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Metals and persistent organic pollutants as ecological determinants of human health in Naivasha, Kenya

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Graduate Program in Biology
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science
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Metals and persistent organic pollutants as ecological determinants of human health in Naivasha, Kenya

(Spine title: Metals, POPs and implications for health in Naivasha, Kenya)

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By

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Graduate Program in Biology with Environment and Sustainability

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

School of Graduate and Postdoctoral Studies
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London, Ontario, Canada

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ABSTRACT AND KEY WORDS

The main industries in Naivasha are floriculture and geothermal energy, with both industries beginning in the 1980s. Increased employment caused a 20-fold increase in population over 3 decades. These changes have the potential to increase the release of environmental contaminants, such as metals and persistent organic pollutants (POPs). This study uses an ecosystem health approach to study the distribution and health risks associated with metals in airborne dust and POPs and metals in *Cyprinus carpio* dorsal muscle, in Naivasha, Kenya. Findings suggest that Ni in airborne dust may be derived from natural catchment substrate, but still exists at concentrations above World Health Organization guidelines. Of the POPs and metals quantified in *Cyprinus carpio,* only dieldrin and Hg exceeded the U.S. Environmental Protection Agency guidelines for unlimited fish consumption. Concentrations of Hg and dieldrin are still low enough for safe fish consumption 16 times/month and more than 3 times/month, respectively.

Keywords: Lake Naivasha, persistent organic pollutants, organochlorines, PCBs, metals, mercury, *C. carpio*, atmospheric dust, health

CO-AUTHORSHIP STATEMENT

The data in this thesis was collected using funds from the International Development Research Center (IDRC) of Canada grant to Dr. Charles Trick and Dr. William Shivoga, for the study entitled: "*Lake Naivasha Sustainability Project: Managing Resources for Continual Improvement of the Ecosystem for Human Health and Well-being in the Lake Naivasha Basin, Kenya*". If any of the content of this thesis is submitted for publication, Dr. Charles Trick and Dr. Irena Creed will be listed as co-authors for their contributions to the project conceptualization, interpretation of results, and editing of the manuscript.

DEDICATION

I dedicate this thesis to my parents, Mary and Michael Hicks.
You have always been my biggest fans, believing in me, even with I didn’t believe
in myself. Without your confidence, guidance, and support,
I don’t know where I would be.

From the bottom of my heart, thank you.

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LIST OF ABBREVIATIONS

DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
HCH	Hexachlorocyclohexane
PCB	Polychlorinated biphenyl
POP	Persistent organic pollutant
USEPA	U.S. Environmental Protection Agency
WHO	World Health Organization
BMF	Biomagnification factor
RAF	Relative accumulation factor
KWS	Kenya Wildlife Service

CHAPTER 1: General Introduction

1.1. Ecosystem Health: a framework for studying the ecological determinants of human health

Human communities depend on ecosystems to provide services, such as the provision of food and clean water, flood control mechanisms, waste decomposition and aesthetic and recreational services. Human use of these ecosystem services can also degrade them (Charron, 2012). Because the quality of ecosystem services can contribute to the health of human communities, they are often referred to as ecological determinants of health.

Contaminated freshwater systems are an example of a negative ecological determinant of health. Freshwater lakes provide numerous ecosystem services, including clean water for drinking and agriculture, and fish protein. For these reasons, many urban and agricultural activities are often located in close proximity to freshwater resources. Wastewater, runoff, and airborne dust from cities and agriculture often contain contaminants, such as metals or persistent organic pollutants. Because water bodies are repositories for much of what comes from the land, they often accumulate contaminants and can become an ecological cause of human health problems (Laing, et al., 2007). The study of interactions between human health and environmental health (the 'social-ecological system') is called ecosystem health.

Ecosystem health research is founded on 3 main principles (Charron, 2012). Those include:

Systems thinking

To think systematically implies the need to understand how all components of a system work together at various scales. The components that should be considered in the social-ecological system include ecology, culture, economics and governance (Charron, 2012).

Transdisciplinary

Transdisciplinary research is not an easy objective. It involves the integration of many academic disciplines, which have traditionally worked independently. The goal is a synergistic understanding of the social-ecological system, which no one discipline could have achieved on its own. Academics from the social, natural and health sciences, work together to design the research project, collect the data, and make suggestions for change based on the results.

Participatory Research

Participation involves the meaningful engagement of community stakeholders in developing the research objectives and implementing change based on research findings. The premise is that research will be more useful to a community and proposed solutions will be more robust, if the community is involved in the planning and implementation.

1.2. Employing an ecosystem health approach in Naivasha, Kenya

Lake Naivasha is a highly valuable freshwater lake in central Kenya. It is so important that it was given a RAMSAR designation as a wetland of international importance in 1995 (Harper, et al., 2011). The lake provides ecosystem services to a huge number of stakeholder groups, meaning that the temptation to use it to the point of degradation is high.

1.3. The History of Naivasha

Prior to 1980, the main economic activity in the Lake Naivasha catchment was small scale farming and non-irrigated fodder. In the early 1980s, there was an important shift in economic activity, which began to alter Naivasha's social-ecological system (Becht, et al., 2005).

In 1981, the Kenya Electricity Generating Company (KenGen) opened their first geothermal production facility in the Lake Naivasha catchment (Kenya

Electricity Generating Company, 2010). Since that time, 2 more geothermal facilities have opened, with all facilities located on the south shore of the lake. Naivasha now produces about 128 MW of electricity annually, amounting to about 20% of the Kenyan power supply (Kenya Bureau of Statistics, 2009). While energy production is an obvious example of a useful ecosystem service in the Naivasha catchment, it is not without risk. Geothermal steam is rich in many metals, including arsenic, zinc, and boron (Simiyu & Tole, 2000). Extraction of steam for energy could potentially lead to increased concentrations of these metals at the surface.

Another change that occurred in the 1980s was the shift towards intensive horticulture (Becht, et al., 2005). The most successful form of horticulture has been the cut-flower industry. Naivasha now produces over 25 varieties of cut flowers, mostly for export to Europe. All flowers are irrigated with water from the basin. The total amount of irrigated land in the catchment has grown from only 14.26 km^2 in 1976 to over 46 km^2 in 2000 (Alfarra, 2004). In addition to the growth of industrial agriculture, small-scale, rain-fed farms in the upper catchment continue to be a source of livelihood for many Naivasha residents (World Wildlife Fund, 2011). Like energy production, agriculture has the potential to improve economic conditions, but is not without risk. Use and runoff of agrochemicals presents a potential source of environmental contamination.

These economic activities have had a major impact on the community. The past 30 years has seen a 20-fold increase in population in the Naivasha catchment as people come in search of work. The catchment population is now approximately 400,000 (Harper, et al, 2011). Most of the arrivals live in unplanned settlements adjacent to the shores of the lake and on subsistence farms in the upper catchment. Lack of waste disposal and sewage treatment means that most waste is never treated. Urban centers, even those with modern sanitation and waste management systems, are typically sources of environmental contaminants. With waste management and sanitation being poor in Naivasha, the risk of direct contamination posed by urban centers may be particularly high.

