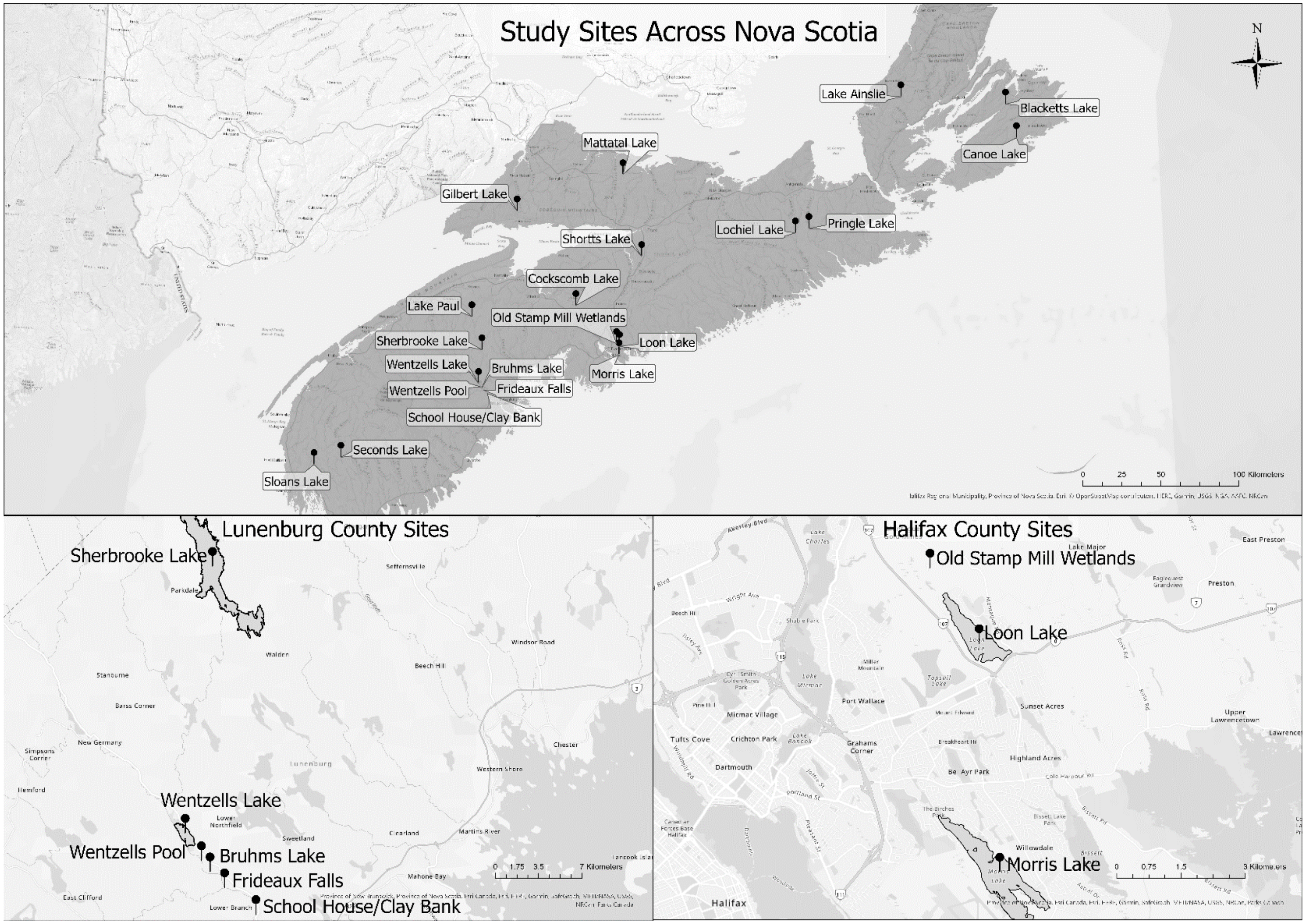

Figure 1. 21 study sites across Nova Scotia. 15 lakes sampled in 2013-2015; 6 sites sampled in 2020-2021.

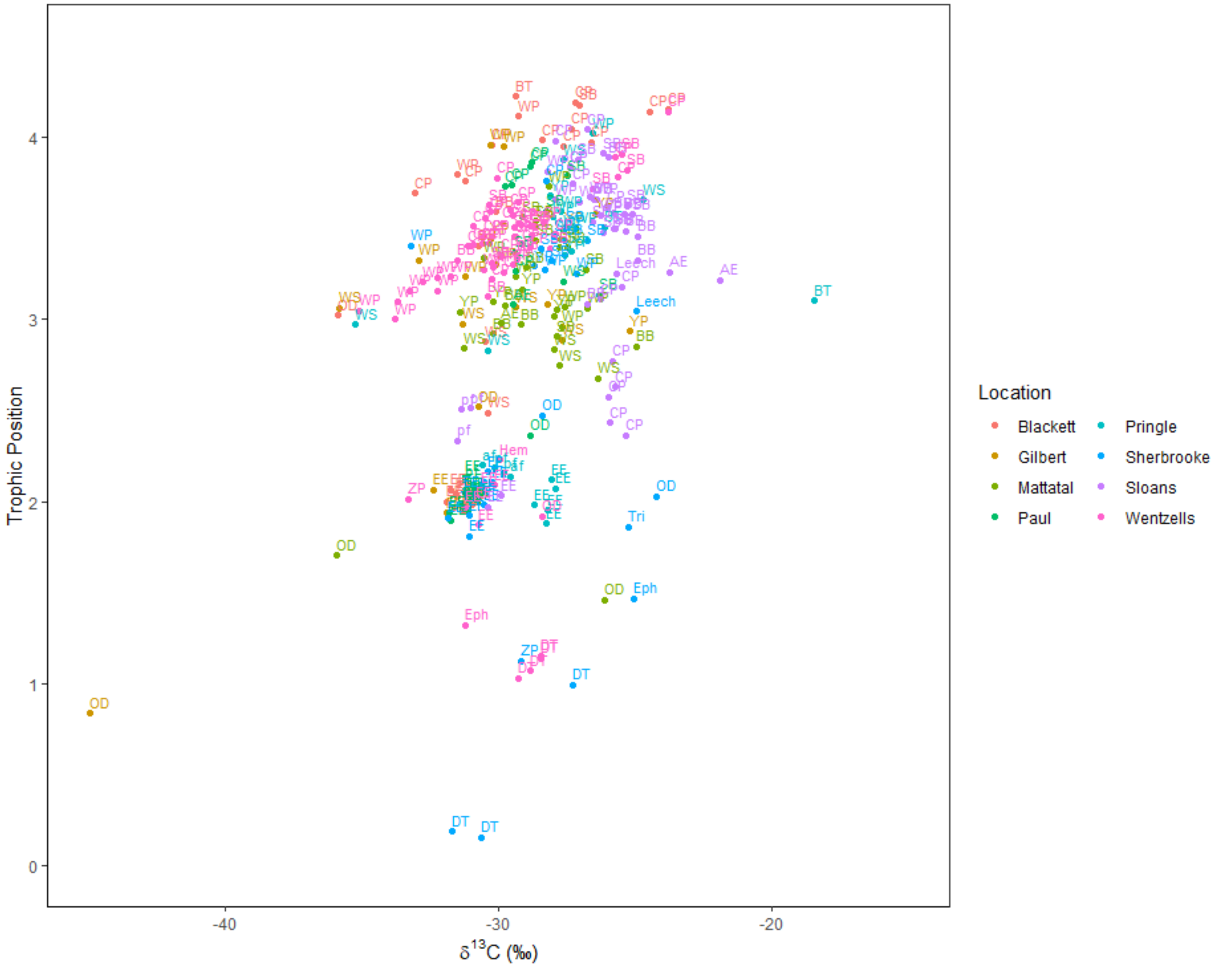

Figure 2. Eight freshwater food webs of Nova Scotia standardized to $\delta^{15}N$ of baseline organism eastern elliptio (*Elliptio complanata*). See table 1, appendix A for species codes. Only sites that had data for eastern eliptio and sufficent data for TMS comparison were included in this analysis. Lake Ainslie was excluded due to lack of Hg data. (n = 8).

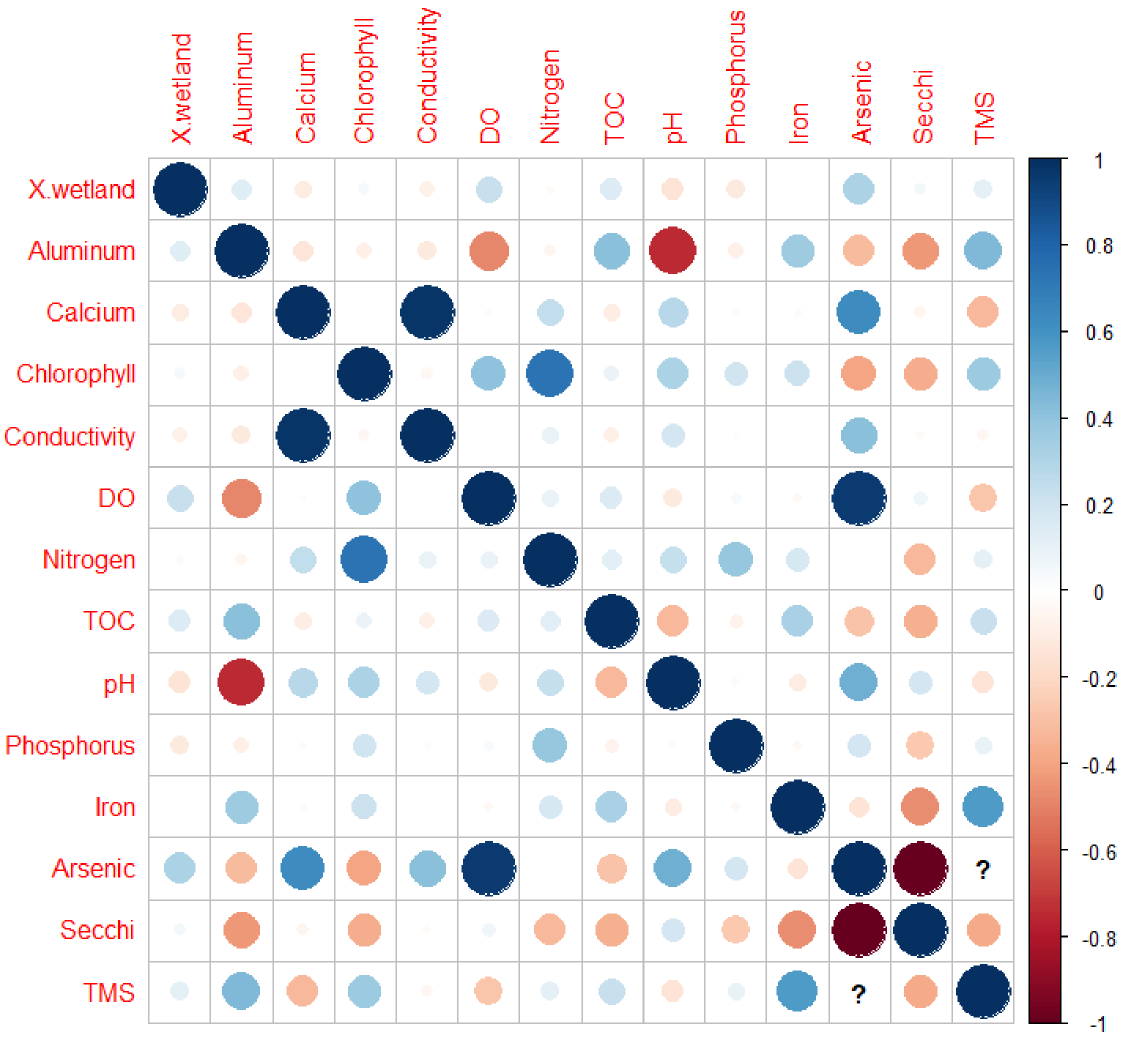

Figure 3. Correlation matrix for various water quality parameters and trophic magnification slope. X.wetland is the percent cover of wetland of the primary watershed. (n = 13).

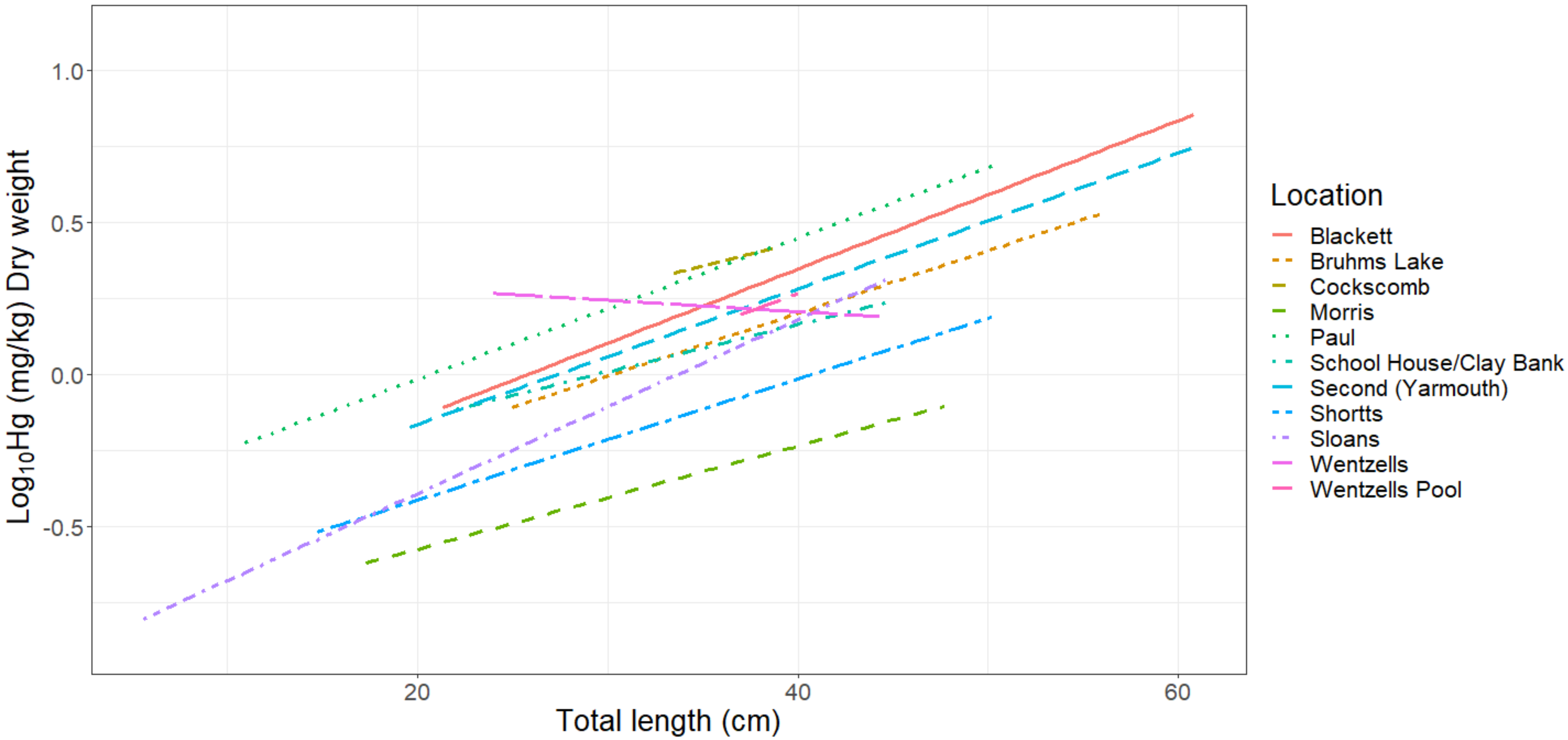

Figure 4. Regression of total length and $\log_{10}$ THg for chain pickerel for 11 sites containing chain pickerel. Total number of chain pickerel included = 115. Frideaux Falls and Sherbrooke Lake were excluded due to limited data.

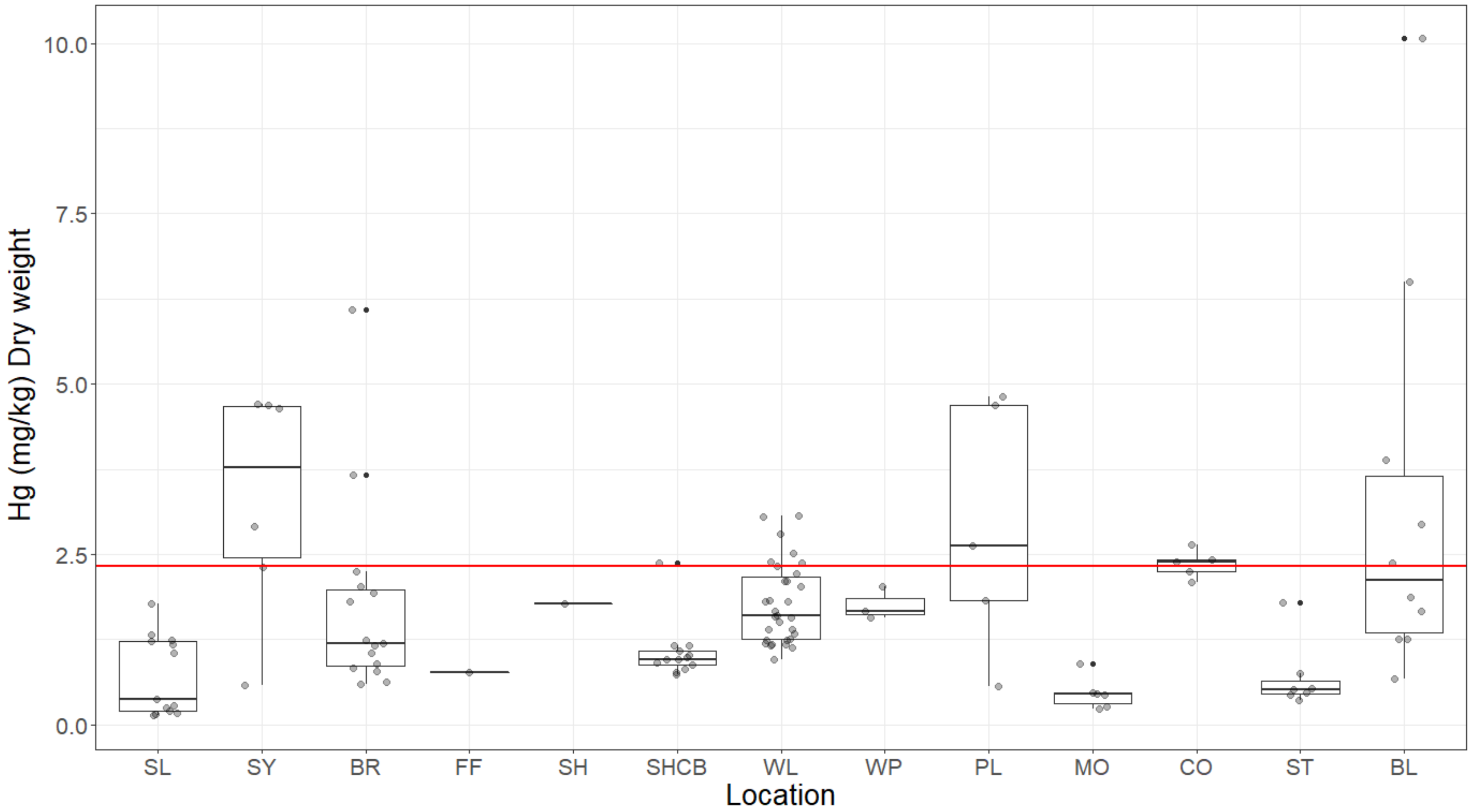

Figure 5. Boxplot of mercury concentration in invasive chain pickerel (*Esox niger*) grouped from east to west across study sites. Red line indicates Health Canada guidelines for mercury in fish converted from wet weight (0.5mg/kg) to dry weight (2.33mg/kg). See table 1 for site codes. (n = 117).

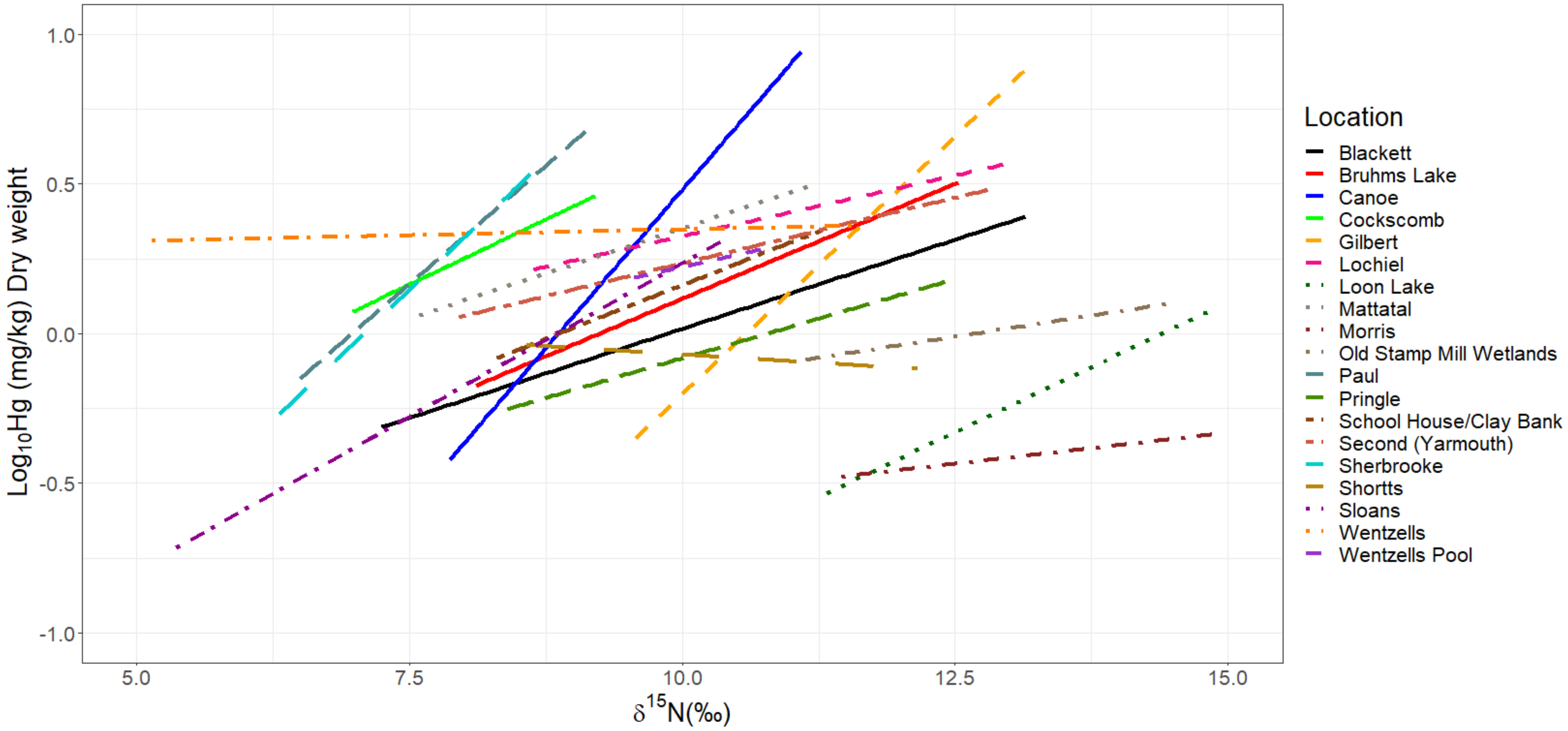

Figure 6. Trophic magnification slopes for 19 freshwater lakes across Nova Scotia.