1.4. Community identification of contaminants as an important issue

Participation is an important principle of ecosystem health research. For this reason, our project leaders, with the support of the International Development Research Center (IDRC) of Canada, held a meeting for Naivasha stakeholders in October 2008. Stakeholders were asked to identify the ecological determinants they felt were most important to their health and to guide our team's research objectives (Trick & Shivoga, 2008). My research project is motivated by objectives 4 and 6, concerning the sources, distribution and exposure risk caused by environmental pollutants. The remaining stakeholder objectives motivated the research projects of over 10 other students in the natural, social and health sciences.

Community identified objectives:

1. Identify all stakeholders that influence or are influenced by activities within the basin.
2. Conduct a systematic review of information, and reports and a synthesis of existing traditional knowledge and scientific data on water, environmental pollutants, and human health within the basin.
3. Conduct an assessment of the water balance of the basin (inputs, outputs and, storage).
4. Establish sources, amounts, and pathways for transfer of environmental pollutants (such as pesticides, nutrients, metals and microorganisms) in the hydrologic system and the food web.
5. Establish possible levels of exposure (vs. body burdens) to environmental pollutants among residents and workers.
6. Identify associations between environmental pollutants and possible adverse health effects.

7. Assess effects on the health and well-being of the residents and workers of the basin, particularly among vulnerable groups such as women and children.

8. Identify current management practices that affect water resources within the basin, to recommend best management practices, and showcase these to demonstrate effectiveness to stakeholders.

9. Identify relevant policies and associated rules and regulations that affect water resources, to share these with stakeholders, and together to recommend appropriate changes to these policies (and/or their implementation) to safeguard health.

1.5. Introduction to persistent organic pollutants and metals

Persistent organic pollutants (POPs) are man-made organic compounds, often halogenated. POPs are resistant to photolytic, biological and chemical degradation, meaning they persist in the environment (Ritter, et al., 1995). Because of their persistence and their organic, lipophilic nature, they are known to accumulate in organic matrices, such as sediment, soil, and the fatty tissue of organisms. For these reasons, many organochlorines made the Stockholm Convention's "dirty dozen" list for POPs of global concern. Problems with contamination by organochlorines are an especially significant challenge in developing countries, where efforts to control their use have begun only recently (USEPA, 2002).

Unlike POPs, metals are found naturally in every ecosystem on earth (Ochieng, et al., 2007; USEPA, 2007). Their concentrations, however, are increased by many anthropogenic activities. At low concentrations many metals, such as Fe, Se and Zn, are essential to biological functioning. At high concentrations, these same metals can harm human health through oxidative stress (Riordan, 1977). Some metals, such as mercury, have no known biological function and can be toxic even at very low concentrations.

The toxicity, sources and distribution of POPs and metals in the environment are discussed in more detail in sections 1.7-1.10.

1.6. Exposure routes

To understand exposure risk caused by POPs and metals, it is necessary to know how people are exposed. There are 3 possible exposure routes:

- *Ingestion:* This occurs though the consumption of contaminated food, water, or dust.
- *Inhalation:* This occurs when one breathes in hazardous vapours or atmospheric particulate matter that contains contaminants. The fate of inhaled particulate depends largely on its size. Larger particles are likely to be ingested rather than inhaled. Airborne particulate matter with a diameter smaller than 2.5 μm ($PM_{2.5}$) is of particular concern for inhalation because they are fine enough to make it to the gas exchange region of the lungs (Australian Department of Environment and Conservation, 2008).
- *Dermal contact:* This occurs when a substance comes into contact with and is absorbed through the skin.

The current research explores exposure through contaminant ingestion via the consumption of fish and contaminant inhalation via contaminants in dust. To study these exposure routes, there are several factors to consider (Figure 1.1), including: How much fish is consumed and how much dust is inhaled? What chemicals are found in those matrices? How toxic are those chemicals? What are the controls on contaminant exposure? The follow sections give more detail on each of these factors.

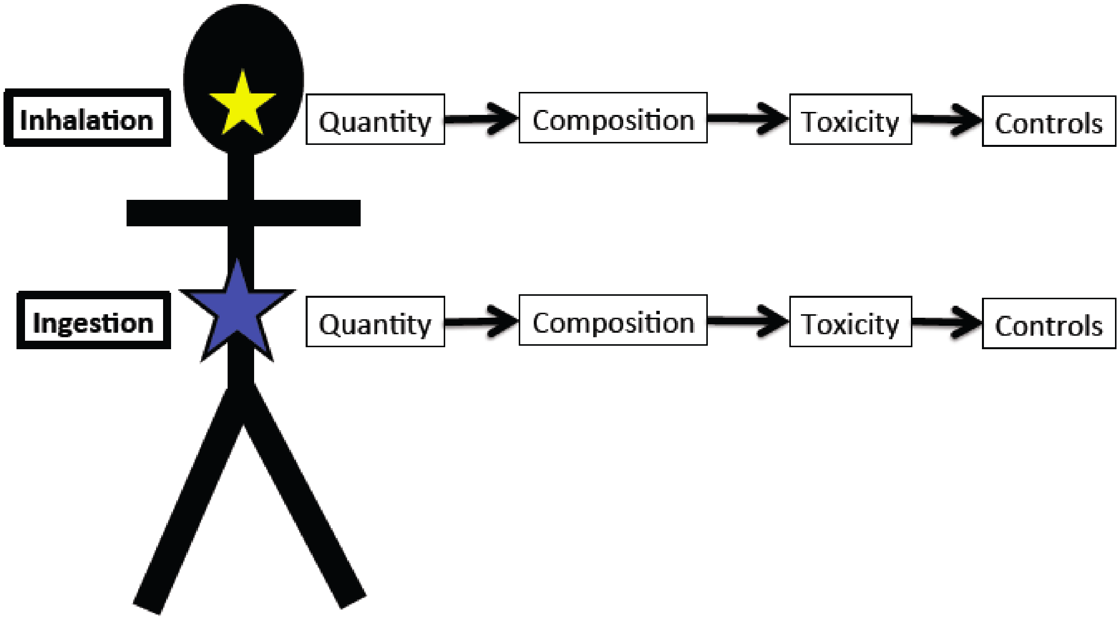

Figure 1.1: Factors to consider when researching contaminant exposure through inhalation and ingestion: Quantity of material inhaled or ingested, chemical composition of the material, toxicity of chemical contaminants, and controls on exposure risk.

1.7. Quantity

To date, no work has been done on the quantity of dust in the Naivasha catchment. Literature on dust within cities in developing countries suggests that a conservative estimation of dust density is 200 $\mu g/m^3$ (Panyacosit, 2000). Dust density is an important measure, because it approximates the amount of dust available for inhalation.

The quantity of fish consumed in Naivasha was estimated by a survey of 100 Naivasha residents in 2007-2008 (Keriko et al., 2010). Results suggest that 76% of Naivasha residents consume fish more than once per month, while 36% consume fish more than once per week. The majority of this fish is *Cyprinus carpio*, or common carp, as this species makes up over 90% of the fish caught in Lake Naivasha (Britton, et al., 2007).

1.8. Composition

Several previous studies have attempted to quantify metals (Table 1.1) (Campbell, et al. 2003; Njogu, et al., 2011; Mutia, et al., 2012) and persistent organic pollutants (Table 1.2) (Mugachia, et al., 1992; Gitahi, et al., 2002) in various matrices of the Naivasha catchment. While these studies provide some insight on exposure, there are some important gaps in knowledge. Firstly, at the turn of the century, *Cyprinus carpio*, a bottom feeding fish, was introduced to the lake. It now dominates fishery catches in both weight and number (Britton, et al., 2007). Despite this important ecological shift, no work has been done on the body burden of POPs in *C. carpio.*

There has also been no work done on contaminant concentrations in oligochaetes, the benthic worms that make up over 90% of Naivasha's benthic macro-invertebrate community and form an important part of the diet of *C. carpio* (Britton et al., 2007). To fully understand the movement of environmental contaminants within the lake, it is important to look at accumulation between sediment, benthic macro-invertebrates and fish.

The role of dust as an ecological determinant of health is also yet to be explored. This is an important oversight. Dust inhalation can cause respiratory illness, either directly through mechanical damage caused by fine dust particles or through the toxic effects of contaminants in dust. The air in Naivasha is heavily dust laden, and respiratory disorders are the second leading cause of hospital admission in Naivasha (Henley, pers. comm.). These facts suggest that dust may be a major ecological determinant of health in Naivasha and the contaminant composition of dust should be explored.

Table 1.1: Summary of results from all studies of metal body burdens in the biota of Lake Naivasha. All concentrations are given in ppm (wet weight). Dorsal muscle was the tissue used for all studies.

Source	**Mutia et al. 2012**	**Njogu et al. 2011**	**Campbell 2003**
Sampling date	2010	2008	2000
Organism	*Cyprinus carpio*	*Cyprinus carpio* & *Oreochromis leucostictus*	*Oreochromis leucostictus*
Cu	1.06 - 1.60	0.27 - 0.28	n. m.
Pb	<0.03 - 2.29	1.49 - 1.56	n. m.
Zn	n. m.	7.21 - 8.87	n. m.
Cd	5.21 - 58.11	1.30 - 3.60	n. m.
Ni	n. m.	1.34 - 1.36	n. m.
Cr	n. m.	n. m.	n. m.
As	n. m.	n. m.	n. m.
Hg †	n. m.	n. m.	0.0037 - 0.0066

n. m. = not measured

Table 1.2: Summary of results from all studies of persistent organic pollutant body burden in the biota of Lake Naivasha. All concentrations are given in ppb (wet weight). Dorsal muscle was the tissue used for all fish studies. For *Procambarus clarkii* (crayfish), muscle from the claw was used.

Source	**Gitahi et al. 2002**	**Mugachia et al. 1992**	**Gitahi et al. 2002**
Sampling date	1998	1989	1998
Organism	*Micropterus salmoides*	Various fish species	*Procambarus clarkii*
Total DDT	4.6 - 345.5	<0.5	n. m.
o,p'-DDT	1.5 - 186.6	n. m.	0.5 - 11.9
p,p'-DDT	2.6 - 100.7	<0.5	1.1 - 25
p,p'-DDE	0.5 - 58.2	<0.5	0.3 - 4.2
Lindane	3.7 - 1595.9	<0.5	0.2 - 10.4
Dieldrin	1.8 - 265.8	n. m.	0.4 - 11.1
Aldrin	0.8 - 70.7	n. m.	0.1 - 6.1
α-HCH	n. m.	<0.5	n. m.
β-Endosulfan	1.2	n. m.	0.3 - 7.5

n. m. = not measured

1.9 Toxicity

Some metals, such as iron, selenium and zinc, are essential to organismal physiology at low concentrations, as they serve as co-factors of metabolism (Riordan, 1977). These same metals, however, can be toxic if present at high concentrations. There are also metals, such as mercury, which have no known biological function and can be toxic, even at very low concentrations. The health risks associated with exposure to metals in the environment have been well documented. Adverse health effects include cancer, organ and bone damage, impaired fetal development, neurological and psychological damage and behavioral changes (WHO, 1992; Järup, et al., 1998; Järup, 2003).

Like metals, persistent organic pollutants have also been shown to cause a range of adverse health effects in humans. Effects include increased risk of cancer, diabetes, reproductive and developmental issues, neurologic problems and behavioural changes (USEPA, 2002; Henley, et al., 2011). POPs are also known to cause ecological damage, including eggshell thinning in birds, and reduced hatchability of fish eggs (Chang & Stockstad, 1975; Mugachia, et al., 1992).

What is perhaps less obvious is that there are also health risks posed by a community simply *perceiving* that their exposure to environmental contaminants is high (House, et al., 1979). A high level of concern about exposure can lead to increased levels of stress (Bend, et al., 2010). Higher stress levels have the potential to increase suicide rates and susceptibility to disease, and to decrease overall quality of life (Wieman, 2006; Bend, et al., 2010). For this reason, even where studies show levels of environmental contamination to be low, these results may still have a positive effect on community health.

One way to interpret the level of risk posed by actual contaminant exposure is to compare concentrations to guidelines set by a reputable organization, such as the World Health Organization (WHO) or the U.S. Environmental Protection Agency (USEPA). These organizations set concentration guidelines for contaminant exposure routes, including dust inhalation (Table 1.3), and ingestion of contaminated food products, such as fish (Table 1.4).

Table 1.3 Human health guidelines, set by the World Health Organization, for metal content in dust (WHO, 2005).

Metal	**Guideline (ng/m^3)**
Pb	500
Cd	5
Ni	0.38
Cr (IV)	40
As	1.5
Mn	150
Hg	1000

Guidelines adopted by the WHO in the update and revision of WHO air quality guidelines for Europe.
No guidelines are set for organochlorines or PCBs in dust.

Table 1.4: Human health guidelines, set by the U.S. Environmental Protection Agency, for safe concentrations of select metals and persistent organic pollutants in fish (USEPA, 2000). U.S. EPA guidelines were used because they recommend safe contaminant concentrations at several frequencies of fish consumption. This table shows the two extremes – the contaminant concentration that is safe for unlimited fish consumption, and the concentration above which no fish should be eaten.

Contaminant	**Unrestricted consumption (ppm wet weight*)**	**Do not eat (ppm wet weight*)**
Cd	0.088	5.6
As (inorganic)**	0.002	0.13
CH_3Hg	0.029	1.9
Selenium	1.5	94
Tributyltin	0.088	5.6
Chlordane**	0.0084	0.54
Total DDTs** (2,4'-DDD, 4,4'-DDD, 2,4'-DDE, 4,4'-DDE, 2,4'-DDT, 4,4'-DDT)	0.0086	0.55
Dieldrin**	0.00018	0.012
Endosulfan (I, II)	1.8	110
Endrin	0.088	5.6
Heptachlor Epoxide**	0.00032	0.021
Hexachlorobenzene**	0.0018	0.12
Lindane**	0.0023	0.14
Mirex	0.059	3.8
Total PCBs**	0.0015	0.094

*Guidelines are set for concentration in an 8 oz. “meal” of fish
All health guidelines are set for non-cancer health effects, unless otherwise noted
**Guidelines for cancerous health effects.