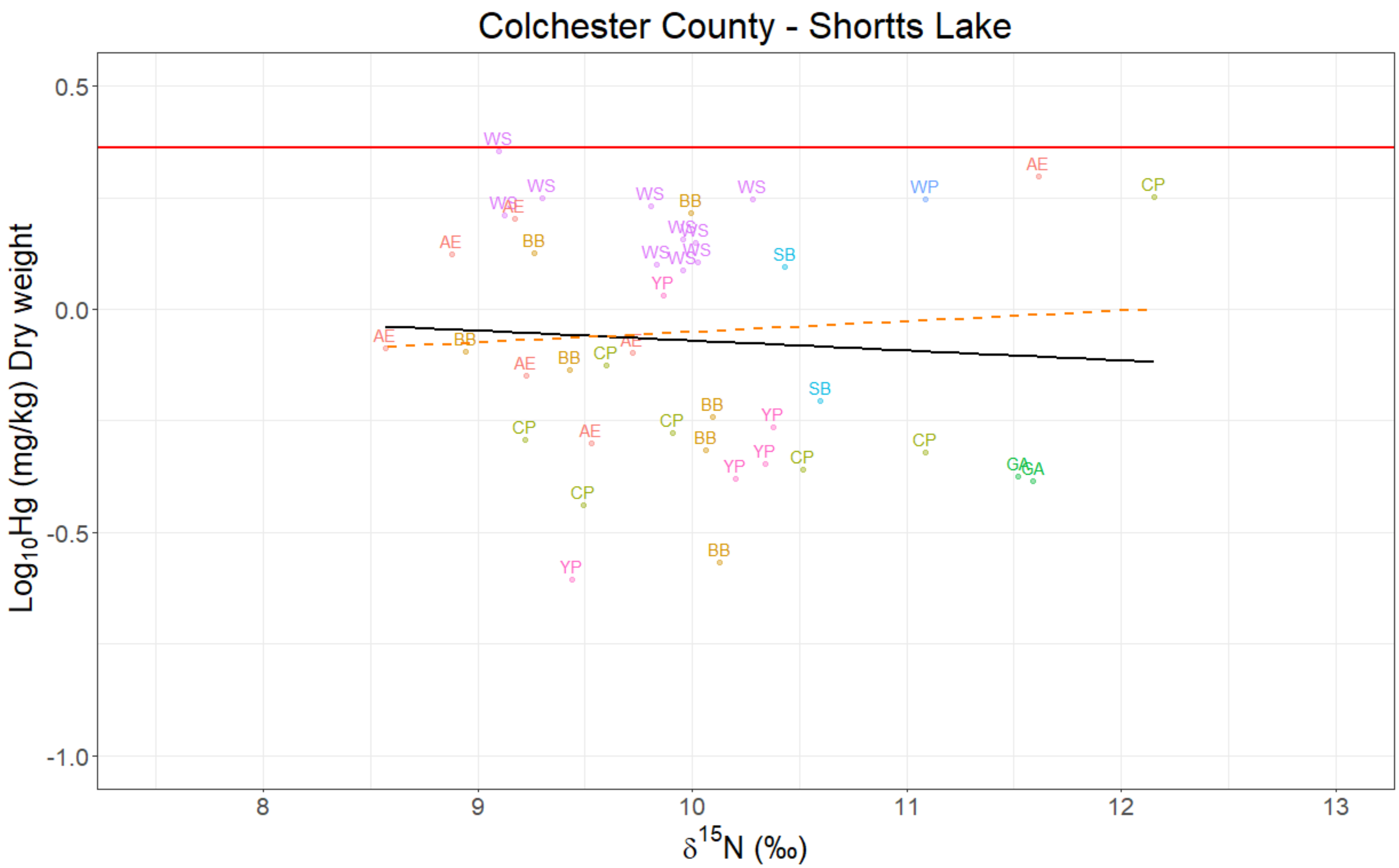

Figure 7. Shortts Lake trophic magnification slopes for freshwater species (orange dashed line; Slope = -0.26322 (δ^{15}N) (n = 39) + 0.02108, r^2 = 0.003526) and all species (black line; Slope = 0.15206 (δ^{15}N) – 0.02226, r^2 = 0.004558) (n = 41).

Chapter 2. Tables

Table 1. Site coordinates and year of sample collection, with the year of chain pickerel (CP) and smallmouth bass (SMB) presence confirmed (n = 21). Note: The date of confirmation is confirmed presence by NS Fisheries, may not correlate with the date of introduction. Data on presence confirmed provided by NS Fisheries and Aquaculture.

County	Data Collection Site	Site Code	Lat, Long	Year Sampled	CP confirmed	SMB confirmed
Cape Breton	Blacketts Lake	BL	46.066972, -60.308781	2013	2010	2009
	Canoe Lake	CL	45.871346, -60.228088	2013	-	-
Colchester	Shortts Lake	ST	45.219106, -63.31812	2014	1994	1988
Cumberland	Gilbert Lake	GI	45.474441, -64.339832	2013	-	2015
	Mattatal Lake	MA	45.690769, -63.474066	2013	-	2001
Guysborough	Lochiel Lake	LO	45.351968, -62.060528	2013	-	-
	Pringle Lake	PG	45.37667, -61.95028	2013	-	-
Halifax	Loon Lake	LN	44.700, -63.502	2015	-	1984
	Morris Lake	MO	44.651519, -63.497253	2014	2000	1975
	Old Stamp Mill Wetlands	OS	44.716, -63.518	2015	-	-
Hants	Cockscomb Lake	CO	44.9333, -63.85	2014	1999	2002
Inverness	Lake Ainslie	AI	46.126552, -61.173557	2013	-	2003
Kings	Lake Paul	PL	44.86026, -64.692135	2014	2002	2002
Lunenburg	Bruhms Lake	BR	44.448663, -64.601745	2020	-	1997
	Frideaux Falls	FF	44.437261, -64.586734	2020	-	1997
	School House/Clay Bank	SHCB	44.418016, -64.554507	2020	-	1997
	Sherbrooke Lake	SH	44.670580, -64.605887	2021	2010	1997
	Wentzells Lake	WL	44.475650, -64.627756	2020/2021	2010	1998
	Wentzells Pool	WP	44.456549, -64.610424	2020	-	1997
Yarmouth	Second Lake	SY	44.02936, -65.715808	2014	2018	-
	Sloans Lake	SL	43.982166, -65.927802	2014	2009	2009

Table 2. Regression of Log$_{10}$ THg and δ^{15}N (‰) in aquatic food webs of Nova Scotia. See Table 1 for site codes. Lake Ainslie was not included due to limited data. * Indicates chain pickerel-only sites; [f] Indicates freshwater species only; [a] indicates all species included.

Location	Slope	SE slope	Intercept	SE intercept	Multiple r^2	Adj. r^2	p-value
ST[f]	0.0212	0.0583	-0.2632	0.5787	0.004	-0.0234	0.7195
ST[a]	-0.0223	0.0527	0.1521	0.5277	0.005	-0.0210	0.6749
OS	0.0561	0.0320	-0.7119	0.4086	0.090	0.0608	0.0896
LO	0.0811	0.0502	-0.4865	0.5204	0.157	0.0970	0.1285
SY[f]	0.1303	0.0396	-1.0497	0.4178	0.351	0.3184	0.0037
SY[a]	0.0878	0.0507	-0.6429	0.5377	0.125	0.0834	0.0978
MO[f]	0.1448	0.0459	-2.3697	0.6574	0.302	0.2713	0.0045
MO[a]	0.0895	0.0300	-1.5618	0.4089	0.241	0.2148	0.0050
SH	0.1088	0.0241	-0.5583	0.1286	0.440	0.4182	0.0001
MA	0.1159	0.0601	-0.8018	0.5510	0.129	0.0945	0.0654
BL[f]	0.1452	0.0400	-1.4143	0.4779	0.447	0.4119	0.0024
BL[a]	0.1375	0.0452	-1.3577	0.5361	0.352	0.3139	0.0074
SHCB*	0.1435	0.0277	-1.2754	0.2481	0.709	0.6824	0.0003
WL	0.1469	0.0140	-1.0140	0.1230	0.623	0.6169	5.72E-15
BR*	0.1537	0.0209	-1.4212	0.2158	0.806	0.7908	5.65E-06
CO	0.1742	0.0430	-1.1426	0.3643	0.701	0.6581	0.0049
PG	0.1763	0.0973	-1.9462	1.0326	0.202	0.1403	0.0931
LN	0.1917	0.0620	-2.7336	0.8365	0.389	0.3485	0.0074
SL	0.2043	0.0257	-1.8088	0.2174	0.644	0.6337	2.34E-09
PL	0.3156	0.0736	-2.2020	0.5903	0.672	0.6352	0.0020
GI	0.3599	0.0464	-3.8096	0.5153	0.822	0.8084	3.16E-06
CL	0.4232	0.0673	-3.7524	0.6269	0.798	0.7778	9.09E-05

Table 3. Water quality parameters of lakes sampled for mercury and stable isotope analysis. - indicates no data available. Data from the Nova Scotia water quality database. Chl-a = Chlorophyll-a; SPC = Specific Conductance; DO = Dissolved Oxygen; Al = Aluminum; Ca = Calcium; P = Total Phosphorus; TOC = Total Organic Carbon; Fe = Iron. (n = 13).

Site Code	**Chl-a (ug/L)**	**SPC (us/cm)**	**DO (mg/L)**	**pH**	**Al (mg/L)**	**Ca (mg/L)**	**P (mg/L)**	**TOC (mg/L)**	**Fe (mg/L)**	**Secchi depth (m)**	**Max. depth (m)**	**Surface area (km^2)**
BL	2.4	156.0	12.1	7.8	0.021	13.4	0.003	4.5	0.05	1.2	25	1.72
CL	2.9	39.4	-	7	0.044	2.5	0.004	6.6	0.07	3.4	-	0.249
ST	3.0	134.0	-	7.6	-	11.8	0.004	4.8	0.05	4.5	14	1.781
GI	7.3	49.8	-	7	0.095	3.1	0.006	5.4	0.14	2.4	-	0.227
MA	2.7	47.2	-	7.4	-	4.5	0.009	4.8	0.11	-	9	1.068
SL	1.3	42.9	-	7	0.036	1.5	0.003	4.5	0.05	4.3	-	1.564
LO	2.9	50.4	-	7.4	0.012	3.7	0.002	3.7	0.05	-	28	1.292
PG	1.5	66.8	-	7.2	0.006	2.7	0.002	2.7	0.05	-	75	0.627
LN	1.1	331.0	8.0	7.61	-	9.9	0.005	-	-	3.5	6	-
MO	0.9	-	-	6.9	0.015	12.9	0.006	-	0.05	-	10	-
CO	1.8	30.5	-	5.8	0.150	1.2	0.005	6.5	0.08	-	30	1.455
SH	4.6	26.8	9.5	6.2	-	-	-	-	-	3.1	27	16.94
WL	-	42.1	6.2	5.8	-	-	-	-	-	1.5	12	-

Table 4. Regression of Log_{10} THg and total length (cm) of chain pickerel across freshwater sites in Nova Scotia. See Table 1 for site codes.

Location	**Slope**	**SE slope**	**Intercept**	**SE intercept**	**Multiple r^2**	**Adj. r^2**	**p-value**
WL	-0.0038	0.0062	0.3565	0.2134	0.0127	-0.0214	0.5464
SHCB	0.0155	0.0048	-0.4587	0.1473	0.4836	0.4367	0.0083
CO	0.0157	0.0041	-0.1929	0.1480	0.8292	0.7722	0.0317
MO	0.0170	0.0033	-0.9151	0.1102	0.8666	0.8333	0.0070
ST	0.0199	0.0032	-0.8132	0.1015	0.8830	0.8596	0.0017
SY	0.0223	0.0027	-0.6118	0.1397	0.9465	0.9332	0.0011
WP	0.0231	0.0247	-0.6600	0.9628	0.4677	-0.0646	0.5206
PL	0.0232	0.0024	-0.4807	0.0941	0.9684	0.9579	0.0024
BL	0.0244	0.0049	-0.6306	0.2117	0.7541	0.7234	0.0011
SL	0.0286	0.0017	-0.9649	0.0451	0.9631	0.9597	3.14E-09
BR	0.2062	0.0030	-0.6253	0.1191	0.7788	0.7618	1.33E-05

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Chapter 2. Appendix A

Table 1, App. A. Mean $\delta^{13}C$ (‰), $\delta^{15}N$ (‰) and mercury concentration (ppm) of samples.
* indicates sub-order, ** indicates family, *** indicates sub-class. See table 1 for site codes.

Site	Species	Code	n (#inv)	Mean $\delta^{13}C$ (‰) ± SD	Mean $\delta^{15}N$ (‰) ± SD	Mean THg (ppm) ± SD
BL	Aeshnidae**	OD	1	-35.89	9.06	
BL	*Alosa pseudoharengus*	GA	3	-20.23 ± 0.50	12.58 ± 0.27	0.53
BL	*Ameiurus nebulosus*	BB	2	-30.41 ± 0.46	10.68 ± 0.45	0.83 ± 0.12
BL	*Anguilla rostrata*	AE	1	-32.94	11.37	
BL	*Catostomus commersonii*	WS	4	-29.37 ± 1.25	9.06 ± 1.49	0.94 ± 0.37
BL	*Elliptio complanata*	EE	8	-31.48 ± 0.28	5.59 ± 0.15	
BL	*Esox niger*	CP	10	-27.99 ± 2.87	12.33 ± 0.55	3.25 ± 2.93
BL	*Fundulus diaphanus*	BK	3	-26.34 ± 0.28	10.02 ± 0.57	
BL	*Micropterus dolomieu*	SB	1	-27.05	12.98	3.29
BL	*Morone americana*	WP	4	-29.68 ± 1.25	12.45 ± 0.75	3.77 ± 3.18
BL	*Salvelinus fontinalis*	BT	1	-29.38	13.14	1.53
CL	*Ameiurus nebulosus*	BB	2	-31.78 ± 0.34	9.14 ± 0.15	1.34 ± 0.23
CL	*Anguilla rostrata*	AE	2	-30.27 ± 0.47	9.91 ± 0.54	3.67 ± 1.04
CL	*Catostomus commersonii*	WS	1	-31.29 ± 0.91	8.39 ± 0.73	0.44
CL	*Fundulus diaphanus*	BK	4	-30.30 ± 0.74	9.07 ± 0.45	
CL	*Morone americana*	WP	5	-30.09 ± 0.76	9.42 ± 0.95	4.37 ± 4.74
CL	*Salvelinus fontinalis*	BT	7	-29.97 ± 1.00	9.44 ± 0.48	0.86 ± 0.24
ST	*Alosa pseudoharengus*	GA	2	-21.45 ± 0.46	11.56 ± 0.04	0.42 ± 0.01
ST	*Ameiurus nebulosus*	BB	7	-26.60 ± 0.59	9.70 ± 0.48	0.83 ± 0.49
ST	*Anguilla rostrata*	AE	7	-28.19 ± 1.58	9.53 ± 1.00	1.11 ± 0.54
ST	*Catostomus commersonii*	WS	10	-28.42 ± 1.42	9.74 ± 0.41	1.57 ± 0.32
ST	Coenagrionidae	OD	1	-25.39	6.33	
ST	Corduliidae	OD	1	-27.86	3.64	
ST	*Esox niger*	CP	7	-26.81 ± 2.43	10.28 ± 1.05	0.69 ± 0.50
ST	*Micropterus dolomieu*	SB	2	-25.37 ± 1.07	10.52 ± 0.12	0.93 ± 0.44

ST	*Morone americana*	WP	1	-27.71	11.09	1.76
ST	*Perca flavescens*	YP	5	-26.58 ± 1.04	10.05 ± 0.40	0.55 ± 0.31
GI	Anisoptera*	OD	2	-37.84 ± 10.03	5.47 ± 4.04	
GI	*Anguilla rostrata*	AE	2	-31.00 ± 3.28	10.34 ± 1.61	
GI	*Catostomus commersonii*	WS	4	-31.05 ± 3.51	9.95 ± 0.29	0.69 ± 0.47
GI	*Elliptio complanata*	EE	2	-32.15 ± 0.36	6.56 ± 0.30	
GI	*Fundulus diaphanus*	BK	4	-27.25 ± 0.68	10.81 ± 0.31	
GI	*Morone americana*	WP	5	-30.87 ± 1.25	11.83 ± 1.24	4.21 ± 4.20
GI	*Perca flavescens*	YP	6	-27.73 ± 1.77	11.11 ± 0.90	2.12 ± 1.45
MA	*Ameiurus nebulosus*	BB	5	-28.61 ± 2.11	8.76 ± 0.58	1.55 ± 0.96
MA	*Anguilla rostrata*	AE	1	-29.89	8.62	1.59
MA	Anisoptera**	OD	2	-31.04 ± 6.94	3.88 ± 0.59	
MA	*Catostomus commersonii*	WS	4	-28.34 ± 2.07	7.92 ± 0.26	3.70 ± 2.08
MA	*Elliptio complanata*	EE	1	-30.76	5.29	
MA	*Micropterus dolomieu*	SB	7	-28.05 ± 0.80	9.90 ± 0.75	2.28 ± 1.39
MA	*Morone americana*	WP	6	-28.34 ± 1.37	9.48 ± 0.94	2.67 ± 1.32
MA	*Perca flavescens*	YP	5	-29.31 ± 1.51	8.94 ± 0.19	0.89 ± 0.07
MA	Zygoptera**	OD	1	-27.7	10.17	
LO	*Alosa pseudoharengus*	GA	2	-20.73 ± 0.13	12.34 ± 0.09	
LO	*Ameiurus nebulosus*	BB	4	-28.49 ± 0.98	9.75 ± 0.50	1.24 ± 0.18
LO	*Anguilla rostrata*	AE	3	-26.34 ± 1.64	11.42 ± 1.03	3.91
LO	Anisoptera*	OD	2	-34.03 ± 9.04	7.4 ± 0.41	
LO	*Catostomus commersonii*	WS	2	-26.64 ± 1.87	10.04 ± 0.26	1.14 ± 0.50
LO	*Fundulus diaphanus*	BK	5	-24.82 ± 1.54	10.48 ±1.02	
LO	*Morone americana*	WP	4	-29.26 ± 0.99	10.57 ± 0.64	4.07 ± 1.06
LO	*Osmerus mordax*	RS	2	-30.58 ± 0.19	12.98 ± 0.05	3.30 ± 0.36
LO	*Perca flavescens*	YP	3	-32.02 ± 2.64	9.00 ± 0.61	2.51 ± 0.94
LO	Planorbidae**	pn	1	-31.5	6.04	
PG	*Anguilla rostrata*	AE	2	-28.075 ± 1.83	11.51 ± 1.51	
PG	*Catostomus commersonii*	WS	5	-29.19 ± 3.93	10.21 ± 1.52	0.52 ± 0.25
PG	*Elliptio complanata*	EE	5	-28.21 ± 0.29	5.59 ± 0.32	
PG	*Morone americana*	WP	5	-27.42 ± 0.56	11.13 ± 0.75	1.77 ± 0.87

PG	*Perca flavescens*	YP	3	-27.68 ± 0.38	10.57 ± 0.62	1.92 ± 1.17
PG	*Pyganodon fragilis*	Pf	2	-29.98 ± 0.25	6.17 ± 0.07	
PG	*Salvelinus fontinalis*	BT	2	-22.30 ± 5.43	10.01 ± 0.97	0.27 ± 0.25
PG	*Utterbackiana implicata*	af	2	-30.06 ± 0.73	6.16 ± 0.15	
LN	*Ameiurus nebulosus*	BB	6	-24.54 ± 1.07	13.14 ± 0.44	0.53 ± 0.22
LN	*Fundulus diaphanus*	BK	15	-23.44 ± 0.66	12.36 ±0.43	
LN	*Micropterus dolomieu*	SB	7	-25.30 ± 2.00	13.98 ± 0.92	1.39 ± 0.44
LN	*Salvelinus fontinalis*	BT	4	-25.77 ± 4.58	13.03 ± 1.42	0.44 ± 0.22
MO	*Alosa pseudoharengus*	GA	6	-19.89 ± 1.24	11.81 ± 0.23	0.39 ± 0.12
MO	*Anguilla rostrata*	AE	1	-26.98	13.08	0.41
MO	*Catostomus commersonii*	WS	1	-26.01	11.46	0.33
MO	Chironomidae	ch	1	-30.55	6.08	
MO	*Esox niger*	CP	6	-24.95 ± 2.15	14.70 ± 0.66	0.46 ± 0.24
MO	*Micropterus dolomieu*	SB	8	-24.51 ± 0.89	14.95 ± 0.33	0.86 ± 0.38
MO	*Morone americana*	WP	3	-26.12 ± 0.62	14.54 ± 0.36	0.99 ± 0.89
MO	*Perca flavescens*	YP	6	-25.18 ± 1.65	13.51 ± 0.61	0.29 ± 0.05
MO	Plankton	Pk	1	-30.94	6.14	
OS	*Ameiurus nebulosus*	BB	4	-29.35 ± 0.64	12.79 ± 1.45	1.41 ± 0.56
OS	*Micropterus dolomieu*	SB	14	-26.16 ± 2.01	13.39 ± 0.86	1.39 ± 0.46
OS	*Salvelinus fontinalis*	BT	15	-29.63 ± 1.25	12.05 ± 0.76	0.78 ± 0.42
CO	Aeshnidae**	OD	1	-29.71	4.7	
CO	*Catostomus commersonii*	WS	1	-27.99	8.61	1.63
CO	Ephemeroptera	ep	1	-30.9	1.52	
CO	*Esox niger*	CP	5	-27.79 ± 0.07	8.60 ± 0.15	2.36 ± 0.21
CO	*Micropterus dolomieu*	SB	1	-26.69	9.2	3.2
CO	*Perca flavescens*	YP	2	-28.56 ± 0.08	7.61 ± 0.89	1.64 ± 0.68
AI	*Alosa pseudoharengus*	GA	5	-20.06 ± 0.48	12.70 ± 0.26	
AI	*Anguilla rostrata*	AE	2	-26.41 ± 0.25	9.73 ± 0.38	
AI	*Catostomus commersonii*	WS	6	-21.02 ± 1.35	9.34 ± 0.31	
AI	*Elliptio complanata*	EE	4	-27.81 ± 0.22	4.23 ± 0.31	
AI	*Fundulus diaphanus*	BK	7	-23.71 ± 0.87	9.76 ± 0.25	
AI	*Gasterosteus aculeatus*	SK	1	-25.12	9.98	

AI	*Micropterus dolomieu*	SB	22	-24.07 ± 1.73	11.22 ± 1.02	1.59 ± 0.87
AI	*Morone americana*	WP	6	-25.4433 ± 0.61	11.33 ± 0.58	
AI	*Salvelinus fontinalis*	BT	11	-23.02 ± 2.94	10.13 ± 1.08	0.56 ± 0.27
PL	*Alasmidonta varicosa*	bf	1	-31.23	3.22	
PL	*Anguilla rostrata*	AE	5	-30.60 ± 1.50	7.77 ± 0.81	0.9
PL	*Catostomus commersonii*	WS	1	-27.62	6.94	1.32
PL	Corduliidae*	OD	1	-28.86	4.07	
PL	*Elliptio complanata*	EE	11	-31.25 ± 0.27	2.83 ± 0.23	
PL	*Esox niger*	CP	5	-29.24 ± 0.42	8.57 ± 0.82	2.90 ± 1.84
PL	*Micropterus dolomieu*	SB	4	-27.87 ± 1.31	7.83 ± 0.96	3.81 ± 3.29
BR	Anisoptera*	OD	3	-29.88 ± 0.45	4.73 ± 0.34	
BR	*Didymops transversa*	OD	3	-30.50 ± 2.70	5.56 ± 0.22	
BR	*Esox niger*	CP	15	-27.06 ± 3.12	10.18 ± 1.65	1.74 ± 1.45
BR	*Helobdella elongata*	Leech	1	-28.78	8.06	
BR	*Somatochlora ensigera*	OD	1	-30.12	5.47	
FF	*Esox niger*	CP	1	-27.5	9.25	0.76
SHCB	*Alosa pseudoharengus*	GA	4	-30.31 ± 0.66	5.49 ± 0.64	
SHCB	*Didymops transversa*	OD	2	-29.41 ± 1.00	4.67 ± 0.26	
SHCB	*Esox niger*	CP	13	-29.05 ± 1.72	8.92 ± 0.74	1.06 ± 0.42
SHCB	*Helobdella elongata*	Leech	1	-28.97	7.54	
SHCB	*Leucorrhinia proxima*	OD	1	-31.88	3.51	
SH	Detritus	DT	3	-29.86 ± 1.89	-2.50 ± 1.32	0.06 ± 0.01
SH	*Elliptio complanata*	EE	10	-30.90 ± 0.48	2.77 ± 0.35	1.51 ± 0.48
SH	Ephemerellidae	Eph	1	-25.07	0.96	
SH	*Esox niger*	CP	1	-28.26	8.75	1.78
SH	*Helobdella elongata*	Leech	3			
SH	*Micropterus dolomieu*	SB	6	-27.72 ± 0.59	7.61 ± 0.22	1.62 ± 0.59
SH	*Morone americana*	WP	3	-29.54 ± 3.24	7.22 ± 0.28	1.86 ± 0.56
SH	*Perca flavescens*	YP	1	-28.67	7.16	2.01
SH	*Salvelinus namaycush*	LT	1			7.1097
SH	*Sympetrum vicinum*	OD	1	-24.22	2.87	
SH	Trichoptera**	Tri	1	-25.23	2.3	0.13

SH	Zooplankton	ZP	1	-29.19	-0.2	0.11
SH	Zygoptera*	OD	1 (2)	-28.39	4.38	0.14
WL	*Alosa pseudoharengus*	GA	1	-44.89	4.31	
WL	*Ameiurus nebulosus*	BB	2	-30.95 ± 0.78	8.53 ± 0.49	1.67 ± 0.72
WL	Detritus	DT	4	-28.76 ± 0.34	1.30 ± 0.17	0.07 ± 0.02
WL	*Elliptio complanata*	EE	5	-30.71 ± 0.38	4.37 ± 0.30	1.06 ± 0.59
WL	Ephemerellidae**	Eph	1	-31.21	2.06	0.08
WL	*Esox niger*	CP	31	-29.28 ± 1.61	9.50 ± 0.63	1.78 ± 0.59
WL	Libellulidae*	OD	1 (6)	-28.38	4.09	0.26
WL	*Micropterus dolomieu*	SB	9	-28.11 ± 1.91	9.75 ± 0.68	4.11 ± 2.13
WL	*Morone americana*	WP	11	-32.26 ± 1.72	8.39 ± 0.35	3.80 ± 1.56
WL	Zooplankton	ZP	1	-33.29	4.41	
WP	*Esox niger*	CP	3	-26.58 ± 1.55	10.25 ± 0.63	1.76 ± 0.24
SY	*Alosa pseudoharengus*	GA	1	-19.1	12.02	0.36
SY	*Ameiurus nebulosus*	BB	1	-29.57	10.36	1.97
SY	*Anguilla rostrata*	AE	4	-30.88 ± 1.40	10.29 ± 0.30	
SY	*Catostomus commersonii*	WS	1	-28.22	10.47	
SY	*Esox niger*	CP	6	-26.26 ± 3.75	11.90 ± 1.06	3.31 ± 1.69
SY	*Micropterus dolomieu*	SB	4	-29.88 ± 1.25	10.19 ± 0.31	1.57 ± 0.36
SY	*Morone americana*	WP	10	-32.28 ± 3.95	9.81 ± 0.94	2.57 ± 1.84
SY	*Perca flavescens*	YP	1	-30.56	9.97	0.78
SL	*Ameiurus nebulosus*	BB	9	-25.69 ± 0.65	8.53 ± 0.76	0.92 ± 0.52
SL	*Anguilla rostrata*	AE	2	-22.84 ± 1.30	7.62 ± 0.11	0.49 ± 0.02
SL	*Elliptio complanata*	EE	2	-30.13 ± 0.35	3.42 ± 0.15	
SL	*Esox niger*	CP	13	-26.41 ± 0.84	7.63 ± 2.14	0.72 ± 0.59
SL	Hirudinea***	Leech	1	-25.66	7.67	
SL	*Micropterus dolomieu*	SB	7	-26.03 ± 0.69	8.99 ± 0.61	1.21 ± 0.62
SL	*Morone americana*	WP	6	-27.08 ± 0.81	9.08 ± 0.27	2.05 ± 0.94
SL	*Pyganodon fragilis*	Pf	3	31.28 ± 0.24	4.95 ± 0.34	

Chapter 2. Appendix B.

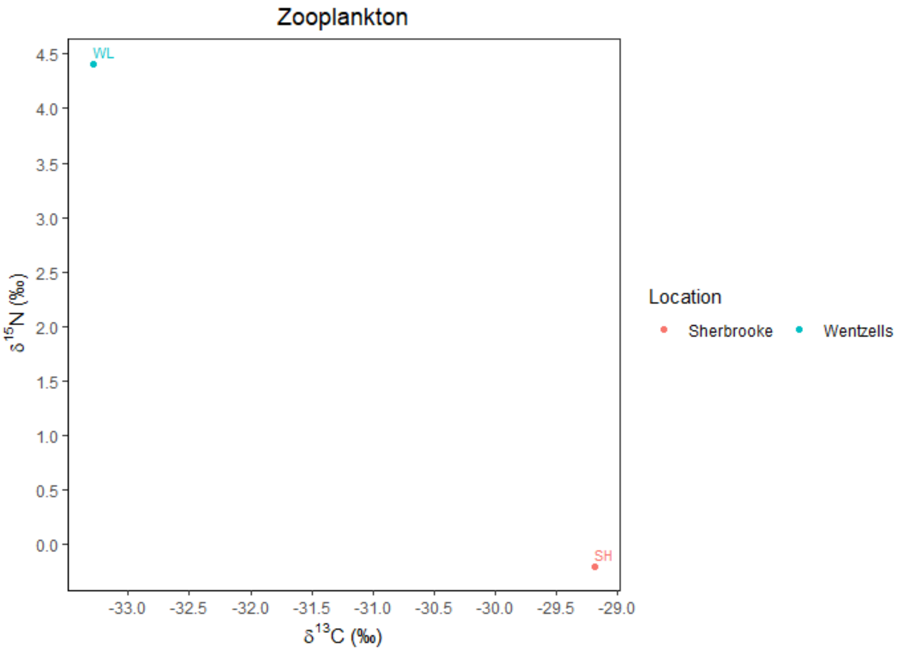


Figure 1. App. B. Zooplankton δ^{15}N and δ^{13}C stable isotope values.

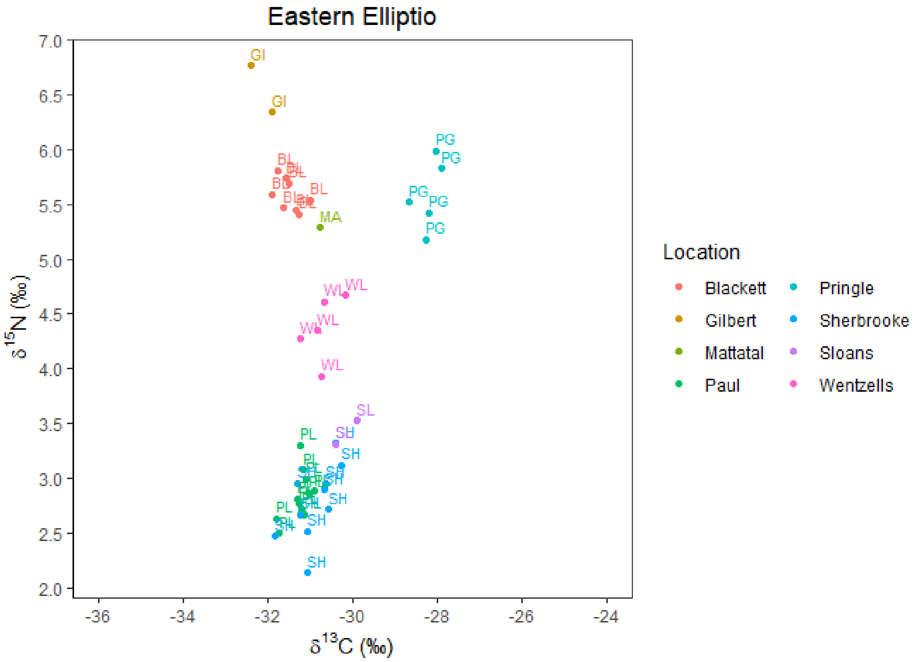


Figure 2. App. B. Eastern elliptio (*Elliptio complanata*) δ^{15}N and δ^{13}C stable isotope values.

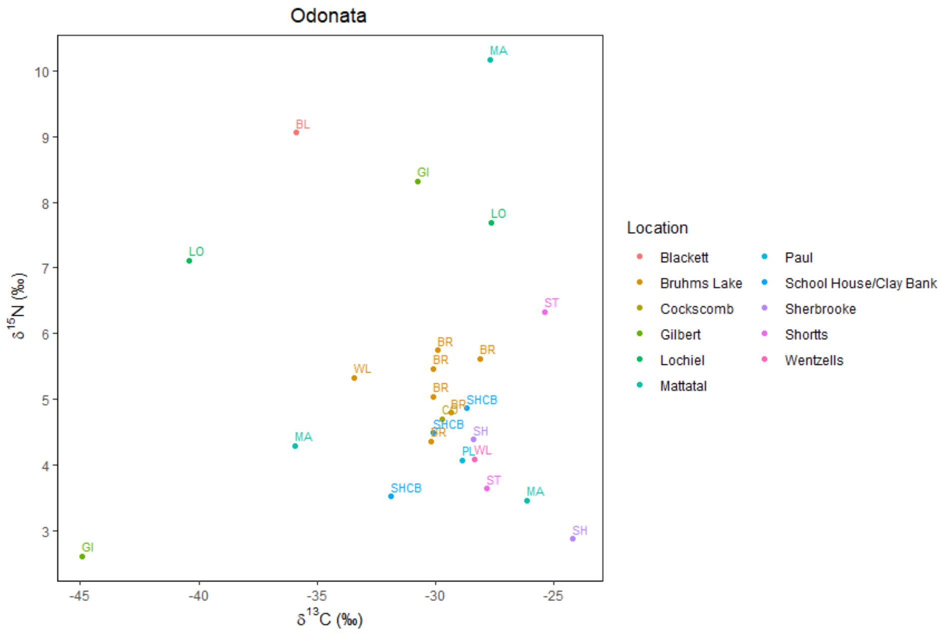


Figure 3. App. B. Odonata δ^{15}N and δ^{13}C stable isotope values.

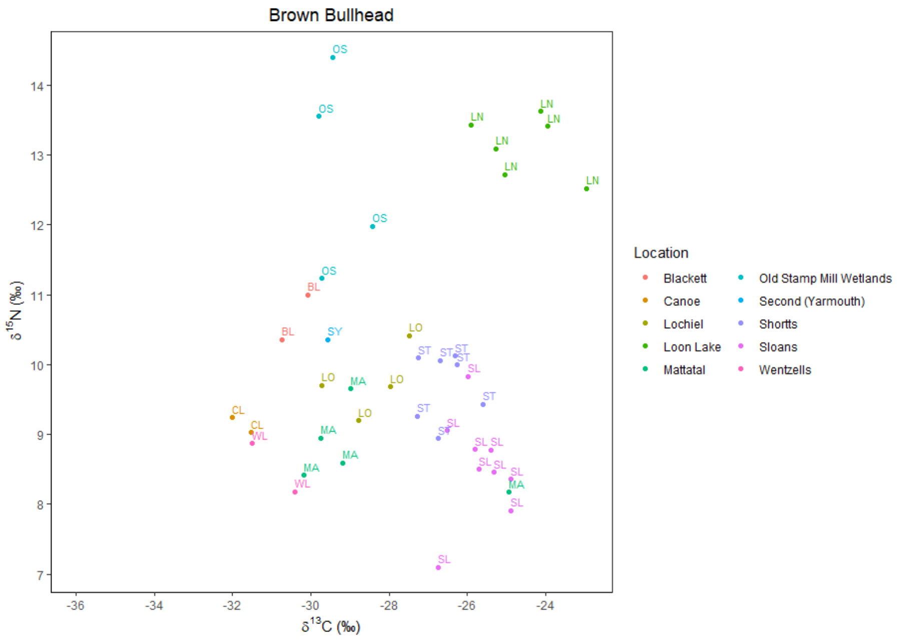


Figure 4. App. B. Brown bullhead (*Ameiurus nebulosus*) δ^{15}N and δ^{13}C stable isotope values.

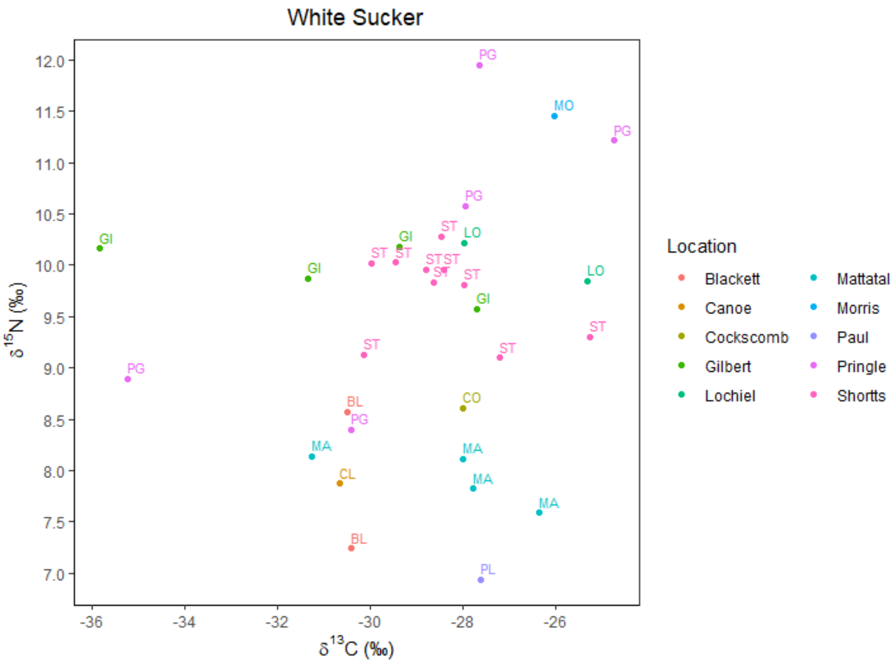


Figure 5. App. B. White sucker (*Catostomus commersonii*) [*Gomgwej*] δ^{15}N and δ^{13}C stable isotope values.

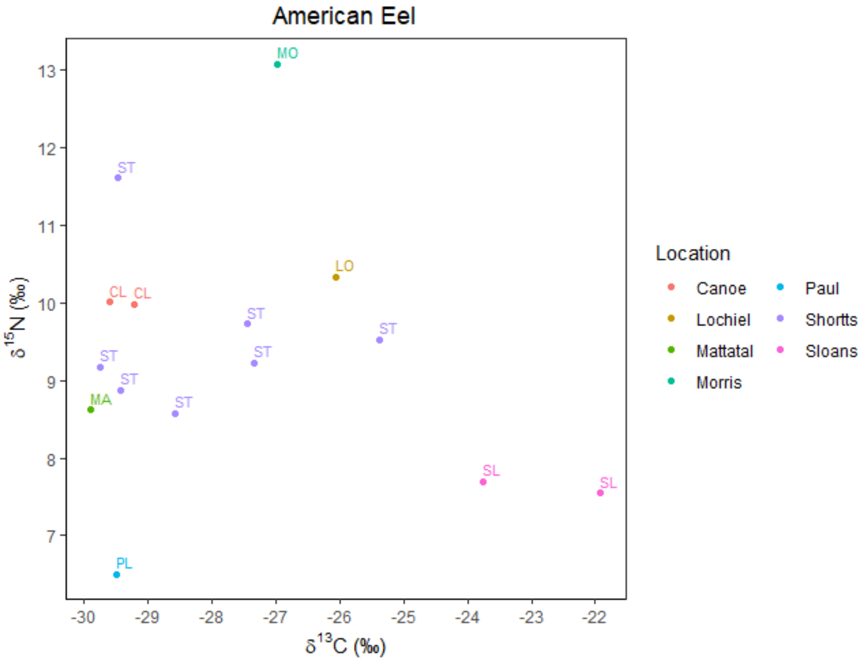


Figure 6. App. B. American eel (*Anguilla rostrata*) [*Katew*] δ^{15}N and δ^{13}C stable isotope values.

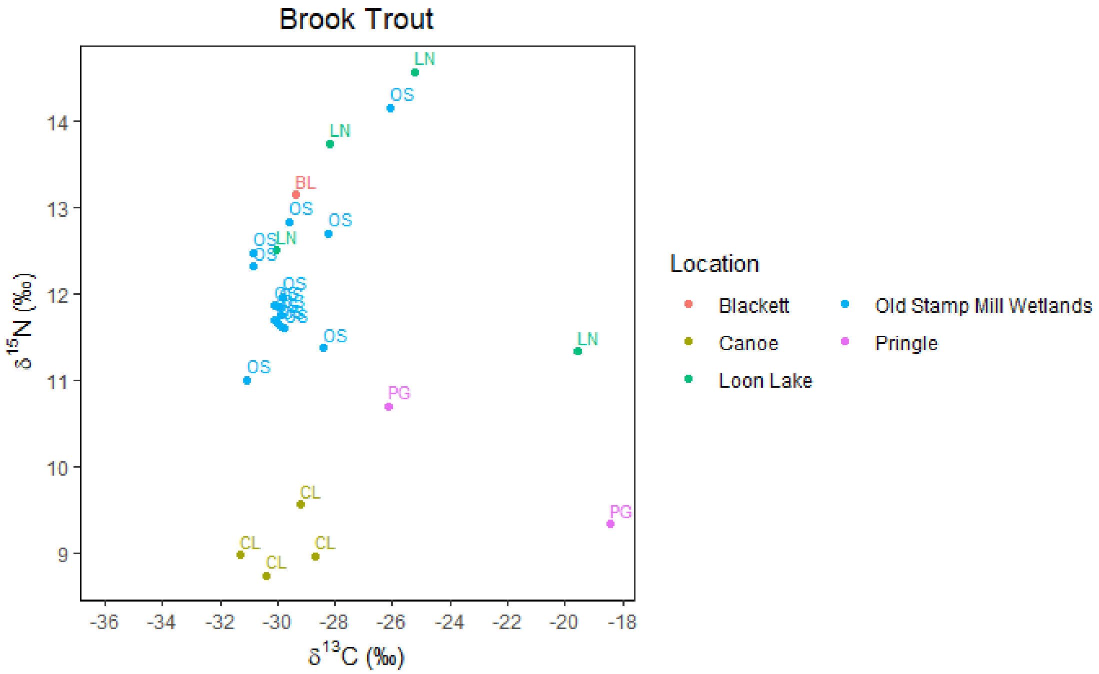


Figure 7. App. B. Brook trout (*Salvelinus fontinalis*) [*Atoqwa'su*] $\delta^{15}N$ and $\delta^{13}C$ stable isotope values.