1.10 Controls

1.10.1 Sources

Metals exist at some concentration in all ecosystems. They are released from geological substrate by natural processes such as weathering of rocks and soil (Ochieng, et al., 2007; USEPA, 2007). Since the industrial revolution, however, human activities have begun to increase the concentrations of metals in the environment. Potential anthropogenic sources of metals include:

- Release through the combustion of carbon fuels that contain metals, such as coal or wood (Vouk & Piver, 1983)
- Application of agrochemicals containing metals either as active ingredients or undesired contaminants (Njogu, et al., 2011)
- Urban wastewater discharge (Ochieng, et al., 2007)
- Release of metals from natural reservoirs, such as geothermal steam during geothermal energy production (Simiyu & Tole, 2000)

Unlike metals, persistent organic pollutants do not have natural background levels. There are a large number of POPs, but all are either purposefully or accidently made by humans (USEPA, 2002). Because of their structure, typically including a stable, halogenated benzene ring, POPs are resistant to photolytic, biological and chemical degradation and persist for long periods of time (Ritter, et al., 1995).

One class of POPs of particular concern in agricultural areas is organochlorines pesticides. Kenya has now banned the use of many organochlorine pesticides, although some bans are as recent as 2011. Banned organochlorines include: chloradane, DDT (agricultural use only) and endrin since 1986; aldrin and dieldrin since 2004; endosulfan and lindane since 2011 (Kenyan Pest Control Products Board, 2012).

Another notorious class of POPs is the polychlorinated biphenyls (PCBs). PCBs are highly persistent in the environment and their environmental concentration has increased because of human use. The major sources of PBCs are urban centers, because of their use in (Baird & Cann, 2005):

- Coolant fluids of power transformers and capacitors
- Plasticizers
- Heat transfer fluids in machinery
- Waterproofing agents

The use of PCBs in manufacturing has been banned in Kenya since 1985, but equipment containing PCBs is still in use (Saoke, 2005).

1.10.2 Environmental partitioning

Many studies focus on the role of human land use activities in controlling environmental contamination. Often, there is a very clear correlation between the proximity of a site to a pollution point source and contaminant concentrations (Ward, et al., 1986; Kelly, et al., 2010). While it is often true that contaminants are found in higher concentration near their source, proximity to a source is not the only driver of distribution. Lake or atmospheric mixing and environmental conditions control the movement of contaminants away from their source.

One form of contaminant movement occurs through the movement of contaminant-containing particles. Both persistent organic pollutants and metals are often found bound to the surface of particles, including sediment and dust (Harner, et al., 2004; Laing, et al., 2007). Metals bind to the surface of particles with high organic matter or mineral content, such as silt and clay, because the negative charge associated with these particles attracts metal cations. Metals can also exist as free ions or in complex with a number of inorganic ligands, including insoluble precipitates that settle out of solution (USEPA, 2007). The state of metals is influenced by lake or atmospheric mixing, pH, redox potential, organic matter content, clay content, and salinity (Laing, et al., 2007).

Like metals, persistent organic pollutants tend to adsorb to the surface of sediment and dust, particularly particles rich in organic matter. They do so because they are highly hydrophobic, binding easily to the lipophilic, organic component of particulate matter (Karickoff, et al., 1979). The degree of hydrophobicity of organic compounds can be described by a compound's partitioning co-efficient between octanol (an organic liquid) and water (K_{ow}), where a lower K_{ow} indicates higher hydrophobicity (K_{ow} is often seen expressed as a negative log function. In this case, a larger value indicates greater hydrophobicity):

$$K_{ow} = \text{concentration in octanol} / \text{concentration in water}$$

Most persistent organic pollutants have a log K_{ow} value greater than 3 (Table 1.5), indicating that dissolution in octanol will be at least 3 orders of magnitude greater than dissolution in water. In the environment, rather than preferentially dissolving in octanol, POPs will sorb to particles, particularly particles with a high content of organic carbon, such as silt (Karickhoff, et al., 1979).

Table 1.5: The chemical formula, log K_{ow}, and uses of common persistent organic pollutants.

Chemical	**Formula**	**Log K_{ow}[a]**	**Examples of use**
DDT	$C_{14}H_9Cl_5$	6.79[b]	Agriculture, disease vectors
DDD	$C_{14}H_{10}Cl_4$	5.87[b]	Agriculture
DDE	$C_{14}H_8Cl_4$	6.0[b]	
Aldrin	$C_{12}H_8Cl_6$	6.75	Corn, termites
Chlordane	$C_{10}H_6Cl_8$	6.22	Corn, citrus, termites
Dieldrin	$C_{12}H_8Cl_6O$	5.45	Agriculture, disease vectors
Endrin	$C_{12}H_8Cl_6O$	5.45	Agriculture, cotton
Endosulfan	$C_9H_6Cl_6O_3S$	3.5	Agriculture
Heptachlor	$C_{10}H_5Cl_7$	5.86	Agriculture
Hexachlorocyclohexane	$C_6H_6Cl_6$	4.26	Ornamentals, soil pests, head lice
Mirex	$C_{10}Cl_{12}$	7.01	Fire ants, flame retardant
PCBs[c]		4.5-8.5 for all 209 congeners	Fire prevention, insulation, transformers, capacitors, electromagnets, circuit breakers, voltage regulators, switches, hydraulic fluid

[a] Log K_{ow} estimated in EPA EPI Suite KOWWIN
[b] Log K_{ow} for p,p' isomers
[c] WHO/IPCS (1993) for selected Arochlors
Table modified from Beyer and Meador 2011

1.10.3 Bioaccumulation

Metals and POPs entering a lake accumulate in the sediment, where they can become available for consumption and accumulation in aquatic organisms, such as benthic macro-invertebrates and bottom feeding fish. Bioaccumulation, or the ratio of a chemical in an organism relative to the water column, is one way to measure containment accumulation (Dallinger, et al., 1987; Beckvar, 2011). For bottom-dwelling organisms that consume organic matter in sediment, it is more relevant to consider the chemical concentrations in the sediment than those in the water (Dallinger, et al., 1987). In this case, we can calculate a relative accumulation factor (RAF), where the concentration of a chemical in an organism is compared to the concentration in the sediment:

$$\text{RAF} = [\text{Chemical X}] \text{ in tissue} \div [\text{Chemical X}] \text{ in sediment}$$

Accumulation can also occur between trophic levels. This process is known as biomagnification and is quantified by a biomagnification factor (BMF), where:

$$\text{BMF} = [\text{Chemical X}] \text{ in predator} \div [\text{Chemical X}] \text{ in prey}$$

The body burden of metals in aquatic organisms can be highly variable, both between species for the same metal and between metals for the same species (Dallinger, et al., 1987; Rainbow & Luoma, 2011). Metal accumulation is dependent on a number of organismal and environmental factors, including rates of uptake and excretion, and accumulation processes (Rainbow & Luoma, 2011). The organismal stoichiometry of nutrients and metals also depends on whether they are macronutrients, which are highly regulated by organisms, micronutrients, which are weakly regulated by organisms, or non-essential metals, which are not regulated and can be toxic, even at very low concentrations (Karimi & Folt, 2006). The most likely metals to exhibit bioaccumulation are organometals, such as methylmercury.