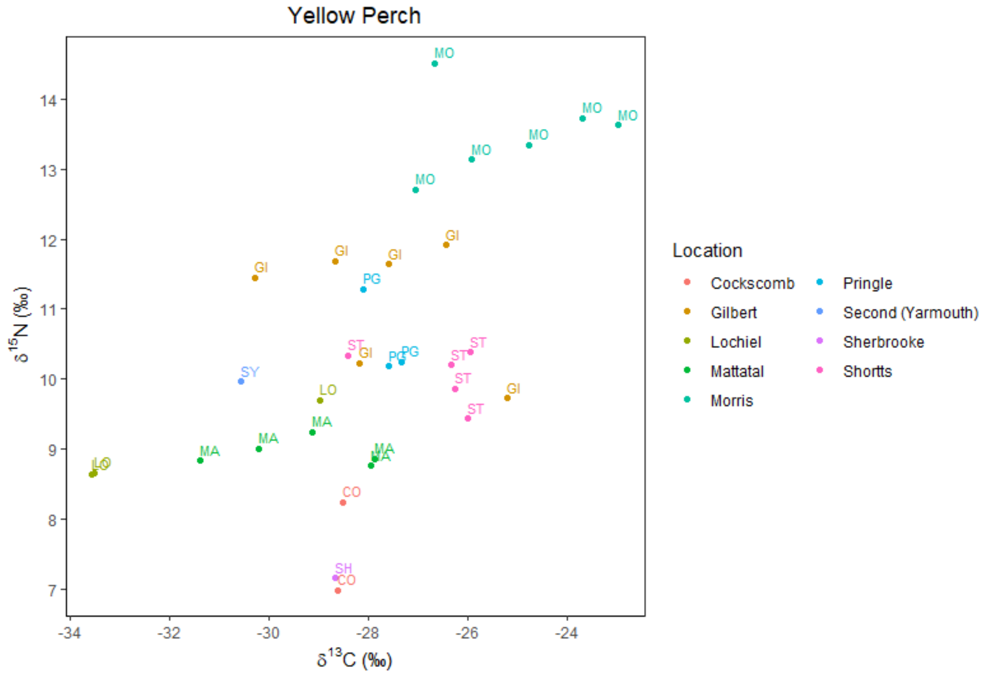


Figure 8. App. B. Yellow perch (*Perca flavescens*) [*Antaliej*] $\delta^{15}N$ and $\delta^{13}C$ stable isotope values.

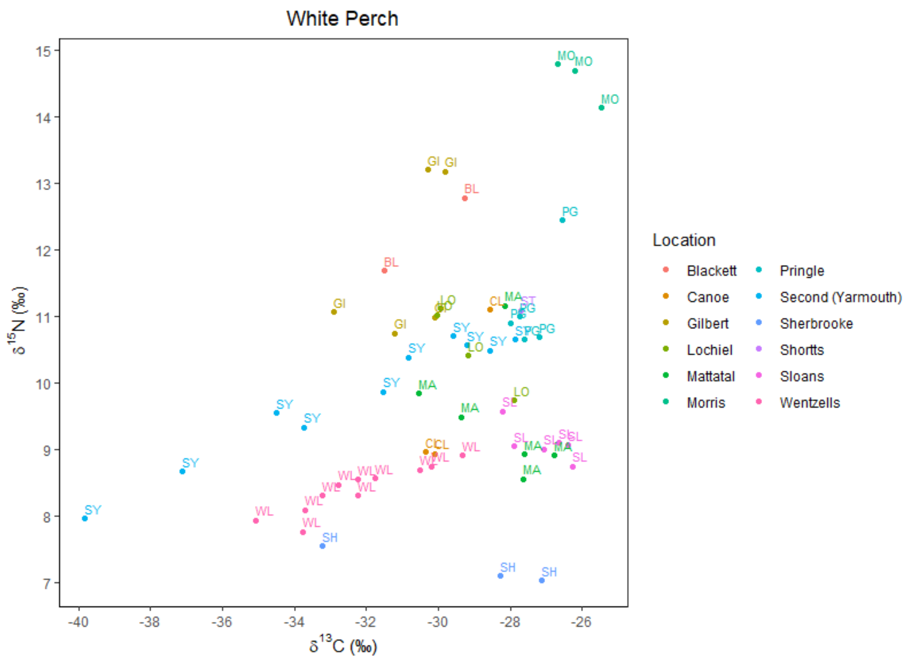


Figure 9. App. B. White perch (*Morone americana*) δ^{15}N and δ^{13}C stable isotope values.

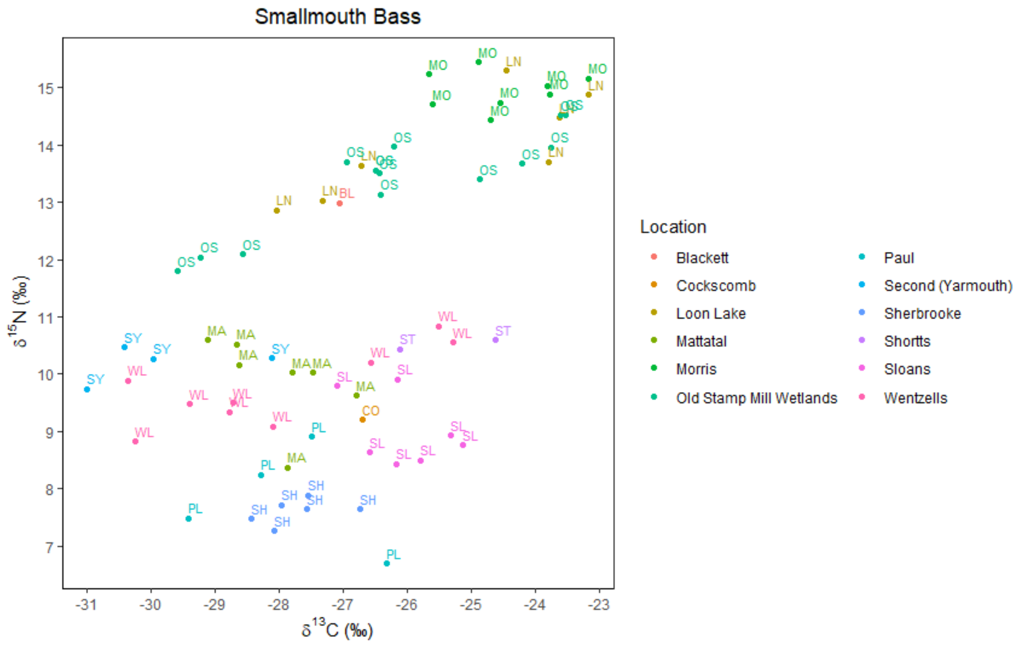


Figure 10. App. B. Smallmouth bass (*Micropterus dolomieu*) δ^{15}N and δ^{13}C stable isotope values.

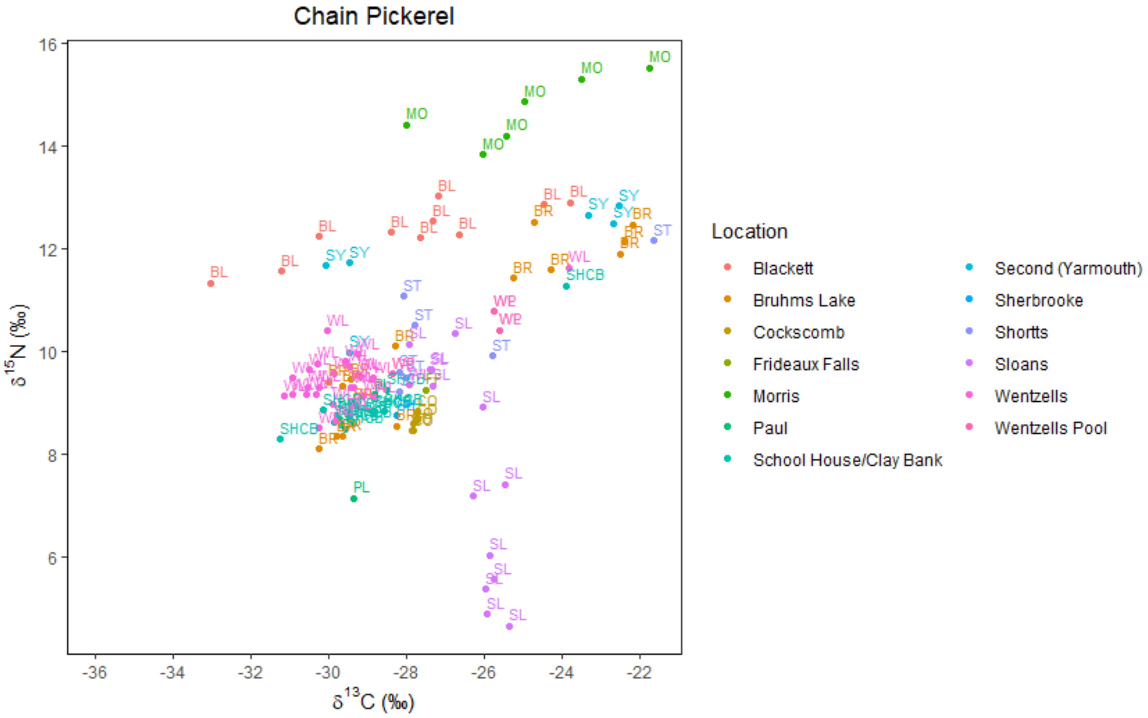


Figure 11. App. B. Chain pickerel (*Esox niger*) δ^{15}N and δ^{13}C stable isotope values.

Chapter 2. Appendix C

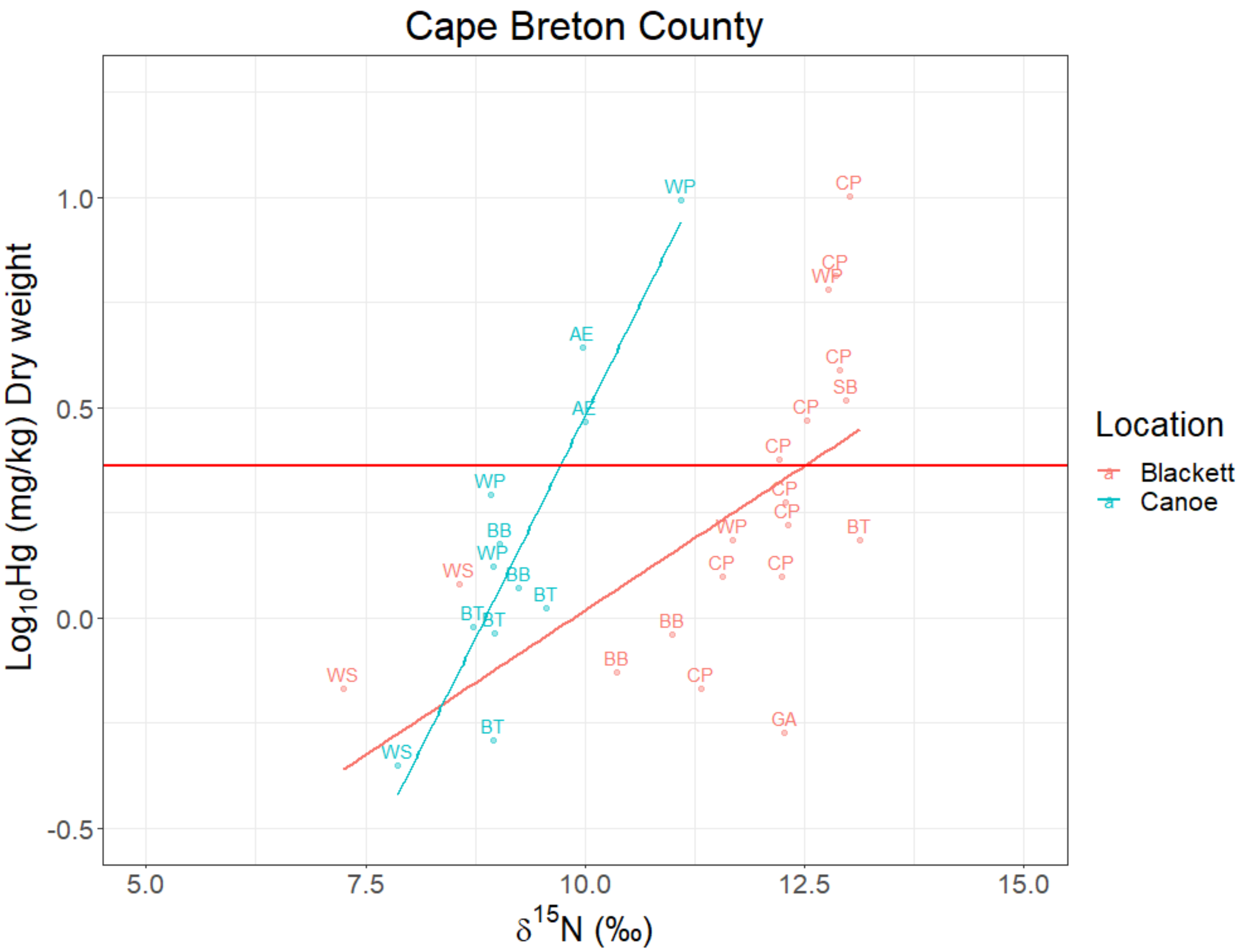


Figure 1. App. C. Cape Breton County trophic magnification slopes and species data. Red line indicates Health Canada Guideline of 0.5ppm for commercial fisheries (converted to dry weight and $\log_{10}$).

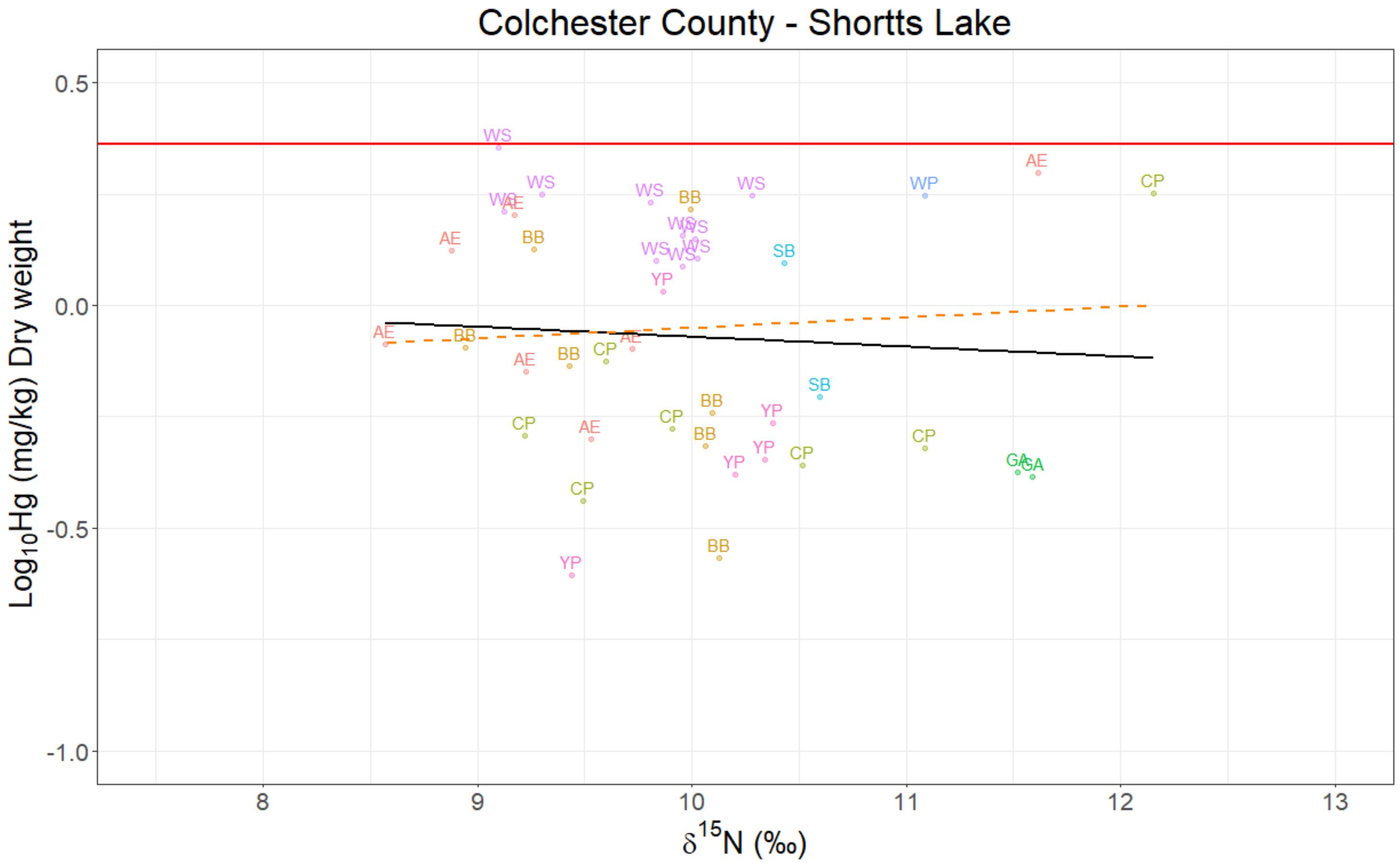


Figure 2. App. C. Shortts Lake (Colchester County) trophic magnification slope and species data for freshwater species (dashed orange line) and all species (black line). Red horizontal line indicates Health Canada Guideline of 0.5ppm for commercial fisheries (converted to dry weight and $\log_{10}$).

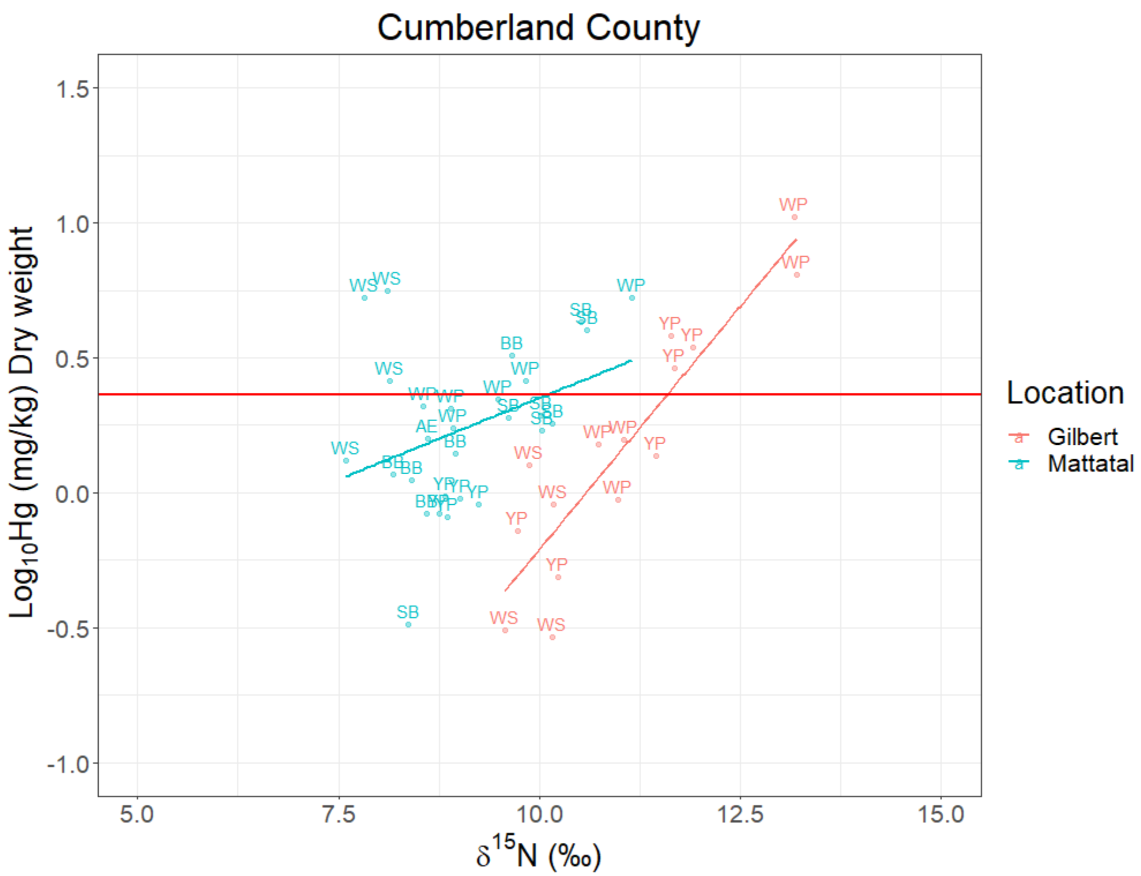


Figure 3. App. C. Cumberland County trophic magnification slopes and species data. Red horizontal line indicates Health Canada Guideline of 0.5ppm for commercial fisheries (converted to dry weight and $\log_{10}$).

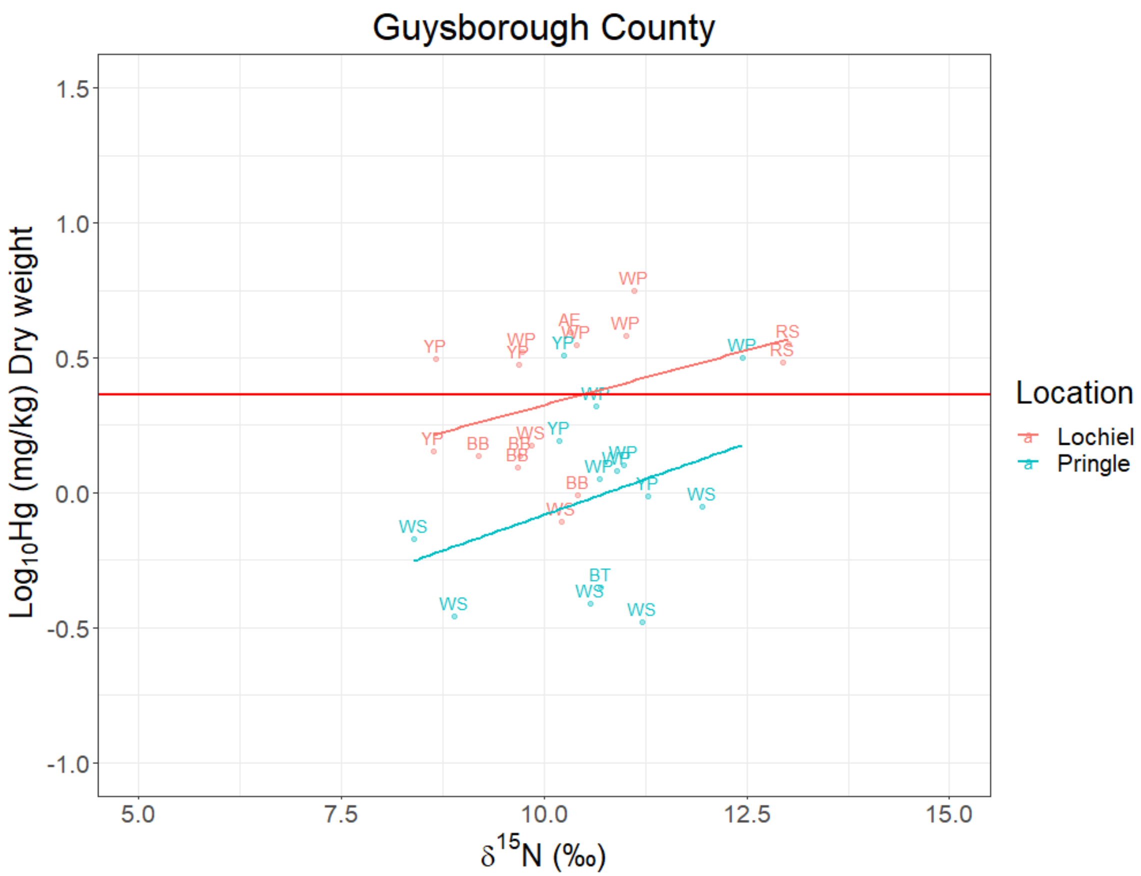


Figure 4. App. C. Guysborough County trophic magnification slopes and species data. Red horizontal line indicates Health Canada Guideline of 0.5ppm for commercial fisheries (converted to dry weight and $\log_{10}$).

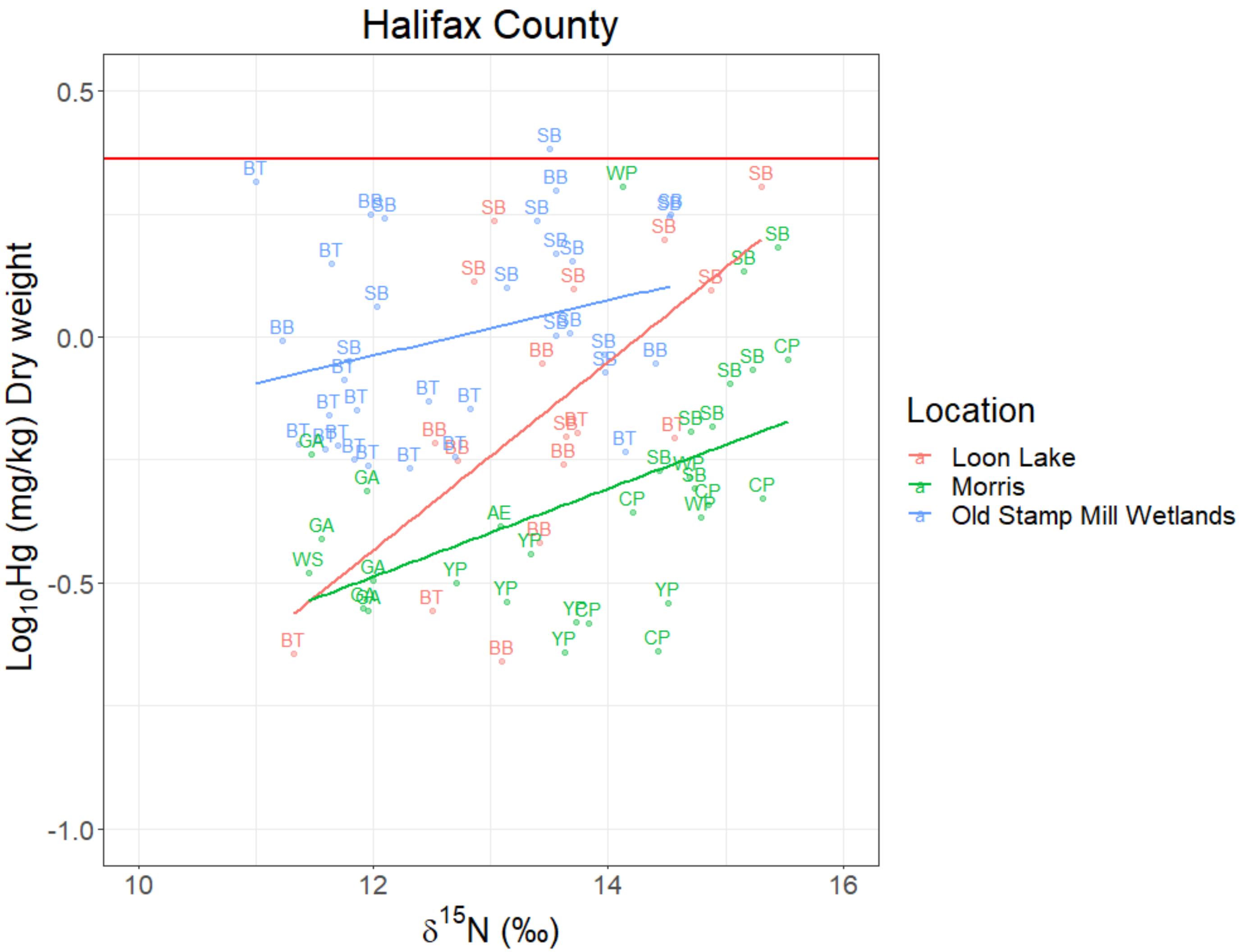


Figure 5. App. C. Halifax County trophic magnification slopes and species data. Red horizontal line indicates Health Canada Guideline of 0.5ppm for commercial fisheries (converted to dry weight and $\log_{10}$).

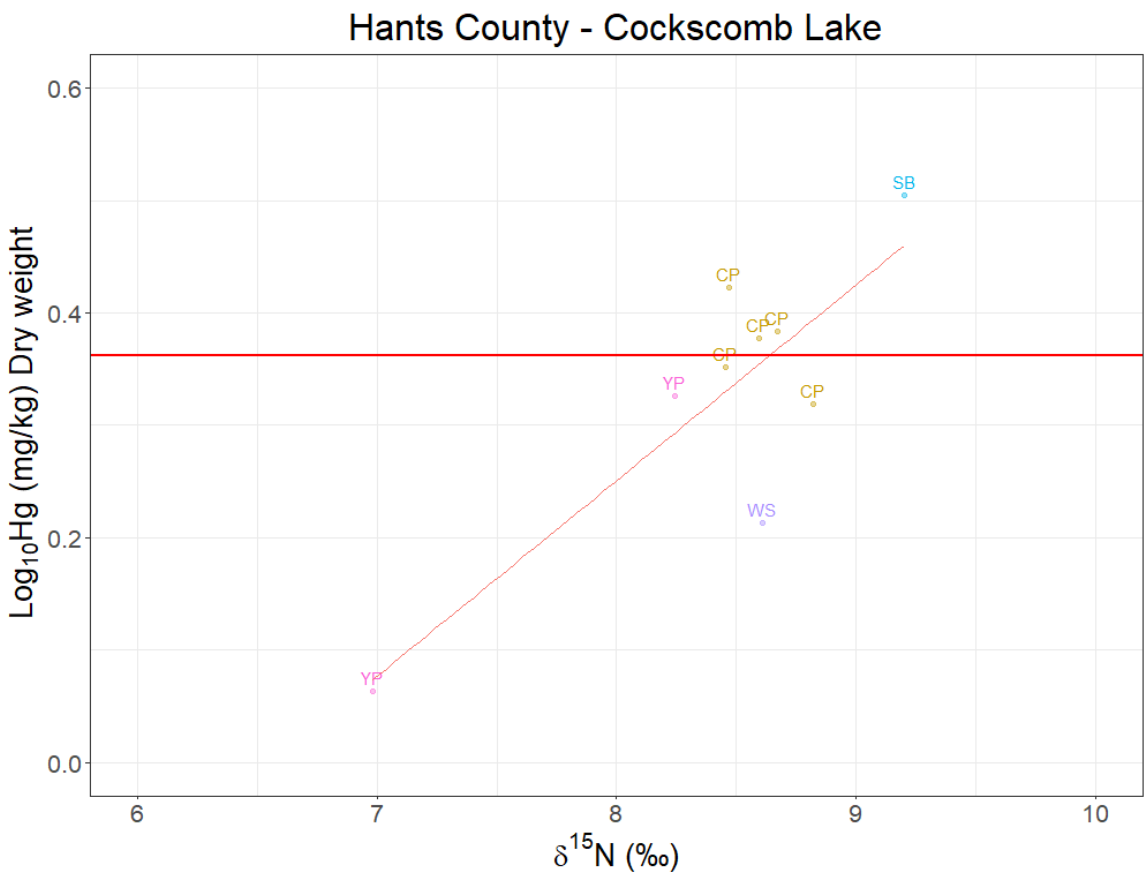


Figure 6. App. C. Cockscomb Lake (Hants County) trophic magnification slope and species data. Red horizontal line indicates Health Canada Guideline of 0.5ppm for commercial fisheries (converted to dry weight and $\log_{10}$).

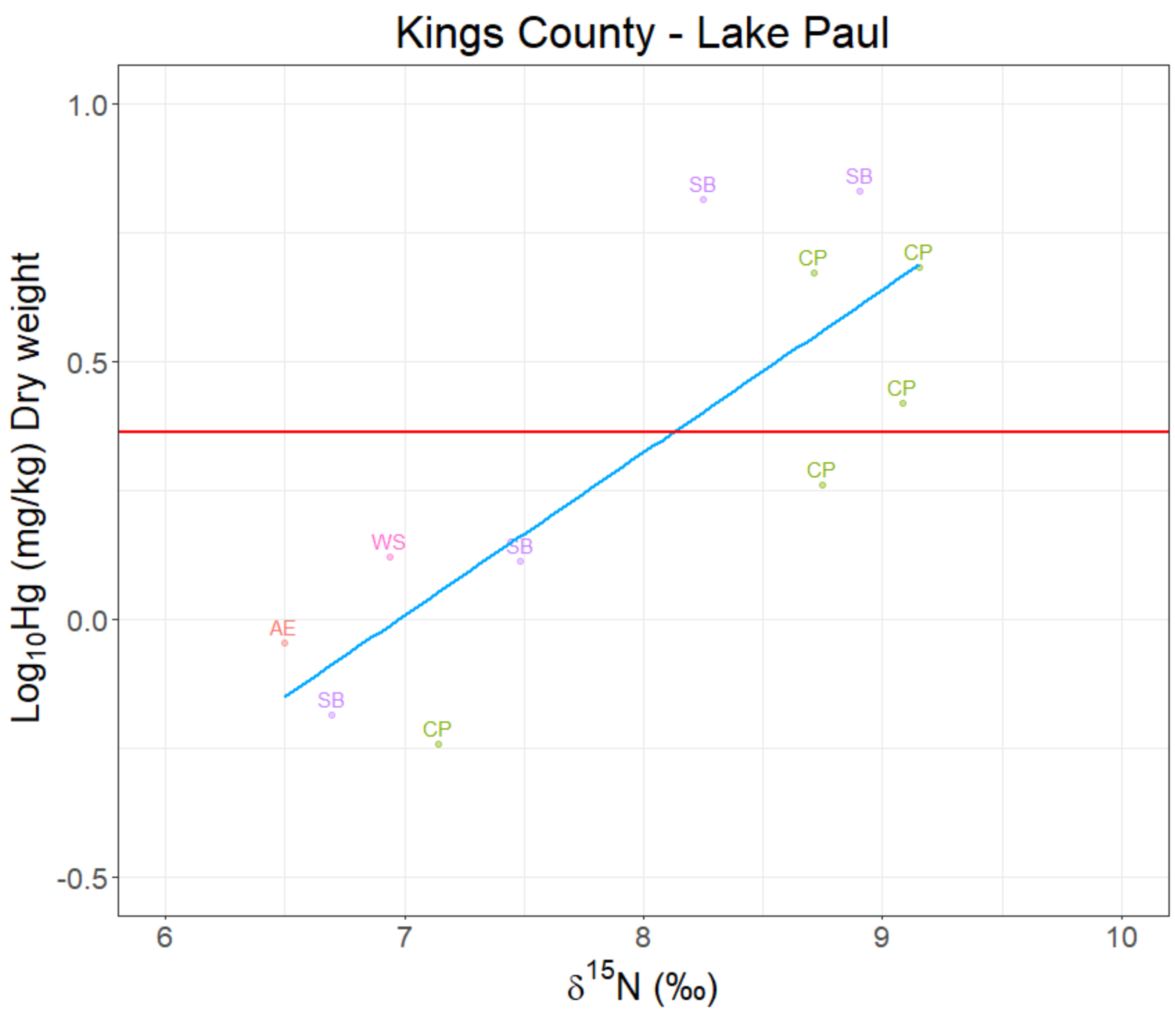


Figure 7. App. C. Lake Paul (Kings County) trophic magnification slope and species data. Red horizontal line indicates Health Canada Guideline of 0.5ppm for commercial fisheries (converted to dry weight and $\log_{10}$).

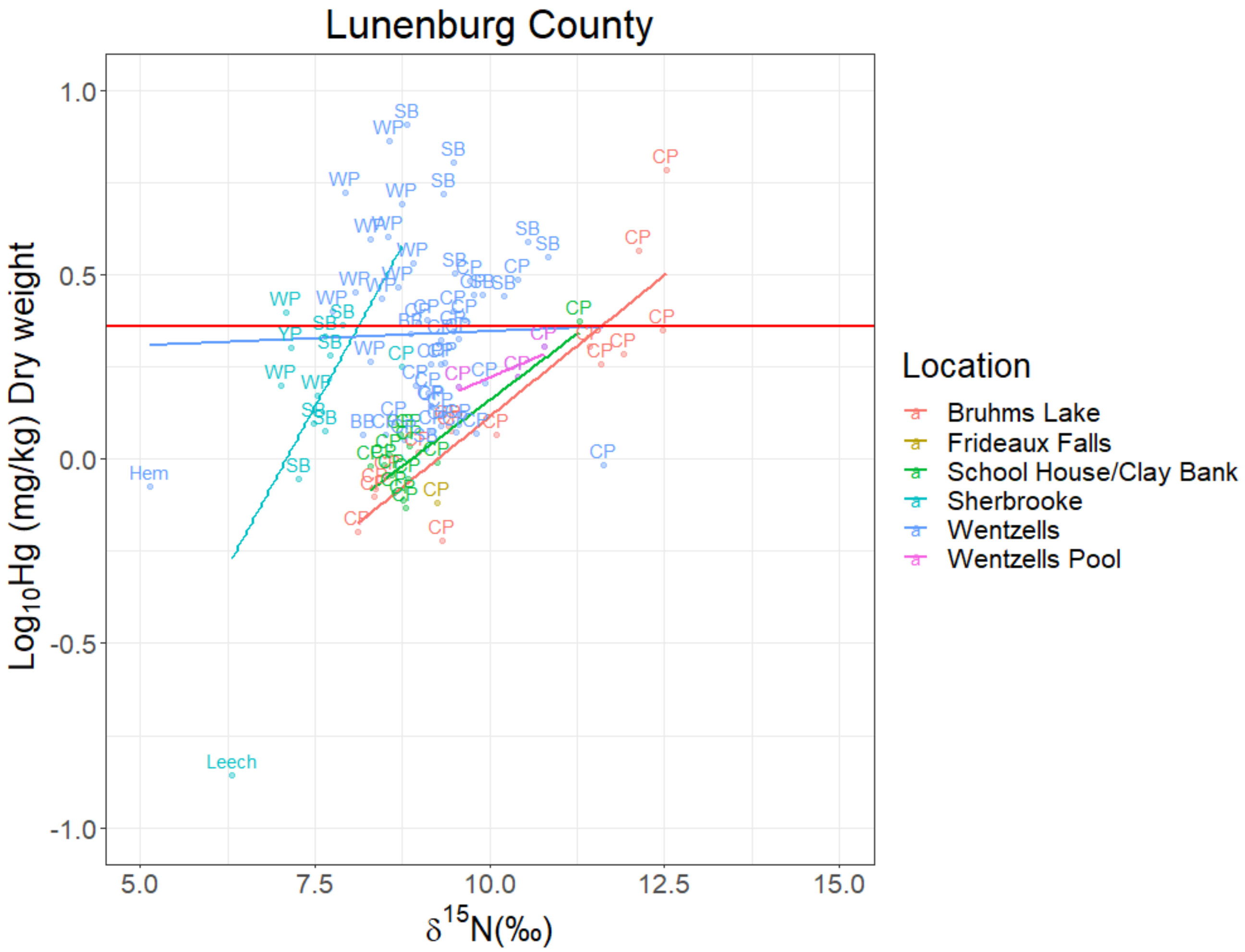


Figure 8. App. C. Lunenburg County trophic magnification slopes and species data. Red horizontal line indicates Health Canada Guideline of 0.5ppm for commercial fisheries (converted to dry weight and $\log_{10}$).

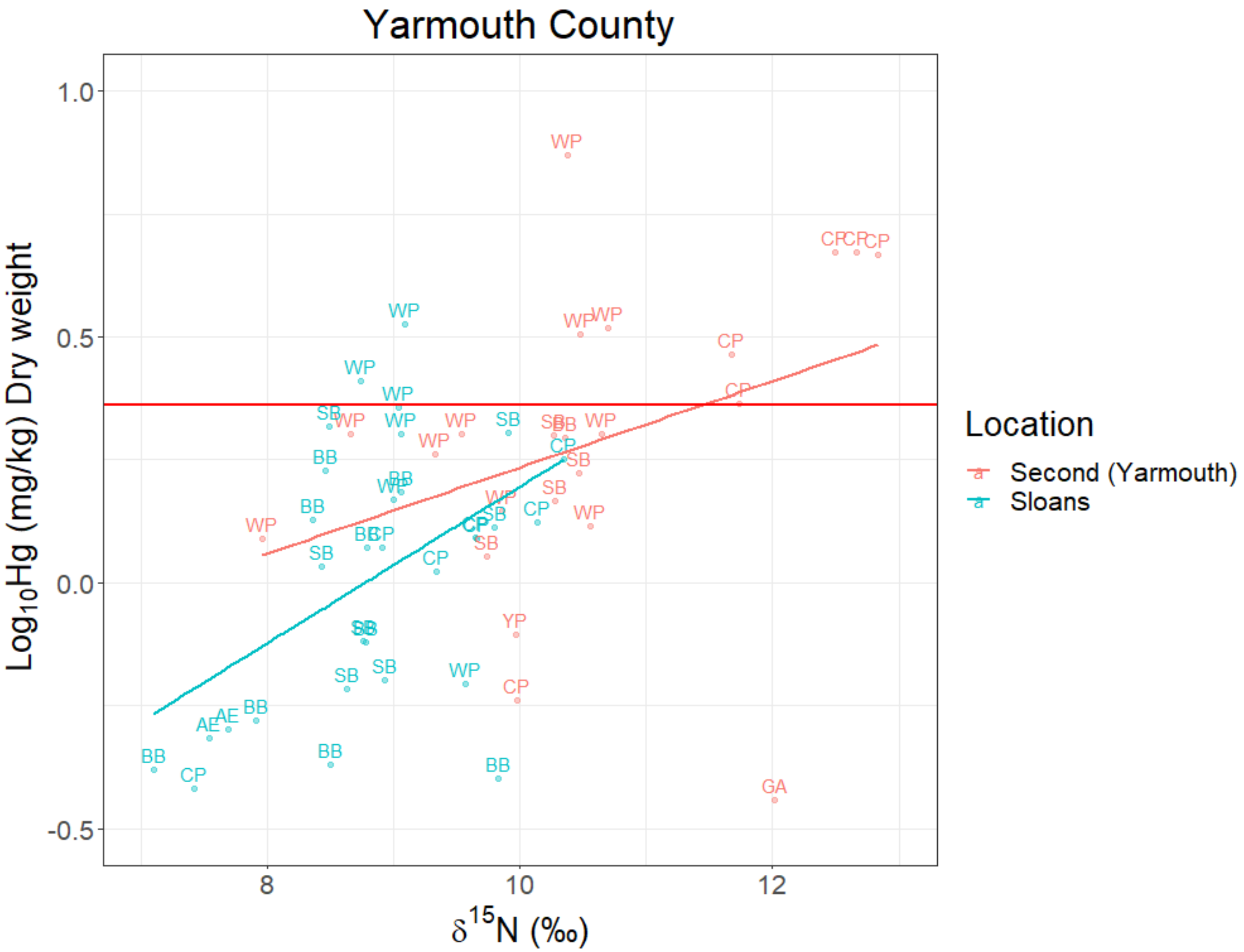


Figure 9. App. C. Yarmouth County trophic magnification slopes and species data. Red horizontal line indicates Health Canada Guideline of 0.5ppm for commercial fisheries (converted to dry weight and log$_{10}$).

Chapter 3. Framework for Mercury Risk in Freshwater Across Nova Scotia.

ABSTRACT

Mercury concentrations are influenced by a variety of key physiochemical and environmental characteristics, including dissolved organic carbon, nutrients, alkalinity, and percent wetland cover. Mercury concentrations in fish can be a human health concern in areas with large recreational fisheries or subsistence fishing. We found that Canada has a wide range of fish consumption guidelines and recommendations, ranging from no recommendations (i.e., Nunavut) to comprehensive recommendations by waterbody and species (i.e., Ontario and Quebec). To expand on limited datasets, studies have previously estimated mercury in fish based on water quality and environmental parameters. We compiled water quality data across Nova Scotia from 2000-2022 and calculated percent area of wetland for each primary watershed. Water quality data exists for 344 freshwater water bodies. Data availability varies by county: Halifax County has the most available data (n = 150), while Richmond County has the lowest (n = 0). Many parameters varied by several levels of magnitude; pH was the parameter observed most frequently (n = 343; range 3.49 – 9.79). Based on key water quality parameters (chlorophyll-a, phosphorus, pH, and total organic carbon) and percent wetland cover for each primary watershed, I created a risk map of mercury in primary watersheds across Nova Scotia. These risk values ranged from three (low risk) to nine (high risk), with nine watersheds having a score of zero due to no existing data. This risk map is a starting point to expand limited mercury datasets within Nova Scotia, providing information to scientific, governmental, and community groups to develop guidelines on the safe consumption of fish within the province.

INTRODUCTION

Mercury (Hg) exists in many forms, but the main concern for human health is the organic Hg compound, methylmercury (MeHg). Hg is a non-essential element for biological functioning and can be harmful even at low concentrations (Park & Zheng, 2012; Varol & Sünbül, 2018). Methylmercury is a potent neurotoxin; at low doses, it can impact the central nervous system and at higher doses, it can affect neurological functions (tingling limbs, lack of coordination and muscle control, impairment of hearing and vision, etc.) (Julvez et al., 2012). The effects of MeHg are more prominent with fetal exposure and in developing brains (Sager & Matheson, 1988). The main pathway of MeHg in humans is through diet, so this leads to concerns for food items that may be elevated in this contaminant.

Fish is often recommended as a part of a healthy balanced diet, as it contains omega-3 fatty acids, eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) which can help maintain healthy heart functions (Health Canada, 2019), but unfortunately fish can often be elevated in certain contaminants. While there is no "legal limit" for fish consumption in terms of mercury, jurisdictions can recommend consumption limits or release advisories if contaminants exceed levels that would negatively impact human health. Mercury contamination is widespread, and fish consumption advisories or recommendations based on mercury risk exist in most Canadian provinces and territories. Health Canada and the Canadian Food Inspection Agency have recommended guidelines for commercial fish (often called "market" guidelines), in which Hg levels cannot exceed 0.5mg/kg in most retail fish, except for tuna, shark, swordfish, and escolar where the limit is 1mg/kg (Health Canada, 2020).