Because of their hydrophobicity, POPs are known to bioaccumulate and biomagnify. They enter the body with dietary lipids, accumulate in fatty tissue and biomagnify up the food chain. Body burdens increase with the age, size and trophic status of the organism (Borgå, et al., 2004).

Contaminant concentration in mobile organisms, such as fish, presents another mechanism of contaminant movement away from a source. In previous research of *C. carpio* movement, results on site fidelity, or the tendency of fish to stay in the same location, have been inconsistent (Osborne, et al., 2009). The home range of carp in Lake Naivasha is not known. It is therefore not known whether the body burden of accumulated contaminants in fish caught at a given site is representative of local contaminant conditions.

1.11 Hypotheses and Objectives

Hypothesis 1

My first hypothesis is that the concentrations persistent organic pollutants and metals in dust and in *C. carpio* dorsal muscle is high enough to pose a risk to human health in the Lake Naivasha catchment. To test this hypothesis, I set two objectives:

> Objective 1: Determine the concentration of POPs and metals in the dorsal muscle of *Cyprinus carpio* from Lake Naivasha. Compare these data to human health guidelines set by the EPA.
>
> Objective 2: Determine the concentration of metals in airborne dust at various sites in the Lake Naivasha catchment. Compare these data to human health guidelines set by the WHO.

Hypothesis 2

My second hypothesis is that the concentrations of POPs and metals are not evenly distributed in the catchment. To test this hypothesis, I set the following objectives:

Objective 3: Compare the concentration of POPs and metals in dust from various sites to determine if spatial variability exists.

Objective 4: Compare the concentrations of POPs and metals in fish from various sites, to determine if spatial variability exists.

1.12 Thesis Organization

This thesis has been prepared in monograph format. The introduction (Chapter 1) provides a summary of the ecosystem health paradigm, which was the foundation of my research. It also provides background information on persistent organic pollutants and metals, their relevance in the Naivasha catchment and the hypotheses of my study.

Chapter 2 discusses the methods used in my research project. In Chapter 3, I share my results, followed by a discussion of the major findings in Chapter 4. I have taken Chapter 5 to draw conclusions and make recommendations for future research.

CHAPTER 2: Methods

2.1. Physical site description

Lake Naivasha is the only freshwater lake in Kenya's Great Rift Valley, making it a highly valuable resource. It is located just south of the equator (0°45'S, 36°20'E) and about 80 km north west of Nairobi, Kenya's capital city (Harper, et al., 2011).

Rainfall in the Lake Naivasha catchment is highly temporally variable (Figure 2.1). The rain comes primarily during two annual rainy seasons, with a major peak in April-May and a minor peak in October-November (Abiya, 1996). Rainfall is also highly spatially variable. The shores of Lake Naivasha are approximately 1890 m.a.s.l. (Becht & Harper, 2002) and considered semi-arid, receiving only about 600 mm of annual precipitation. Areas of the upper catchment, however, are as high as 4000 m.a.s.l (Everard & Harper, 2002) and receive over 1300 mm of precipitation. This is enough rainfall to make the upper catchment suitable for rain fed agriculture (Becht, et al., 2005).

Monthly temperatures show minimal variability, with monthly highs hovering around 25^{o}C (Figure 2.1). Although variability is minimal, the lowest annual temperatures fall in May-August, corresponding to the driest season of the year. Wind patterns vary seasonally, with winds coming predominantly from the South during May-October and predominantly from the North during November-April (Survey of Kenya, 1991).

Naivasha is a relatively small lake, with an average area of only about 150 km^2 (Abiya, 1996; Otiang'a-Owiti & Oswe, 2007). The lake is fed by a catchment of about 3376 km^2 and almost all of the water entering the lake does so via two rivers on the north shore (Ase, et al., 1986). The Malewa River is the largest river, providing approximately 80% of Lake Naivasha's inflow. The drainage catchment of the Malewa covers about 1730 km^2 (Gaudet & Muthiri, 1981; Åse, et al., 1986; Lukman, 2003). The Gilgil River drains an area of about 500 km^2

and contributes about 20% of the lake's inflow (Åse, et al., 1986; Hubble & Harper, 2001; Becht, et al., 2005). Both catchments contain a large amount of small-scale agriculture.

The lake has no surface water outflows. Its water remains fresh because of groundwater outflow to the south and north of the lake (Clarke, et al., 1990; Ojiambo, et al., 2001).