For non-commercial fish caught and consumed by the public, recommended consumption guidelines often focus on two categories: general populations and sensitive populations, although these designations and definitions can vary between jurisdictions. Typically, the general population is defined as individuals aged 12 and older. The sensitive population includes those who are pregnant, women of childbearing years, children less than 12 years of age, and sometimes frequent fish consumers whose dietary fish intake exceeds a certain benchmark. These designations are made because the greatest concern for MeHg exposure is in sensitive and highly exposed populations (e.g., recreational anglers, subsistence fish consumers, etc.) (Evers et al., 2011). In people who are pregnant, fetal exposure to MeHg can cause children to have impaired cognitive issues such as thinking, memory, language, and fine motor skills (EPA, 2022). Therefore, recommendations for those who are pregnant are often to limit consumption and consume smaller-sized fish.

Fish consumption guidelines vary across Canada, from comprehensive guidelines for specific waterbodies (ex. Ontario) to no advisories (ex. Nunavut) (Table 1). Guidelines also vary by groups of at-risk individuals, specific advisories by species or size class, and serving size. The calculations are generally based on Health Canada guidelines for Provisional Tolerable Daily Intake (pTDI) that an adult weighing 60 kgs should consume no more than 0.71 or 0.47 µg THg or MeHg per kg of consumer body mass per day, respectively (Health Canada, 2007).

The Tolerable Daily Intake (TDI) is the quantity of a substance in air, food, or water that can be consumed daily over a lifetime without threatening the consumers' health (Health Canada, 1995). These TDI values can be used by governments to set guidelines for human health concerns, such as mercury in fish. TDI values can be set by individual governing bodies; however, Health Canada uses the Food and Agriculture Organization of the United Nations (FAO)/World Health Organization (WHO) Committee on Food Additives guidelines for methylmercury of 0.47 micrograms per kilogram of body weight per day (Health Canada, 2007). Health Canada developed a TDI for sensitive populations of 0.2 micrograms per kilogram of body weight per day (Health Canada, 2007). Jurisdictions often use the TDI as a basis for creating consumption guidelines for fish.

Factors at both a landscape (e.g., wetland area, type of vegetation cover) and water-body level (e.g., pH, nutrients, dissolved organic matter) influence Hg availability and trophic transfer in freshwater ecosystems (Chasar et al., 2009; Essington & Houser, 2003; Shanley et al., 2012; Wyn et al., 2010) (Table 2). Variables influencing Hg concentrations have been well studied; however, there are often complex mechanisms that can result in conflicting relationships. For example, dissolved organic carbon is often positively correlated with Hg (Evers et al., 2011; Grieb et al., 1990; Watras et al., 1998) but can be negatively correlated with trophic magnification slopes (Lavoie et al., 2013). Fish length is positively correlated with Hg; however, growth dilution (rapid growth results in lower Hg because the growth is greater than the gain of Hg in tissue) can result in a negative correlation between fish length and Hg concentration (Essington & Houser, 2003; Karimi et al., 2007; Kidd et al., 1995). Despite these potentially conflicting relationships, the combination of these factors results in consistent biomagnification rates across the globe.

Southeastern Canada has the highest calculated risk for Hg in freshwater fish across Canada (Depew et al., 2013*b*). Further studies have shown that Southwest Nova Scotia [*Kesputkwit* district] is a biological hotspot for Hg concentrations and was found to have some of the highest levels of Hg in fish in North America (Evers et al., 2007; Kamman et al., 2005; Wyn et al., 2010). This could be a combination of factors associated with elevated methylmercury (MeHg) in the environment, including an abundance of wetlands, acidic dystrophic and mesotrophic aquatic environments, gold mine tailings, and atmospheric deposition of Hg in the area (e.g., Evers, 2007; Wyn et al., 2010; LeBlanc et al., 2020, Wyn et al., 2009).

The recent acknowledgement of two non-indigenous fish species, chain pickerel (*Esox niger*) and smallmouth bass (*Micropterus dolomieu*) as popular recreational species in Nova Scotia has led to concerns regarding high levels of mercury and risks for fish consumers. Due to biomagnification rates, top predators such as these two invasive species are likely to have elevated Hg concentrations. The main uptake of mercury (Hg) in humans is through fish consumption (Baker et al., 2004; Mason et al., 2000), and methylmercury (MeHg) can account for upwards of 90% of THg in fish (Bloom, 1992; Grieb et al., 1990). Understanding, and better modelling of the risks and Hg levels in fish within Nova Scotia could help to inform scientific, governmental, and community groups for guidance regarding fish consumption.

Across North America, various studies have attempted to predict mercury concentrations in fish (Table 3). There are different approaches, such as using existing data to create proxies (Depew et al., 2013*a*; Wente, 2004) or using predictor variables such as fish length, pH, and percent wetland (Qian et al., 2001; Shanley et al., 2012).

These can be at various scales of precision, such as predicting risk for an entire watershed or individual waterbody. Predictor models are often complex with multiple variables, as many environmental characteristics contribute to mercury concentration in freshwater ecosystems. Predicting mercury concentrations in fish can provide cost-effective opportunities to develop consumption guidelines, accounting for high-risk areas.

The goals of this paper are to provide information on existing consumption guidelines and data for mercury risk in freshwater ecosystems across Nova Scotia. By identifying gaps in Nova Scotia water quality data and parameters to assess Hg risk, we intend to provide options to improve the understanding of Hg across the province. Estimating risk of mercury available for uptake into freshwater ecosystems using environmental parameters is a potential cost-effective way to determine areas of risk that need monitoring programs or specific guidelines. Therefore, understanding and predicting mercury concentrations can provide data for creating provincial consumption guidelines and advisories.

METHODS

Current information on Hg consumption guidelines, recommendations, or advisories for each Canadian province and territory was gathered from government documents and websites. Information on species; size classes; portion sizes; groups included and their definition; (i.e., children; the general public; vulnerable populations); and calculations for recommended consumption were collected. Consumption recommendations are defined as advised serving sizes and frequency of consumption, while consumption advisories are noted as an elevated risk of certain species or locations.

Fish consumption guidelines across Canada were located using multiple methods, including online databases held within the Government of Canada, relevant provincial government departmental webpages, Google, Google Scholar as well as searching the bibliographies and literature-cited sections of consulting and government reports on fish consumption guidelines. Key terms included “Provincial Consumption Guidelines”, “Angler’s Handbook”, “Fishing Guide”, “Recommended fish consumption”, “Fish advisories Canada”, and “Mercury in fish”. Documents were downloaded in PDF format and indexed in our Zotero account or website links archived using the “Wayback Machine – Internet Archive” (https://archive.org/web/) for future reference.

Water quality and landscape characteristics most likely to impact Hg concentrations in Nova Scotia were chosen based on data availability and literature reviews. Key terms included “wetlands”, “biodilution”, “chlorophyll-a”, “pH” combined with “mercury” or “freshwater ecosystems”. Reviewing bibliographies and literature cited led to identifying other key papers. Previous studies have identified water quality factors such as nutrient availability, dissolved organic carbon, alkalinity, pH, and Hg availability as important predictor variables for Hg in fish (Chasar et al., 2009; Lavoie et al., 2013; Mattieu et al., 2013; Shanley et al., 2012). Landscape characteristics that are important for Hg in fish include percent wetlands and connectivity (Chasar et al., 2009; Shanley et al., 2012). Other factors previously used to predict Hg in fish include fish weight or length, species, and location (Depew et al., 2013*a*; Qian et al., 2001; Shanley et al., 2012).

Water quality datasets for 251 water bodies (lakes, rivers, ponds, harbours, and bays) across Nova Scotia from 2000 – 2019 from digital sources were compiled as a part of another research project (Kingsbury & Campbell, 2020) and were expanded for this project. Searches were conducted using Atlantic DataStream to add water quality parameters that were of potential interest for mercury risk (i.e., arsenic, iron, selenium, mercury, aluminium; etc.), and add data from 2019 – 2022. Priority water quality parameters included pH, dissolved or total organic carbon, alkalinity, phosphorus, iron, selenium, aluminum, conductivity, calcium, secchi depth, mercury, and chlorophyll-a. Waterbodies with one or more of the priority water quality parameters were included in this dataset. Many data collection sites are regularly sampled (i.e., once per month), so only the newest data were included. For this study, I removed smaller streams, brackish or saltwater sites, waterbodies without fish, and areas unsuitable for angling (e.g., ornamental ponds). The final dataset was composed of 344 waterbodies across Nova Scotia. Statistical analyses were performed using RStudio version 4.1.2 and R version 3.0 (R Core Team, 2021). The data visualization was created using the visdata package (Tierney, 2017) in RStudio. This data was then mapped using ArcGIS Pro version 3.0.2.

Percent wetland cover was calculated in ArcGIS Pro using instructions provided by Greg Baker (Research Instrument Technician, Saint Mary's University). The files used were the Nova Scotia Wetlands Vegetation and Classification Inventory data from the Nova Scotia Department of Natural Resources and Renewables (NS DNRR, 2017) available under Saint Mary's University licencing, and the 1:10,000 Nova Scotia Primary Watersheds data (NS DECC, 2020) obtained from the Government of Nova Scotia website. These datasets were used in ArcGIS Pro to intersect the wetlands in each primary watershed, which was then exported to Excel, and the percent wetland was calculated using the hectares of wetland and the total hectares of land in each watershed.

The variables with the most data available and correlation with Hg biomagnification and bioavailability included percent wetland cover of the primary watershed, phosphorus (mg/L), chlorophyll-a (µg/L), total organic carbon (mg/L), and pH. There can be strong interactions between these variables (Figure 1). Risk values were assigned to primary watersheds, as this was the data available for the percent wetland. Within primary watersheds, the average value of each water quality predictor was assigned a risk score (Table 4). A higher number indicates greater potential risk, while a lower number indicates lower risk. A zero (0) was assigned to watersheds with no existing water quality data to indicate a lack of data. This risk value does not account for fish species or size, it is a general risk for the potential Hg available for uptake into the food web. These variables were focused on water quality parameters associated with Hg in fish, as that is the main human health concern. The cumulative score of these risk values provides a coarse-scale estimate of the potential risk of Hg available for uptake into food webs by primary watersheds in Nova Scotia.

Wetlands are significantly correlated with mercury concentrations in freshwater ecosystems, and of all landscape characteristics of an area, the percent wetland within a watershed can have the strongest effect on Hg in fish (Chasar et al., 2009; Shanley et al., 2012). Wetlands are optimal environments for methylating inorganic Hg compounds due to the presence of organic carbon, abundant microorganisms, and acidic and anaerobic conditions (Miskimmin et al., 1991; St. Louis et al., 1994; Thomas et al., 2020). In other studies, 20% wetland cover was mid-range, or any percentage below this threshold was considered low (Bell & Lutz, 2008; Chasar et al., 2009). Watersheds in Nova Scotia with wetland cover of 20% or less were assigned a risk value of 1, while areas with greater than 20% were assigned a value of 2.

pH is negatively correlated with Hg concentrations in fish (Grieb et al., 1990; Suns & Hitchin, 1990). In acidic water, Hg has greater bioavailability, and organisms have slower growth rates and reduced productivity (Burgess & Meyer, 2008; Essington & Houser, 2003; Winfrey & Rudd, 1990). Methylmercury production tends to be greater at pH 5-7 (Fagerstrom & Jerneloy, 1972; Miskimmin et al., 1991). Therefore, watersheds with an average pH of less than or equal to 5 were assigned a risk value of 3; pH 5-7 were assigned a risk value of 2; and pH above 7 was assigned a risk value of 1.

Total organic carbon (TOC) influences Hg concentrations in fish, as an increase in organic matter results in an increase in Hg (Chen et al. 2005; Driscoll et al. 1995). Aqueous organic matter is often measured as TOC or total dissolved carbon (Braaten et al., 2018). Organic matter in soils retains most atmospherically deposited Hg (80-90%) (Krabbenhoft et al., 2005), which can then be transported to aquatic systems through rainfall events, flooding, or erosion. Inputs of Hg^{2+} from organic matter may be methylated and become bioavailable within the aquatic food web. The effect of TOC on Hg does not have a threshold shown in the literature; however, TOC of 12 mg/L is a mid-range value in Braaten et al. (2018). Primary watersheds with an average TOC value greater than 12 mg/L were assigned a risk value of 2, while areas with average TOC values less than or equal to 12 mg/L were assigned a risk value of 1.

Phosphorus is related to chlorophyll-a concentrations; however, some sites had data for only one of the two variables, so both were included in the risk analysis.

Chlorophyll-a probes are available for YSI multi-parameter sondes, so in-field testing is available, while phosphorus and phosphate concentrations still require lab analysis.

Phosphorus is a limiting nutrient for aquatic organism growth and can contribute to algae and bacteria production (Correll, 1998; Xu et al., 2010). Eutrophic systems tend to have lower mercury concentrations (Pickhardt et al., 2002), likely due to organism growth. Total phosphorus above 0.02 mg/L can lead to excess algae production (measured as chlorophyll-a), which could result in growth dilution (Correll, 1998; Pickhardt et al., 2002). Rapid growth and nutrient availability can lead to growth dilution, where the gain in biomass is greater relative to the gain of Hg in tissue, resulting in lower Hg concentrations within top predators of aquatic systems (Karimi et al., 2007). Therefore, elevated phosphorus levels could increase chlorophyll-a and reduce the overall Hg concentrations in aquatic food webs. Phosphorus values less than or equal to 0.2mg/L were assigned a risk value of 1, as growth dilution could reduce Hg, while greater than 0.2mg/L were assigned a value of 2. Limited data exist for chlorophyll-a influence on Hg levels, but in Chen and Folt (2005), 7mg/L of chlorophyll-a was the mid-range value. For Nova Scotia, watersheds with an average chlorophyll-a concentration less than or equal to 7µg/L were assigned a risk value of 2, while greater than 7µg/L were assigned a value of 1.

RESULTS

Nova Scotia has two separate guidelines for fish consumption. One is published on the NS Environment Website, consisting of two size classes and consumption recommendations for different groups based on vulnerability (Table 5). The other is a fish consumption advisory published in the Nova Scotia Anglers' Handbook, which states some species should be consumed in smaller quantities or avoided by high-risk individuals due to mercury, and fish should not be consumed from certain lakes due to Polychlorinated Biphenyls (PCBs).

In Nova Scotia, 344 freshwater lakes, rivers, and streams in have water quality data from 2000-2022 that fit the criteria. pH is the most observed parameter, with only one lake missing data (Figure 2). The distribution of data is unequal across the province, with data collection being more concentrated in certain areas (Table 6, Figure 3). Halifax County has the highest proportion of sampled waterbodies in the entire province (n = 150), while Richmond County has the lowest (n = 0).

Water quality varies by waterbody, with a range spanning several magnitudes for some variables, especially those used for the predictor framework. pH ranges from 3.49 to 9.79, while total organic carbon ranges from 1.1 mg/L to 72.5 mg/L (Table 7). Chlorophyll-a ranged from 0.074 to 49.800 µg/L and total phosphorus ranged from 0 to 10 mg/L.

Predictor variables for the potential risk of Hg concentrations vary across the province (Table 8). The land cover of wetlands also varies across the province from 1.96% to 37.84%, with various hectares of wetlands in each watershed (Table 9). data.

Based on the chosen variables (percent wetland cover of watershed; pH; chlorophyll-a; phosphorus; and total organic carbon), the predicted risk of mercury in primary watersheds across Nova Scotia ranges from three to nine (Figure 4), with 45% having a total risk score of eight or above. Nine watersheds had no water quality data and were not given a risk score (assigned zero). Data availability varied by predictor variables, pH had the most data, and chlorophyll-a had the least (Figure 5).

DISCUSSION

Consumption Guidelines

Consumption guidelines and recommendations for fish vary widely across Canada. Nunavut is the only region with no published advisories or recommendations on fish consumption. Newfoundland, Prince Edward Island, and British Columbia all have fish consumption advisories for specific waterbodies but no consumption recommendations. Nova Scotia, New Brunswick, and Yukon have similar approaches of publishing general guidelines for the entire province. Alberta, Saskatchewan, and Manitoba provide recommendations at a waterbody level, but do not cover the entire province and are published online in PDF format. While, Ontario, Quebec, and Northwest Territories have interactive maps, Northwest Territories includes only 17 lakes and freshwater waterbodies. Ontario and Quebec have extensive maps with hundreds of waterbodies included with consumption guidelines for various fish species. Most provinces and territories have information on mercury in their respective fishing handbook, often a warning that larger fish are of greater risk if consumed.

Despite an estimated 182,000 kgs of arctic char and 22,000 lake trout harvested annually from 1996-2001 (Priest & Usher, 2004), Nunavut has no consumption recommendations or advisories for fish. Inuit represent the largest fishery in Nunavut by the number of participants and species harvested (Nunavut Department of Environment, Fisheries and Sealing Division, 2016). Many northern communities in Canada are connected to waterways for food, livelihood, and identity but can be exposed to Hg through diet when wild food from local ecosystems is incorporated (Pirkle et al., 2016). Nunavut has high-risk communities due to traditional diets and could benefit from fish consumption recommendations.

Guides published exclusively online are not accessible to all individuals. For example, people in rural areas may not have access to high-speed internet or a device capable of internet access; therefore, these publications are not easily accessible for everyone. Every few years, Ontario's comprehensive fish consumption guide is also published as a free book, which is available to order from their website or at certain retailers. The dual physical and online publishing makes the document accessible to all people in Ontario.

Data in Nova Scotia

Nova Scotia has limited water quality data for freshwater ecosystems. The province has a total of 6674 lakes with a surface area greater than one hectare (Alexander et al., 1986), but only 344 lakes, rivers, and streams have water quality data from 2000-2022. This data is also unequally distributed across regions, with Halifax County having data for 150 separate waterbodies, and the next highest being Lunenburg County with 49 sites. This limited dataset provides a challenge to accurately predict mercury risk from water quality parameters.

Mercury data are often limited due to resource constraints, as it is time-consuming and costly to fully sample a fish community. Recent mercury data within Nova Scotia are from a few studies or projects, and many studies are limited to Kejimikujik National Park and Historic Site (e.g., Evers et al., 2007; Wyn et al., 2009; Wyn et al., 2010). Predicting mercury risk in an area using environmental parameters could help to increase the understanding of mercury in freshwater fish across Nova Scotia. Risk predictions could be calibrated using existing Hg and water quality data to further improve confidence in the data.

Wetlands

Wetlands have complex mechanisms that affect mercury concentrations. Although wetlands are known to be significantly correlated with Hg concentrations, many factors influence this (Chasar et al., 2009; Lavoie et al., 2013; Snodgrass et al., 2000; St. Louis et al., 1994). Wetlands tend to have elevated levels of dissolved organic carbon (DOC), which is positively correlated with Hg concentrations (Chasar et al., 2009). DOC is complex for predicting Hg concentrations in fish, as it can increase the transport of MeHg from wetlands to lakes; however, it can also decrease the trophic transfer of Hg (Lavoie et al., 2013). Several studies have found that environments with high DOC levels and low pH, such as wetlands, had greater methylation rates, resulting in elevated Hg in fish (Snodgrass et al., 2000; Greenfield et al., 2001; Paranjape and Hall, 2017). Fish growth rates tend to decrease with increases in DOC (Benoit et al., 2016), which could result in lower rates of bioaccumulation as fish consume less or smaller prey. Wetland type may be an important factor in Hg accumulation and methylation rates. For example, peatlands sequester more than 20 times annual mercury emissions (Grigal, 2003). Considering wetland type and connectivity to watersheds is an important component for estimating mercury risk in fish.

Although dissolved organic carbon is positively correlated with Hg in fish, it has been shown to have a negative correlation with trophic magnification slopes or bioaccumulation factors (Ex., Lavoie et al., 2013; Braaten et al., 2018). This may be due to the strong binding of inorganic Hg to DOC, which reduces the bioavailability of Hg^{2+} for methylation (Lodenius et al., 1987; Miskimmin et al., 1991). DOC is positively correlated with Hg bioaccumulation in individual fish, so it was still included in this study as a risk factor.

There are multiple wetland classification datasets for Nova Scotia, each compiled using different methods with varying wetland types and percent cover. The Nova Scotia Wetlands Vegetation and Classification Inventory was used for this project, which delineates wetlands by bog, bog or fen, fen, marsh, salt marsh, swamp, and water. The dataset used for calculating the percent wetland per watershed would impact the result; however, for this risk map, the focus was on comparing watersheds. For a more detailed analysis, risk could be calculated for each wetland classification, and each of the wetland databases examined to choose the most robust dataset for this purpose.

Variable Interactions

There are strong interactions between many water quality parameters, including ones that impact the bioavailability and methylation of Hg. Wetlands are generally sites with low pH and high DOC production, which can lead to higher rates of Hg methylation (Snodgrass et al., 2000; Greenfield et al., 2001; Paranjape and Hall, 2017). Excess phosphorus in aquatic systems can contribute to algae production (measured by chlorophyll-a), which could result in a reduction of MeHg within food webs due to bloom dilution (Correll, 1998; Xu et al., 2010). The amount of phosphorus in a system is also correlated with wetlands; as wetlands can effectively reduce the amount of total phosphorus in aquatic systems (Land et al., 2016). The association of wetlands and phosphorus can also influence algae, due to the correlation of total phosphorus and chlorophyll-a. These interactions should be considered for future predictor model frameworks for Nova Scotia.

Anthropogenic Hg Sources in Nova Scotia

Aside from naturally occurring risk factors, anthropogenic sources of mercury are a concern in Nova Scotia. Tailings from historical gold mines have high concentrations of Hg, and there are an estimated 3 000 000 tonnes of historical gold mine tailings throughout Nova Scotia (Parsons et al., 2012). Although Parsons' (2012) report did not conclude that tailings were a concern for fish, 20% of soil samples and 71% of sediment samples from Nova Scotia exceeded the Canadian Council of Ministers of the Environment (CCME) maximum Hg limit. Other industries with legacy mercury reservoirs and sources include the pulp and paper industry. From 1972-1992, Canso Chemicals generated sodium hydroxide, chlorine, and hydrogen for pulping paper, in a process that used mercury (Dillon Consulting Limited, 2019). Legacy sources of Hg can be transported to other areas using biovectors such as aquatic emergent invertebrates (LeBlanc et al., 2020; Speir et al., 2014).

Some other anthropogenic Hg sources include gas- or diesel-powered vehicles from the combustion of fossil fuels (Won et al., 2007) and coal-fired power plants. In 2019 Nova Scotia Power reported 59 kg of Hg emitted as part of their total system emissions (NSPI, 2022). Since 2019, Nova Scotia Power has used mercury credits from the "mercury diversion program" and now only reports net mercury emissions (NSPI, 2022). Household items can also contain mercury, such as fluorescent light bulbs, glass thermometers, and thermostats (Government of Nova Scotia, 2017), and can contaminate areas if improperly disposed of. These anthropogenic sources of Hg are important to consider when examining Hg in fish communities.

Risk map

Risk of mercury in fish varies across the province but was consistently high with more than half of the primary watersheds having a score of seven or above. This elevated risk is not surprising, given the established literature of Nova Scotia as a biological hotspot for mercury (e.g., Evers et al., 2007; Kamman et al., 2005; Wyn et al., 2010). However, with improved water quality monitoring and targeted mercury sampling, the risk map could be refined to a more precise estimate.

Recommendations

Based on the variability of trophic magnification slopes (MacLeod, 2022) and limited mercury data in Nova Scotia, revisions should be considered for fish consumption recommendations. Targeting watersheds with limited or no existing water quality data (i.e., French, Isle Madame, Kennetcook, Missaguash, Parrsboro, Philip/Wallace, River Denys/Big, River Inhabitants, and Tidnish/Shinimicas), and creating guidelines for standardized water quality collections could improve the water quality dataset for Nova Scotia. Parameters that should be collected at each site to improve mercury estimations include chlorophyll-a, pH, total phosphorus, and total organic carbon (or dissolved organic carbon). This data could be used for a more precise estimate of mercury risk across the province. The mercury risk map could be used to target high-risk areas that need increased mercury sampling, and this data combined with the water quality data could be used to calibrate the predicted risk values. Combined, this data could be used to create site-specific fish consumption recommendations for Nova Scotia. Data should be available in both online and physical formats to ensure accessibility to all Nova Scotians.

Recommendations for improving the predictor model include: improving water quality monitoring in areas lacking data, further statistics, considering variable interactions, and collaborating with research groups that have previously created predictor models. Further statistics for improving the quality of the predictor model could include investigating the strength of the relationship between each variable and mercury within Nova Scotia. Correlation plots could further improve our understanding of mercury and its relationship to water quality in Nova Scotia. Variable interactions could also be included in future models to further strengthen the model. Creating a weighted scaling system is one method that could account for the importance and interactions between different water quality variables. Finally, connecting and collaborating with research groups that have developed predictor models for other areas of North America (i.e., Shanley et al., 2012) could help to create a more robust and detailed predictor model for Nova Scotia.

Improved monitoring of both water quality and mercury in freshwater ecosystems across the province could elevate our understanding of mercury risk in Nova Scotia. This data could lead to the creation of targeted and specific fish consumption guidelines.

Chapter 3. Figures

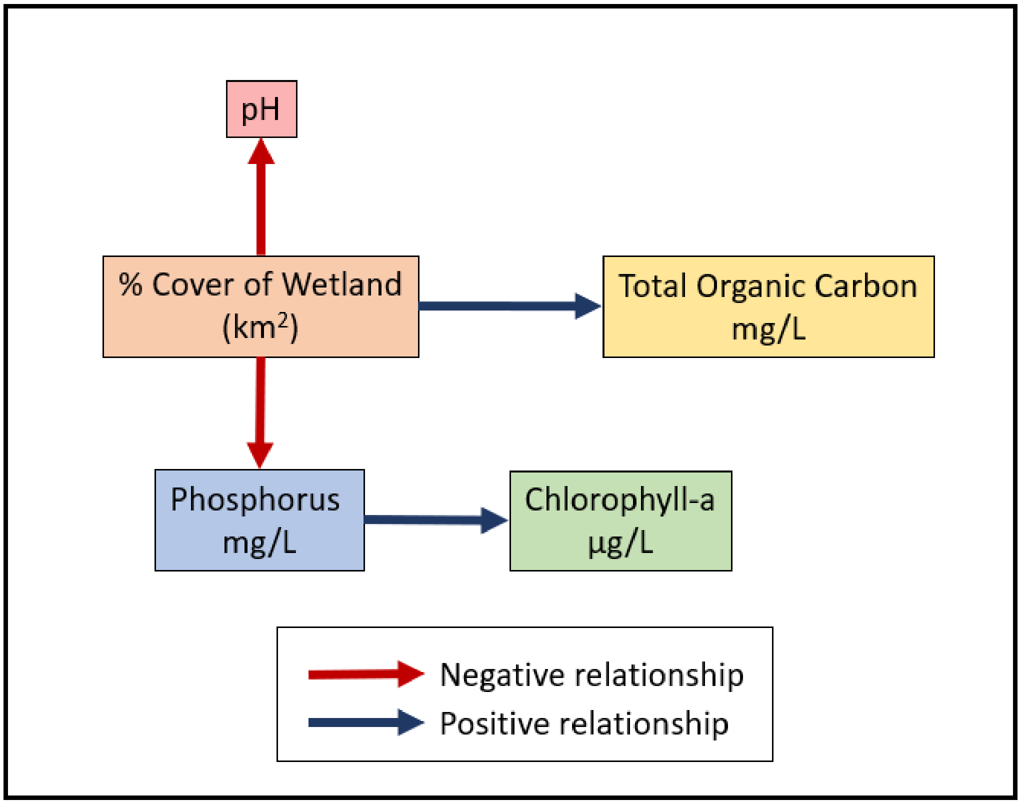


Figure 1. Potential interactions between variables used in the predictor model framework. Arrows indicate relationship direction and correlation. Negative relationships indicate a decrease in affected variable and positive relationship indicate an increase in affected variable.

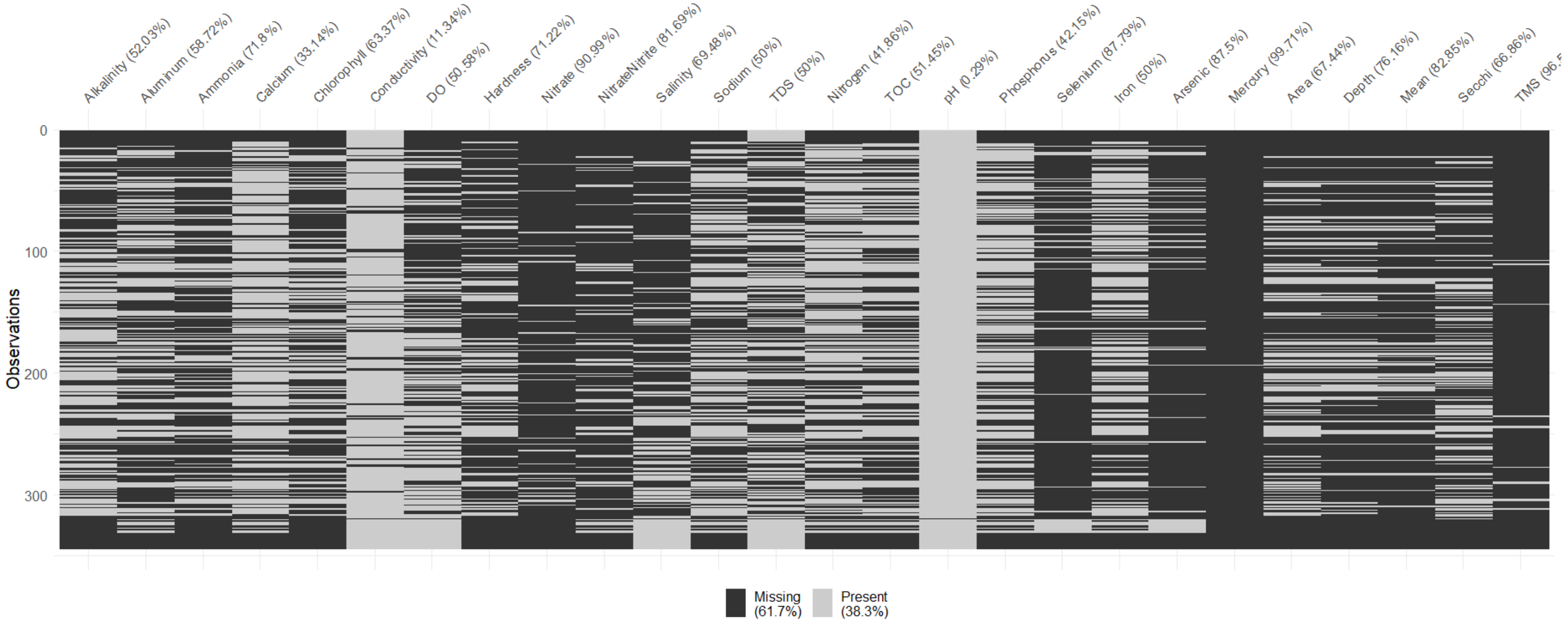


Figure 2. Visual representation of existing freshwater water quality data in Nova Scotia from 2000-2022. Parameters were included in orginal database (Kingsbury & Campbell, 2020) or are relevant to the potential concentration of mercury in freshwater. Each horizontal line represents one site and its corresponding water quality data. (n = 344).

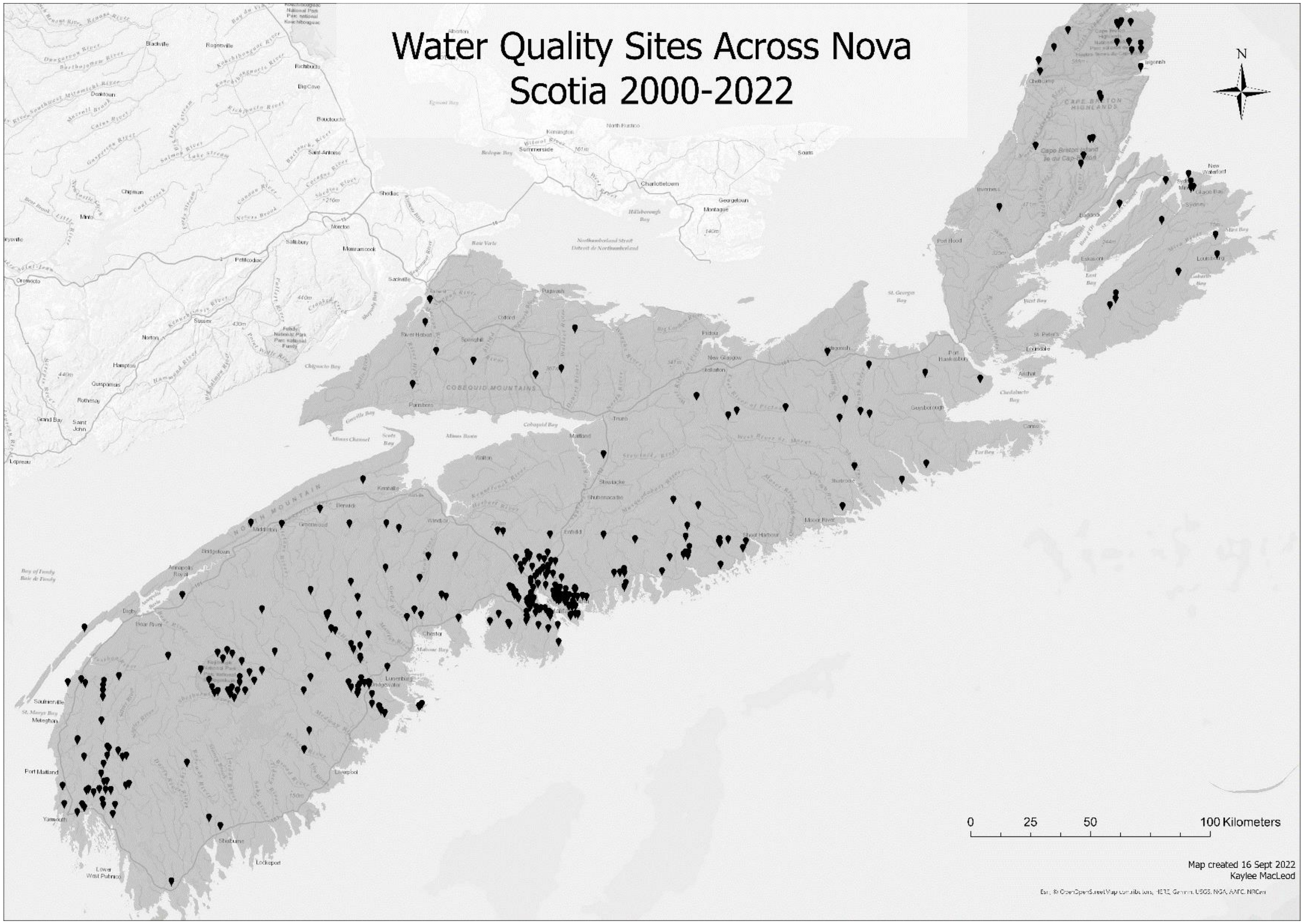


Figure 3. Water quality sampling locations across Nova Scotia from 2000 to August 2022. Data collected from various groups, primarily from the Atlantic DataStream database. (n = 344).

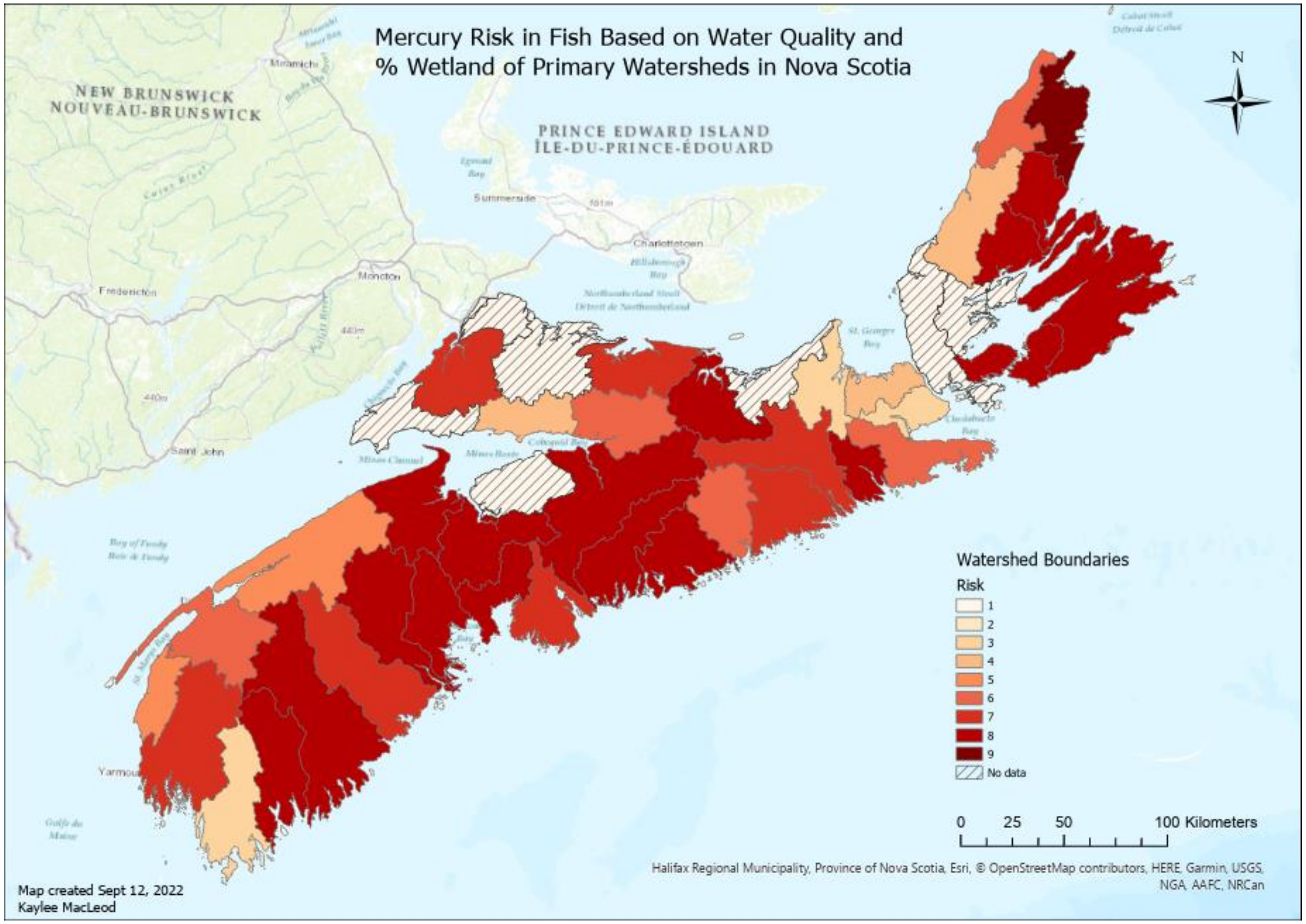


Figure 4. Coarse-scale risk map of potential mercury available for uptake into aquatic food webs across Nova Scotia by primary watershed (n = 46). Cross hatched areas indicate no data, scale increases from 1 (lowest risk) to 9 (highest risk). Risk based on water quality parameters (chlorophyll-a, pH, total phosphorus, and total organic carbon) and percent wetland cover of primary watersheds. See Table 4 for summary of risk value creation.

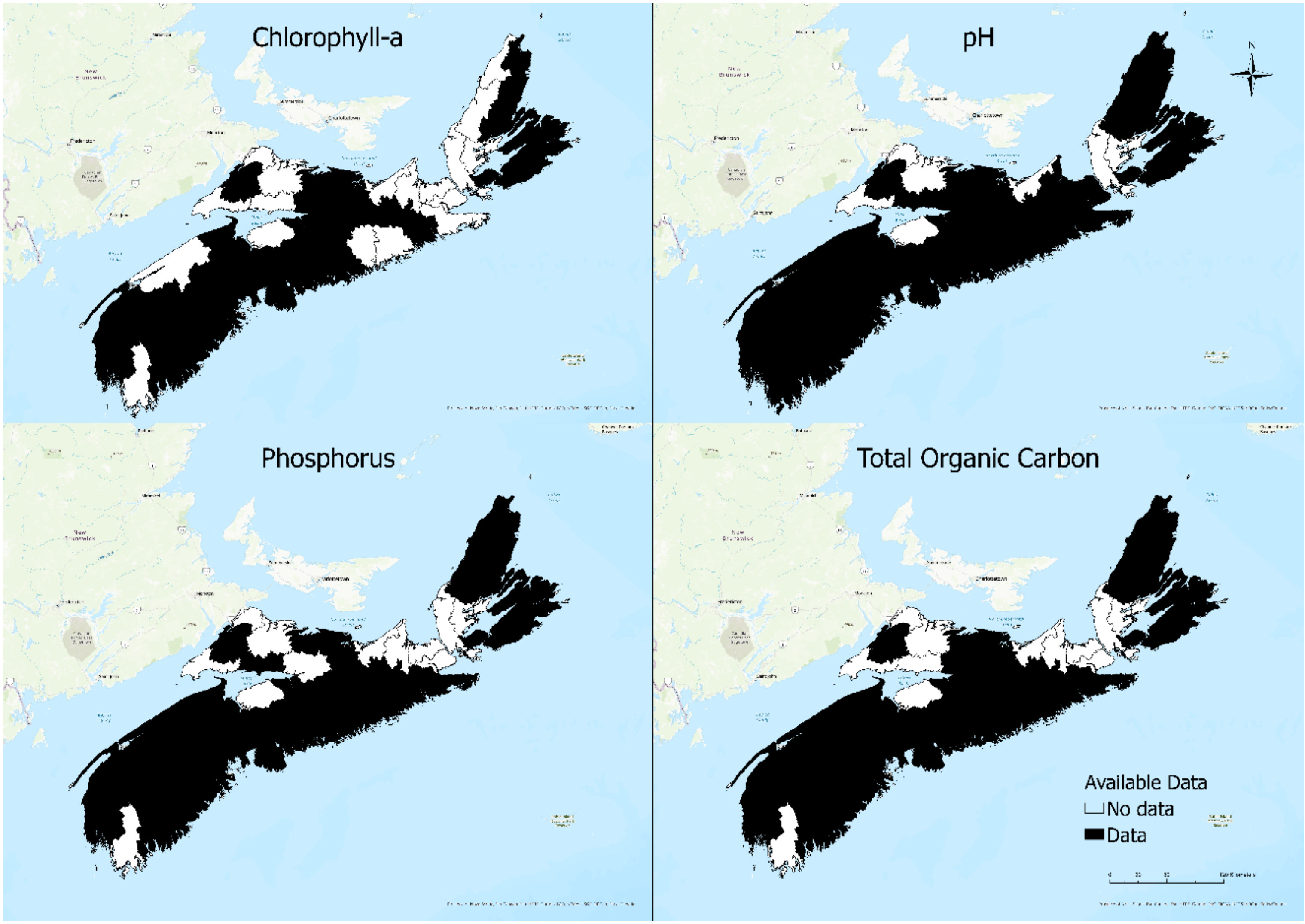


Figure 5. Data availability of predictor variables for the potential mercury risk for each primary watershed across Nova Scotia.

Chapter 3. Tables

Table 1. Provincial consumption guidelines for fish based on Hg concentrations. NP = Northern Pike, LT = Lake Trout, SB = Smallmouth bass, LB = Largemouth Bass, MK = Muskellunge, YP = Yellow Perch, WP = White Perch, CP = Chain Pickerel.

Region	Type of advisory	Groups	Specific advisories	Serving size	Calculations	References
Nunavut	No advisories or recommendations.	N/A	N/A	N/A	N/A	
Northwest Territories	Consumption recommendations; Location; Species; Interactive map	Pregnant/ breastfeeding women	LT <60cm: 24 servings/month LT ≥60cm: 20 servings/month NP <60cm: 24 servings/month NP ≥60cm: 12 servings/month	75 grams; Size of 1 pack of cards	None given	Interactive Map Fish Consumption General Guidelines
		Children 5-11 years	LT <60cm: 12 servings/month LT ≥60cm: 8 servings/month NP <60cm: 8 servings/month NP ≥60cm: 4 servings/month			
		Children 1-4 years	LT <60cm: 6 servings/month LT ≥60cm: 4 servings/month NP <60cm: 4 servings/month NP ≥60cm: 2 servings/month			

Yukon	Consumption recommendations; Species (Lake trout only); Fish size (length cm and weight lbs)	Women of childbearing age and children under 12 years old	LT <40 cm (~2lbs): Unlimited consumption LT 40 - 60 cm (~2-4lbs): 3-4 meals/week LT >60cm (>6lbs): 1-2 meals/week	75 grams; Per week	None given	Yukon Fish Health Handbook
		General population	Consuming LT <60cm gives higher degree of safety in limiting Hg exposure			
British Columbia	Consumption advisories; Location; Species; Health Canada consumption guidelines for commercial fish	N/A	SB large in size in lakes on Vancouver Island and the Gulf Islands LT >45cm in Jack of Clubs Lake LT in Williston Lake and tributaries LT in Pinchi Lake	Limit consumption	None given	2021-2023 Fishing Regulations Mercury in Fish
Alberta	Consumption recommendations; Location; Species; Size (weight in lbs)	Women; Children (1-4yr); Children (5-11yr); Adults	Varies by waterbody	75g; 2.5oz; a piece of cooked fish that fits in the palm of your hand.	CR = pTDI * BW (7 d/wk) / C	Fish Consumption
Saskatchewan	Consumption recommendations; Location; Species; Size (length, cm)	General population; Sensitive	Varies by waterbody	220 grams or 8 ounces; (smaller adults and children = approximately the size of their hand)	None given	Mercury in Saskatchewan Fish

Manitoba	Consumption recommendations; Location; Species; Size (length in cm); Mercury concentration in fish	Women of childbearing age and children under 12 years old	Servings per month: Category 1: 8 Category 2: 3 Category 3: 0 Category 4: 0	227g.	Acceptable daily intake for general population of MeHg: 0.47 (ug/kg bw) Sensitive population: 0.2 ug/kg bw	Mercury in Fish & Guidelines for the consumption of recreationally angled fish in Manitoba
		General population	Servings per month: Category 1: 19 Category 2: 8 Category 3: 4 Category 4: 3			
Ontario	Consumption recommendations; Location; Species; Size (length in cm); Interactive digital map	General population; Sensitive population	Varies by waterbody	227 grams of skinless, boneless fillet for adult weighing 154lbs.	Sensitive pop. restrictions begin at 0.26ppm, complete restrictions at 0.52ppm. General pop. restrictions begin at 0.61ppm and total restriction at 1.84ppm	Eating Ontario Fish
Quebec	Consumption recommendations; Location; Species; Size (length cm); Interactive digital map	Vulnerable people	Recommended to **avoid** consuming species prone to contamination, such as NP, LT, SB, LB and MK.	230 grams	Based on the 0.5 mg/kg issued by Health Canada	Guide to eating freshwater sportfish in Quebec Interactive map
		General population	SB, LB, NP, MK and LT: 2 meals per month.			