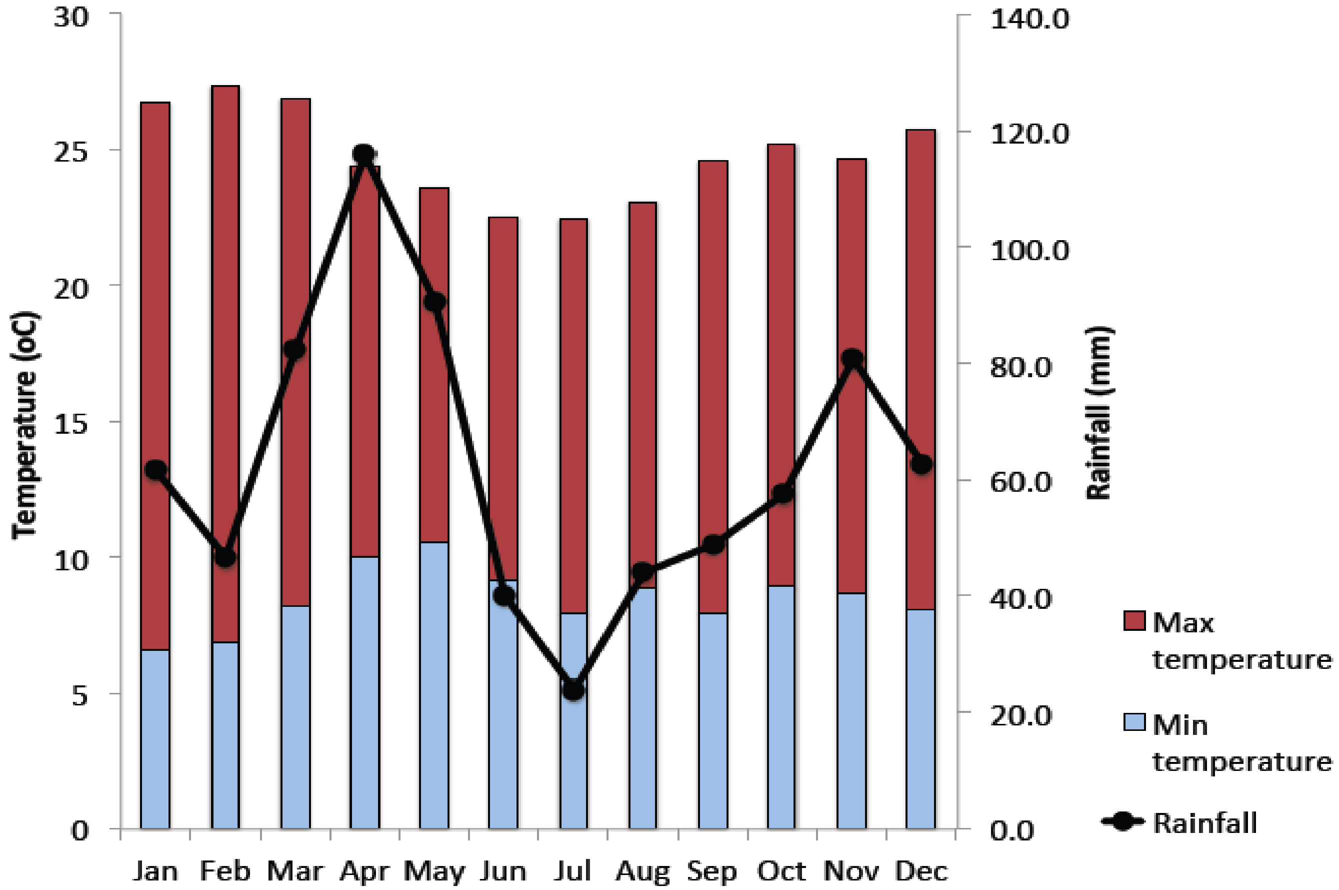

Figure 2.1: Average monthly high and low temperatures (January 2002-February 2012) and average monthly precipitation (January 1995-February 2012) in the Lake Naivasha catchment (raw data provided by the Lake Naivasha Water Resource Users Association).

2.2. Description of dust sites

Dust collection sites represented 4 different types of land use, with the goal of comparing the amount of dust and the composition of the dust between land uses. The 4 land uses were: upper catchment, industrial agriculture, urban, and lakeshore. Within each land use, site selection was made on the basis of practical considerations, such as ease of access, landowner's willingness to participate, and where on their property landowners would let us set up a collector. To respect landowner privacy, no names are given for industrial agriculture or lakeshore sites. These sites are identified only according to an assigned code.

For the geographic locations of dust sites, refer to Figure 2.2. For photos from dust sites, see Appendix 1.

2.2.1 Upper catchment sites

Salmon farm (UC1)

The salmon farm was the furthest site in the upper catchment, located over 25 km from the lake. Located in the northeast corner of the catchment, the dust collector was surrounded almost entirely by natural land, with the exception of a small number of cattle permitted to graze on adjacent land. The digging of a hole was also underway, to eventually be made into fishpond. All construction was done using non-power tools.

Small-scale agriculture (UC2)

This site was approximately 15 km from the lake and was typical of the landscape in most of the upper catchment: small-scale, rain-fed agriculture. This land cover was dominant for 100s of meters in all directions from the collector.

Maasai community (UC3)

Although this was a small settlement for nomadic herders, it was categorized as being an upper catchment site because it is located several kilometers within

Hell's Gate National Park, nearly 9 km south of the lake. The collector was set up in the center of a ring of mud homes, and the immediate surrounding land cover was bare soil. Outside the ring of huts, was several hundred meters of grassland in all directions, which eventually extended into the mountains.

2.2.2 Industrial agriculture sites

Industrial agriculture site 1 (A1)

The dust collector on this site was located about 200 m from the nearest greenhouse. The space it occupied boarded both a large conglomeration of greenhouses, and a wide expanse of natural area.

Industrial agriculture site 2 (A2)

The dust collector at this site was in the middle of a large conglomeration of greenhouses. It was about 1 m from a greenhouse to its east and about 20 m from a greenhouse to its west.

Industrial agriculture site 3 (A3)

Site A3 is the third and final site used for industrial agriculture. It is a standalone farm, located on the northwest shore of the lake. The dust collector was set up between 2 large greenhouses, and within 20 m of a solar panel farm.

2.2.3 Urban sites

Naivasha Town (UR1)

Naivasha Town is the biggest formal settlement in the Naivasha catchment. The dust collector here was situated on the northern edge of the town. Most of the surrounding land use was low-density residential. The subdivision was bound on either side by a major highway.

Karagita (UR2)

Karagita is the largest informal settlement in Naivasha. It is located east of the lake, adjacent to a plot of natural land owned by the Ministry of Fisheries. For political reasons, the collector for Karagita was placed approximately 200 m west of the settlement, on the Ministry of Fisheries property.

Kamere (UR3)

Kamere, like Karagita, is an informal settlement. It is located near the south shore of the lake. The dust collector was set up on the outskirts of the settlement, several kilometers from the lake. It was in the middle of a common courtyard, shared by many households. On two sides, the site was surrounded by natural areas and on the other two sides, it was surrounded by the settlement of Kamere.

2.2.4 Lakeshore sites

Lakeshore site 1 (LS1)

This site is a conservation area run by the Kenya Wildlife Service. While the property itself is protected, it is located only a few kilometers south of Naivasha Town.

Lakeshore site 2 (LS2)

Site LS2 is a tourist resort on the south shore of the lake and is sandwiched between large greenhouse operations. To the north of our collector was open water, to the south was green space and 200-300 m to the southeast and the southwest were large expanses of greenhouses.

Lakeshore site 3 (LS3)

Site LS3 is another tourist resort, located on the south shore of the lake, only a couple of kilometers from the Kenya Electricity Generating Company. The area immediately surrounding the dust collector was natural, with the collector being sandwiched between open water to the north and hundreds of meters of grassland.

Lakeshore site 4 (LS4)

Site LS4 was the most natural lakeshore site. The collector was set up at the edge of the water, with only open water to the east and several hundred meters of acacia forest to the west and acacia forest to the south.

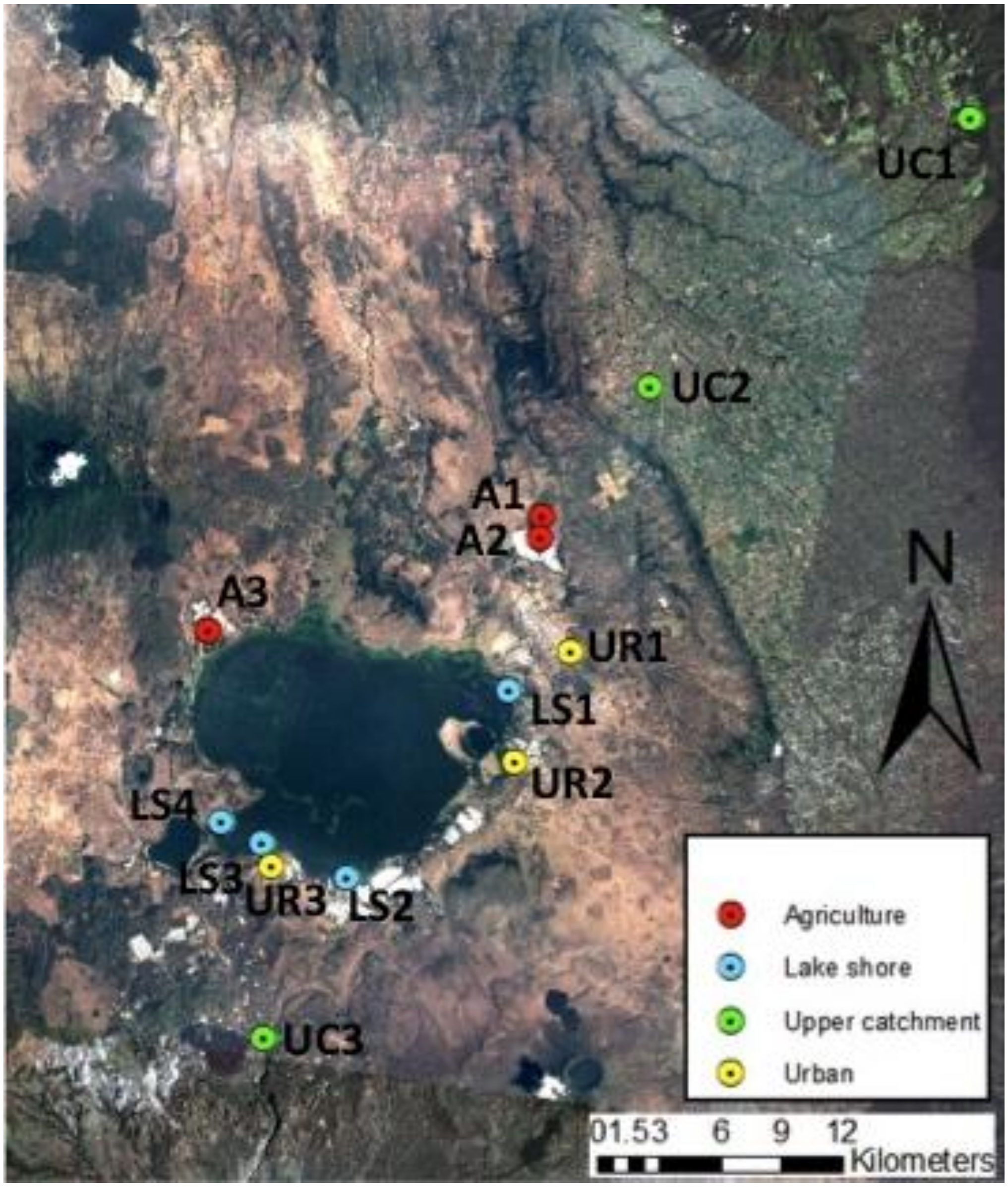

Figure 2.2: Map of the Lake Naivasha catchment, showing sites used for dust collection.

2.3 Sample collection

2.3.1 Equipment cleaning

All equipment used for sample collection was washed in the same way prior to use, unless otherwise noted. Equipment was thoroughly washed with soap and water in the lab and rinsed 3 times with tap water and 3 times with distilled water. All pieces that were used for sediment collection were also rinsed 3 times with lake water between sampling sites.

2.3.2 Dust

The dust collection protocol was a slightly modified version of a protocol endorsed by the U.S. Geological Survey (Reheis & Kihl, 1995; USGS, 2010). The inside of an angel food cake pan was fitted with a plastic screen, which hung 2 inches above the bottom of the pan. The screen supported a layer of glass marbles, which was permeable to dust and allowed dust to fall to the bottom of the pan where it would be protected from the wind (Figure 2.3). Wires, covered with double sided tape were suspended above the top of the collector to prevent birds or wildlife from nesting. The entire apparatus then sat on top of a pole, approximately 2 m above ground level.

Collectors were set up at 13 sites, representing 4 different land uses: upper catchment, industrial agriculture, urban and lakeshore (Figure 2.2). Equipment was left in the field for approximately 3 weeks (between June and August, 2011) before dust was collected. Two collects were attempted at each site. For collection, the pan was carefully removed from the pole and the marbles, the screen and the inside of the pan were washed thoroughly with distilled water. The dust/distilled water mixture was collected in a clean, plastic sampling container and returned to the lab. Great care was taken to ensure no outside dust contaminated the sample during the collection process.

Upon return to the lab, the dust/distilled water mixture was filtered through pre-weighed, GF/F glass fiber filters (pore size: 07 μm), after filters had been rinsed with 300 ml of distilled water. The filtrate was discarded and the filter containing the dust was air-dried and weighed before being stored in a sterile polypropylene conical tube to await analysis.

2.3.3 Surface soil

At each dust collection site, a composite grab sample of surface soil was also taken. Using a clean teaspoon, approximately 5 g of surface soil were collected from 12 points within a 3 m radius of the collector. All soil was added to an unused paper bag and mixed thoroughly. A subsample was then transferred to a 50 ml polypropylene conical tube for storage.

Figure 2.3: Apparatus used for dust collection. On the right is an overhead photo of the dust collector. On the left is a profile shot, showing relative height from the ground.

2.3.4 Surface sediment

Sediment was collected at 22 sites on the lake (Figure 2.4). Sites were at 1 m lake depth intervals on 5 different transects. All transects started at Hippo Point, the deepest point on the main lake, and ran in the cardinal (north, south and east) and inter-cardinal (north east and south east) directions. For some of the transects, it was not possible to obtain near shore samples because of the presence of thick vegetation and dangerous wildlife, such as hippos and buffalo.

When collecting surface sediment, two techniques were employed. The first used a 5 cm diameter gravity corer to collect the top 10 cm of sediment (USEPA, 2001). The corer was deployed slowly, so as not to disturb the sediment density or layering upon impact. Cores were extruded on the boat immediately following collection. This was achieved by plugging the open bottom of the corer's PVC tubing with a homemade extruder prior to removing the equipment from the water. Once on the boat, the PVC tubing containing the core was removed and the top 10 cm of surface sediment were extruded. To do this, an extrusion pallet was used to collect the extruded sediment and funnel it into a clean plastic sample container. Sample containers were then sealed and stored in the shade until returned to the lab. Independent triplicates were collected for each site.

Samples taken with the gravity corer were eventually used to determine bulk density and organic matter content.

The second method used for surface sediment collection employed an Ekman grab sampler (USEPA, 2001). At each site, independent triplicates of the top 6 inches of surface sediment were collected using the Ekman. In sites where sediment was especially soft, an entire replicate may have been collected in a single Ekman deployment, but often 2 or more grabs were required to obtain the desired volume. In all cases, the sediment in a given replicate was shaken thoroughly before downstream use to ensure sediment from all contributing grabs was homogeneously mixed.

Immediately upon return to the lab, sediment collected using the Ekman was used to determine pore water pH, conductivity and redox potential. Ekman sediment was also used to determine particle size distribution and concentration of persistent organic pollutants and metals.

2.3.5 Benthic macro-invertebrate collection and sorting

The method for benthic macro-invertebrate collection and sorting was a modified version of methods proposed by Environment Canada and the U.S. Environmental Protection Agency (USEPA, 2002; Environment Canada, 2010).

The collection sites for benthic macro-invertebrates were the same as those used for sediment collection (Figure 2.4). Sediment was collected using an Ekman grab sampler. The Ekman was deployed as many times as was necessary to collect 5 g of macro-invertebrate tissue. Immediately following collection, sediments were sieved using a 500-μm mesh filter bag and the coarse material retained in the net was stored in plastic bags, in the shade, until return to the lab. Once in the lab, the sieved samples were sorted to the family level, (with the exception of oligochaetes, which were sorted to the level of subclass) (Hilsenhoff, 1988; Bailey, et al., 2001). Tissue was stored at -20^{o}C until analysis.