			YP: 1 meal per week or less.			
New Brunswick	Consumption recommendations; Location (striped bass only); Species; Size (forked length, cm)	General population over 12 years	LT, MK, WP, YP, CP, SB of any size: 2 servings per month	75g or 2.5oz cooked fish; 125mL or 1/2 cup cooked fish; or a portion of cooked fish that fits in the palm of consumer's hand.	None given	New Brunswick Consumption Guideline - Fish and Mercury
		Sensitive population	LT, MK,WP, YP, CP, SB of any size: **Avoid**			
Nova Scotia	Consumption recommendations; Species; Size (forked length, cm)	General Public over age 12	YP <20cm: 1 serving/week YP >20cm: 1 serving/month WP <25cm: 2 servings/month WP >25cm: 1 serving/month CP <35cm: 2 servings/week CP >35cm: 2 servings/month SB <35cm: 3 servings/month SB >35cm: 2 servings/month	75g or 2.5oz cooked fish; 125mL or 1/2 cup cooked fish (Canada's Food Guide)	None given	Nova Scotia Fish Consumption Advisory Nova Scotia Fishing Guide - Hg advisory on page 69

		Women who are or may become pregnant and/or are breast feeding	YP <20cm: 2 servings/month WP <25cm: 1 serving/month WP >25cm: 0.5 serving/month CP <35cm: 1 serving/week CP >35cm: 1 serving/month SB <35cm: 1 serving/month **Avoid:** YP >20cm; SB >35cm			
		Children age 5-11	YP <20cm: 1.5 servings/month CP <35cm: 1.5 servings/month SB <35cm: 1.5 servings/month **Avoid:** YP >20cm; WP; CP and SB >35cm			
		Children age 1-4	CP <35cm: 1 serving/month **Avoid:** YP; WP; CP >35cm; SB.			
		Infants (<1 year of age)	CP <35cm: 0.5 serving/month **Avoid:** YP; WP; CP >35cm; SB.			
Prince Edward Island	Consumption advisories; Location	N/A	Fish in O'Keefe's Lake have mercury levels in excess of recommended guidelines. Fish from this lake should not be eaten.	N/A	None given	Fishing Regulations PEI

Newfoundland and Labrador	Consumption advisories; Location; Species	N/A	Smallwood Reservoir, Lobstick Forebay, Churchill River - lake trout and northern pike should be consumed no more than once a week	No portion size given.	None given	Government of Canada - Mercury in Fish

Table 2. Factors that correlate with mercury concentrations in freshwater ecosystems.
Note: DOC has conflicting results with trophic magnification slopes (Ex., Lavoie et al., 2013); fish length can also have conflicting results due to growth dilution (Ex. Essington & Houser, 2003; Karimi et al., 2007; Kidd et al., 1995)

Factor	**Measured variable**	**Correlation with Hg**	**Mechanism**	**Sources**
Food web length	Species present	+	Hg biomagnifies along the food web and is highest in top predators, a longer food web provides more opportunity for Hg biomagnification	Bowles et al., 2001; Cabana et al., 1994
Trophic level	$\delta^{15}N$ (‰)	+	Hg biomagnifies along the food web and is highest in top predators.	Depew et al., 2013a; Gandhi et al., 2014; Haines, 1997; Kidd et al., 1995; Neumann & Ward, 1999; Wyn et al., 2009
Fish length	Length (mm)	+	Hg bioaccumulates in fish tissue due to diet, a larger bodied individual will likely have elevated Hg compared to a smaller bodied intraspecific individual.	Bowles et al., 2001; Watras et al. 1998; Kamman et al. 2005
Wetland % cover	Area (km^2)	+	Hg becomes methylated in wetland areas, available for uptake by organisms. Primary sites for DOC production	Chasar et al. 2009; Mattieu et al., 2013; Mills et al., 2019; Shanley et al., 2012
Acidity	pH	-	Greater Hg bioavailability in acidic water, slower growth of biota in acidic water	Burgess & Meyer, 2008; Grieb et al., 1990; Essington & Houser, 2003; Miskimmin et al., 1991
Dissolved Organic Carbon	DOC (mg/L)	+	Higher methylation of Hg in high DOC environments	Evers et al., 2011; Grieb et al., 1990; Watras et al., 1998; Driscoll et al., 2007; Broadley et al., 2019

Chlorophyll-a	Chlorophyll-a (mg/L)	-	Increasing algal biomass results in a decrease in concentration of mercury per cell (bloom dilution or growth dilution), reducing uptake in the food web.	Pickhardt et al., 2002
Total phosphorus	Phosphorus (mg/L)	-	Increased productivity can lead to eutrophic conditions and phosphorus can contribute to algae and bacteria production	Mills et al., 2019; Stone et al., 2011

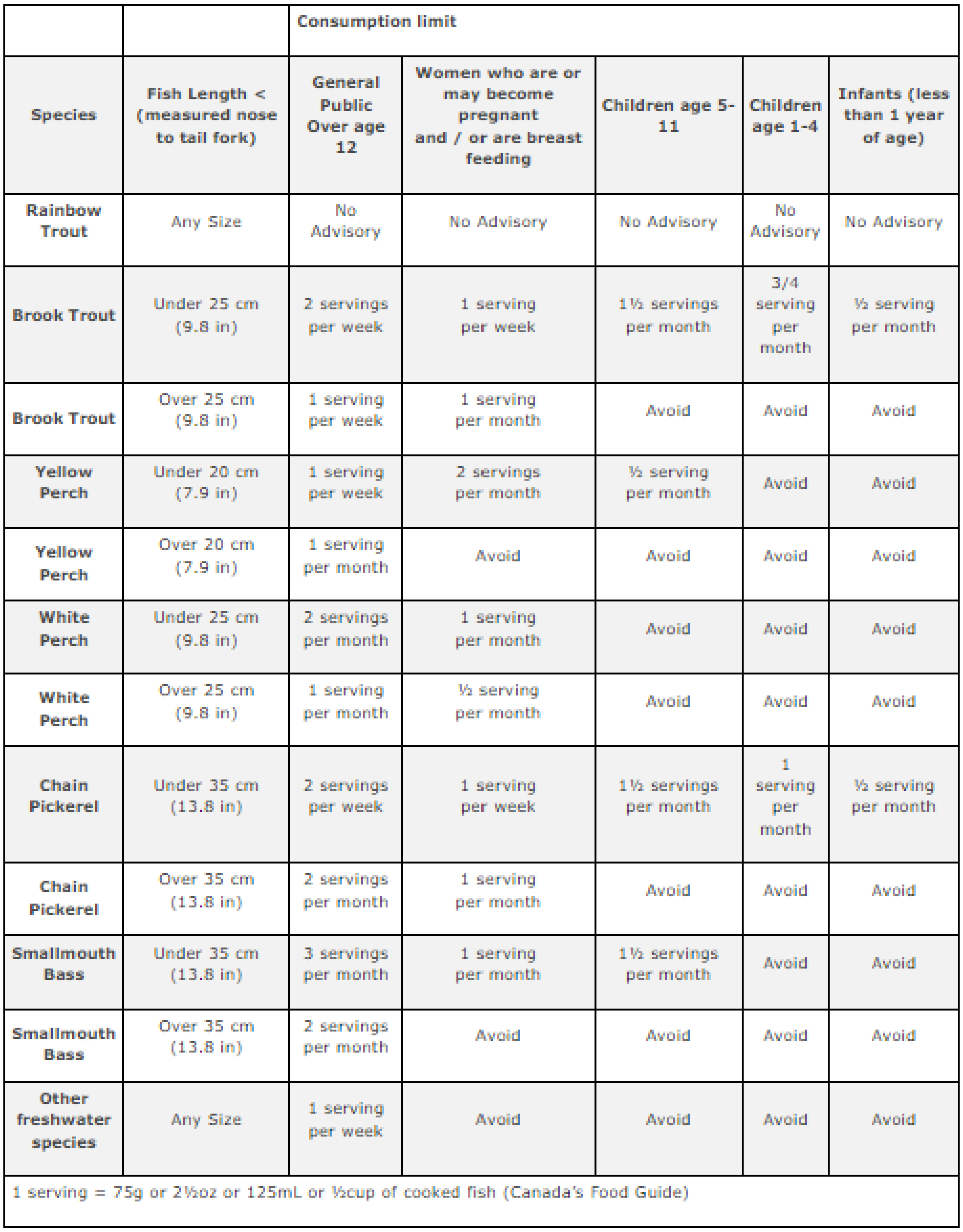
Table 3. Summary of existing North American predictor models for mercury in fish in the last 20 years.

Authors	Year	Model Name	Methods	Limitations
Wente, S	2004	National Descriptive Model for Mercury in Fish (NDMMF)	Statistical model and national fish mercury concentration data set that allow fish-mercury concentration to be partitioned between spatiotemporal and sample characteristics. Calibrated using existing fish Hg dataset.	Needs large existing database
Depew, D., Burgess, N., Campbell, LM.	2013	National Descriptive Model for Mercury in Fish (NDMMF)	Assessed national-scale application of NDMMF model. Used yellow perch length as proximity for missing data.	Requires a minimum set of criteria to be met (minimum of two sample different sample types)
Shanley, J., Moore, R., Smith, R. A., Miller, E. K., Simcox, A., Kamman, N., Nacci, D., Robinson, K., Johnston, J. M., Hughes, M. M., Johnston, et al.	2012	Mercury Geospatial Assessments for the New England Region (MERGANSER)	Interactive model to choose lake and 1-12 fish species and lengths. Predicts Hg concentration in fish by size using predictor variables (Hg deposition, watershed area, % forest canopy, % wetland area, population, mean annual temperature, weighted watershed alkalinity, % shrubland, % agricultural land)	Model is only applicable to lakes analyzed (i.e., only New England region)
Qian, S., Warren-Hicks, W., Keating, J., Moore, D. R. J., & Teed, R. S.	2001	N/A	Classification and regression tree modeling generalized additive modeling, and universal kriging. Factors for predicting mercury fish tissue: location, species, water body pH, fish weight	Does not account for different Hg sampling techniques

Table 4. Scale for Hg risk map, lower numbers indicate low risk, higher numbers indicate increased risk.

Predictor variable	**Hg Risk Values**	**Reason**	**Range in NS**	**Citation**
% Wetland cover of watershed	≤20% = 1 >20% = 2	Hg becomes methylated in wetland areas, being available for uptake by organisms. Also, primary sites for DOC production	1.96 - 37.84 %	Chasar et al. 2009; Mattieu et al., 2013; Mills et al., 2019; Shanley et al., 2012
pH	≤5 = 3 5-7 = 2 >7 = 1	Greater Hg bioavailability in acidic water, slower growth of biota in acidic water. MeHg production higher at pH 5-7.	3.49 - 9.79	Burgess & Meyer, 2008; Grieb et al., 1990; Essington & Houser, 2003; Miskimmin et al., 1991; Fagerstrom & Jernelov, 1972.
Total Organic Carbon (TOC)	≤12 mg/L = 1 >12 mg/L = 2	Increasing TOC resulted in increased MeHg bioaccumulation in fish	1.1 - 72.5 mg/L	Braaten et al., 2018
Chlorophyll-a	≤7mg/L = 2 >7mg/L = 1	An increase in algal mass results in growth dilution (decrease in concentration of mercury per cell)	0.0744 - 49.8000 mg/L	Chen & Folt, 2005; Pickhardt et al., 2002
Phosphorus	≤0.02mg/L = 2 >0.02mg/L = 1	Total phosphorus above 0.02 mg/L led to excess algae production, which could result in growth dilution	0 - 10 mg/L	Correll, 1998; Pickhardt et al., 2002.

Table 5. Nova Scotia fish consumption guidelines, available from https://novascotia.ca/nse/fish-consumption-advisory.asp (accessed June 23, 2022).



		Consumption limit				
Species	**Fish Length < (measured nose to tail fork)**	**General Public Over age 12**	**Women who are or may become pregnant and / or are breast feeding**	**Children age 5-11**	**Children age 1-4**	**Infants (less than 1 year of age)**
Rainbow Trout	Any Size	No Advisory	No Advisory	No Advisory	No Advisory	No Advisory
Brook Trout	Under 25 cm (9.8 in)	2 servings per week	1 serving per week	1½ servings per month	3/4 serving per month	½ serving per month
Brook Trout	Over 25 cm (9.8 in)	1 serving per week	1 serving per month	Avoid	Avoid	Avoid
Yellow Perch	Under 20 cm (7.9 in)	1 serving per week	2 servings per month	½ serving per month	Avoid	Avoid
Yellow Perch	Over 20 cm (7.9 in)	1 serving per month	Avoid	Avoid	Avoid	Avoid
White Perch	Under 25 cm (9.8 in)	2 servings per month	1 serving per month	Avoid	Avoid	Avoid
White Perch	Over 25 cm (9.8 in)	1 serving per month	½ serving per month	Avoid	Avoid	Avoid
Chain Pickerel	Under 35 cm (13.8 in)	2 servings per week	1 serving per week	1½ servings per month	1 serving per month	½ serving per month
Chain Pickerel	Over 35 cm (13.8 in)	2 servings per month	1 serving per month	Avoid	Avoid	Avoid
Smallmouth Bass	Under 35 cm (13.8 in)	3 servings per month	1 serving per month	1½ servings per month	Avoid	Avoid
Smallmouth Bass	Over 35 cm (13.8 in)	2 servings per month	Avoid	Avoid	Avoid	Avoid
Other freshwater species	Any Size	1 serving per week	Avoid	Avoid	Avoid	Avoid

1 serving = 75g or 2½oz or 125mL or ½cup of cooked fish (Canada's Food Guide)

Table 6. Nova Scotia freshwater bodies with existing water quality data from 2000 - 2022 sorted by county. Only waterbodies that fit criteria were included. Larger waterbodies (I.e., lakes, rivers, ponds, harbours and bays) suitable for fishing were included.

County	**Number of Sampled Waterbodies**
Annapolis	13
Antigonish	4
Cape Breton	9
Colchester	2
Cumberland	11
Digby	16
Guysborough	10
Halifax	150
Hants	3
Inverness	6
Kings	4
Lunenburg	49
Pictou	3
Queens	15
Richmond	0
Shelburne	6
Victoria	15
Yarmouth	28

Table 7. Summary results of freshwater quality parameters in Nova Scotia from 2000 - 2022. (n = 344).

Parameter	**Unit**	**Minimum**	**Median**	**Mean**	**Maximum**	**n**	**n below detection limit**
Alkalinity	mg/L	-0.70	4.50	11.09	100.00	231	66
Aluminum	mg/L	0.006	0.106	0.136	0.657	142	0
Ammonia	mg/L	0.002	0.020	0.059	2.370	127	30
Calcium	mg/L	0.076	1.400	6.076	361.500	236	6
Chlorophyll-a	ug/L	0.074	1.700	3.299	49.800	126	0
Conductivity	us/cm	6.7	42.300	323.8	36700.0	305	0
DO	mg/L	0.800	8.405	9.452	96.800	170	0
Hardness (CaCO3)	mg/L	1.69	7.40	26.75	1010.00	101	2
Nitrate	mg/L	0.007	0.850	0.157	0.714	66	35
Nitrate + Nitrite	mg/L	0.01	0.02	0.046	0.33	125	66
Salinity	µg/L or ppm	0.010	0.030	0.126	1.15	105	0
Sodium	mg/L	0.005	4.785	82.340	9507.000	172	0
TDS	mg/L	1.5	30.55	261.740	27763.0	173	1
Total Nitrogen	mg/L	0.08	0.27	0.33	3.23	203	3
Total organic carbon	mg/L	1.1	6.7	9.1	72.5	167	0
pH	0-14	3.49	6.27	6.15	9.79	343	0
Phosphorus	mg/L	0	0.008	0.175	10.000	208	9
Selenium	µg/L	0.04	0.07	0.07	0.11	43	12
Iron	mg/L	0.01	0.13	0.21	1.54	172	0
Arsenic	µg/L	0.07	0.40	0.61	4.92	44	12
Mercury	mg/kg	7.5	7.5	7.5	7.5	1	0
Area of waterbody	km^2	0.03	0.90	2.32	57.36	112	0
Secchi depth	m	0.1	2.0	2.3	8.6	114	0
Mean depth	m	0.67	2.90	4.238	20.3	59	0
Max depth	m	1.8	11.00	13.02	51.20	82	0
% Wetland cover of watershed	%	1.96	5.63	7.53	37.84	344	0

Table 8. Primary watershed area (hectares) with wetland area (hectares) and percent (%) wetlands in Nova Scotia.

Watershed	Total Watershed Area (HA)	Total Wetland Area (HA)	% Wetland
French	74785.8	1465.93	1.96
Tracadie	107579.0	2176.77	2.02
South/West	74785.8	2235.88	2.99
Economy	77965.9	2336.26	3.00
East/Middle/West (Pictou)	118514.0	3563.69	3.01
River John	109063.0	3575.32	3.28
River Denys/Big	78520.9	2651.44	3.38
Annapolis	226037.0	7977.50	3.53
River Inhabitants	119623.0	4252.64	3.56
Salmon/Debert	117390.00	4180.23	3.56
Clam Harbour/St. Francis	107579.00	3891.54	3.62
St. Croix	134558.00	4977.46	3.70
Margaree	137093.00	5121.70	3.74
East/Indian River	77763.60	2911.64	3.74
Gaspereau	132360.00	5266.84	3.98
Sissiboo/Bear	144398.00	6381.74	4.42
Sackville	97233.70	4298.75	4.42
Philip/Wallace	148808.00	6596.49	4.43
Shubenacadie/Stewiacke	270631.00	12765.10	4.72
Gold	106798.00	5091.05	4.77
LaHave	168577.00	8161.50	4.84
North/Baddeck/Middle	76656.20	3775.95	4.93
Parrsboro	85960.20	4351.14	5.06
Kelly/Maccan/Hebert	128548.00	7230.97	5.63
Herring Cove/Medway	202639.00	11475.90	5.66
Meteghan	62029.40	3684.06	5.94
Kennetcook	101419.00	6351.93	6.26
Musquodoboit	138865.00	9449.97	6.81
Grand	76986.60	5355.03	6.96
Tangier	109198.00	7615.96	6.97
St. Marys	152667.00	11947.50	7.83
Tusket River	217645.00	18621.70	8.56
East/West (Sheet Harbour)	100214.00	8766.44	8.75
Wreck Cove	103691.00	10554.40	10.18

Indian	84582.30	8692.38	10.28
Salmon/Mira	285780.00	29411.20	10.29
Liscomb	119876.00	12431.70	10.37
Costal Island	38165.40	4108.89	10.77
Mersey	299285.00	32269.60	10.78
Tidnish/Shinimicas	48387.30	5352.93	11.06
Isle Madame	11524.60	1308.69	11.36
Country Harbour	57235.60	6928.02	12.10
Roseway/Sable/Jordan	143023.00	17755.10	12.41
Cheticamp River	80362.40	12877.70	16.02
New Hbr/Salmon	52655.40	8488.58	16.12
Barrington/Clyde	141245.00	25589.90	18.12
Missaguash	4114.27	1556.69	37.84

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Chapter 3. Appendix A.

Table 1. Chapter 3. Appendix A. Summary of references for water quality data, the data collections year and number of sites.

Data Source	**Data collection years**	**Sites (n)**
ACAP Cape Breton Water Quality Data - Stream Restoration (2014-2017)	2016 – 2017	3
BARA-Dartmouth,NS-Sawmill River Watershed-Baseline YSI Study	2015	13
Blue Mountain Birch Cove Lakes Water Quality Baseline data	2021	22
Carleton River Watershed Area and Tusket Catchment	2013 – 2018; 2019 – 2021	4
Clean Foundation Watershed Restoration Monitoring Data	2015 – 2016	24
Coastal Action	2021	1
Equipping communities in data-deficient areas (citizen scientists)	2019 – 2020	4
Fisheries and Oceans Canada 2011 HRM Lake Data	2011	32
Fox Point Lake Water Quality Monitoring Dataset	2018	1
Historic Gold Mine Tailings Wetland Sites	2017	1
LaHave River Water Quality Monitoring (Coastal Action)	2020	11
Maitime Coastal Basin Long-Term Water Quality Monitoring Data	2018	46
NS Government	2002	2
NS Government Lake Survey Data	2002 – 2003; 2010; 2013 – 2014; 2016 – 2021	29
NS Lake Chemistry Data from the Department of the Environment	2000 – 2009; 2011; 2015; 2018 – 2021	109
Oathill Lake Conservation Society Water Monitoring	2018 – 2022	3
Petite Riviere Lakes and Headwaters Dataset (Coastal Action)	2020	1
Petite Riviere Watershed Water Quality Dataset (Coastal Action)	2019	15
Sackville River Watershed water quality monitoring	2013	2
Sherbrooke Lake Water Quality Monitoring Dataset	2018 – 2019	1
Shubenacadie Watershed Environmental Protection Society - Soldier and Miller Lakes Monitoring Program (SWEPS)	2014	3
TREPA: Water Quality data from the Tusket Catchment	2013 – 2015	17