A subset the invertebrates from each taxonomic group from every site was preserved in 70% ethanol and returned to Canada for identification confirmation. Identification was achieved using a dichotomous key offered online by the University of New Brunswick (Martens, et al., 2011) and the advice of John Schwindt, an Aquatic Biologist from Canada’s Upper Thames River Conservation Authority. Accuracy of identifications was confirmed by comparison with previous literature on Lake Naivasha’s benthic macro-invertebrate community (Harper, et al., 1984; Clark, et al., 1989; Britton, et al., 2007).

2.3.6 Fish

Fish were harvested from 6 sites, each off shore from a land use of interest (Figure 2.4). The sites included two near industrial agriculture, two near natural areas, one near the Naivasha Town sewage outflow and one at the mouth of the Malewa River.

Fish were caught using gill nets, ranging in size from 2” to 7”. Nets were left in the water for 24 hours, after which fish were collected. Two collections were done to obtain enough fish from each site. Upon return to the lab, 10 g of dorsal muscle were collected, stored in a clean 50 ml polypropylene conical tube, and frozen at -20°C until analysis. Other parameters measured include fish weight, fork length, and notes on any obvious damage or health problems. All equipment, including hands, were washed with soap and water, and rinsed with distilled water between fish.

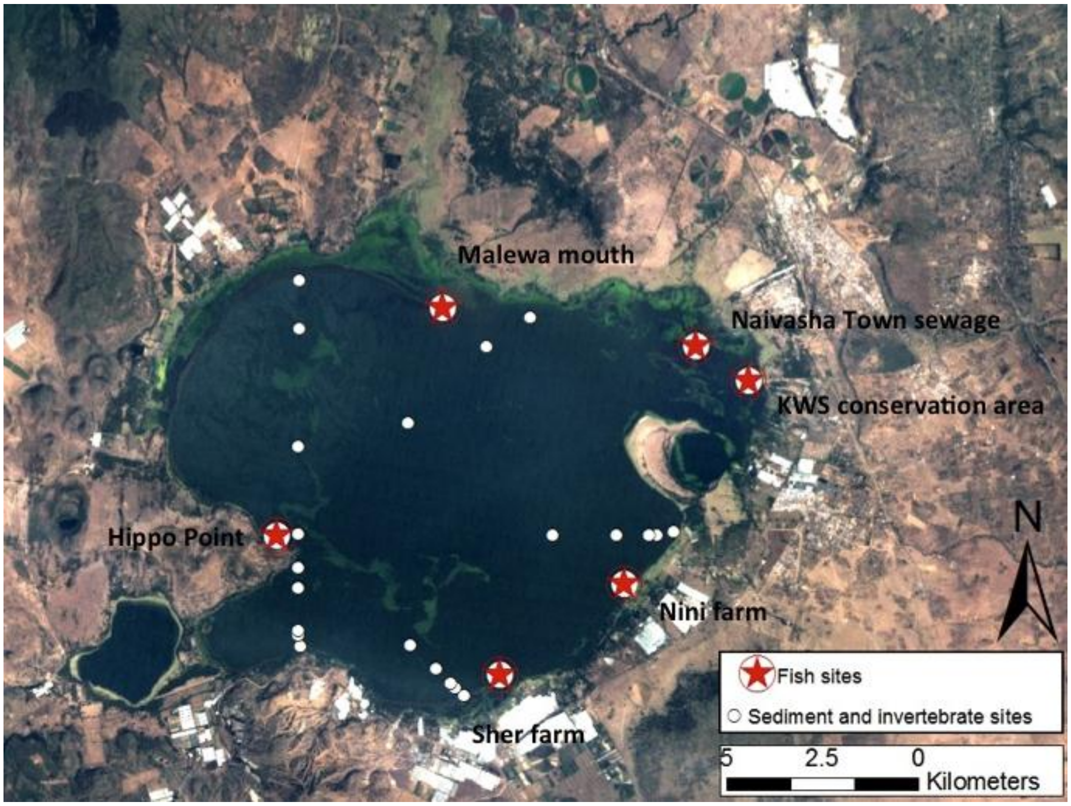

Figure 2.4: Sample sites for sediment, invertebrate and fish collection. Fish collection sites are labeled according the their adjacent land use.

2.4 Sample analysis

2.4.1 Pore water chemistry

Sediment from the Ekman samples was used to determine pore water chemistry. Parameters measured were pH, conductivity, and redox potential (hereafter called ORP).

Upon return to the lab, a modified version of an EPA method for sediment pH and conductivity determination was used (USEPA, 1997). A scoop of sediment was left to air dry for 30 minutes. After drying, sediment was combined at a 1:1 (mass:volume) ratio with distilled water and mixed by inversion for 5 minutes. The samples were then left to settle for 1 hour, after which the supernatant was measured for pH, conductivity, and redox potential.

Prior to use, the HANNA HI 991002 pH/ORP probe with HI 1297D electrode was calibrated for pH using pH=4.01 and pH=7.01 calibration solutions. The probe was factory calibrated for OPR, so no ORP calibration was conducted. The Oakton EC Testr11+ Multi-Range conductivity probe was calibrated using 0.1 M, 0.01 M and 0.001 M KCl solutions.

2.4.2 Bulk density

Bulk density is a measure of the dry mass per unit volume of sediment. In our case, the bulk density was determined using the top 10 cm of surface sediment (see the gravity coring method described above). Upon return to the lab, samples were stored at -20^{o}C until analysis. Prior to analysis, samples were thawed at room temperature for approximately 24 hours.

Analysis began by rinsing an entire sample into a clean melamine bowl. Samples were then dried in an oven at 105^{o}C for 24 hours, or until a constant mass was reached. Dry weight of sediment was then converted to bulk density by dividing the dry mass by the volume of the cylinder from which the sediment was taken (core volume = pi*r^2*h).

2.4.3 Organic matter content

Sediments for this procedure were collected according to the Ekman grab sampling method described above. Upon return to the lab, bottles were stored at -20^{o}C until analyzed. Prior to analysis, samples were thawed at room temperature for approximately 24 hours and mixed well by shaking.

During analysis, samples were oven dried at 105^{o}C for 24 hours. Following drying, samples were ground using a clean, dry mortar and pestle. After drying, 5 g of sample were transferred to a ceramic crucible and heated at 550^{o}C for 4 hours, to volatilize organic matter (Dean, 1974). After combustion, the mass of sediment lost was determined. The mass lost-on-ignition divided by the initial dry mass of sediment gives the fraction of organic matter.

2.4.4 Particle size distribution

A subsample of each of the Ekman triplicates from a given site was mixed to give a single, composite sample. Particle size distribution was determined by sieving sediments through a nested sieve set (sieve sizes: 10, 6.3, 1, 0.5, 0.1 and 0.0063 cm). The size fraction of importance to this study was the fraction < 0.0063 cm (< 63 μm). This fraction represents silt and clay, which have been shown to be correlated with higher contaminant concentration and sediment transport (Förstner & Salomons, 1980; Mudroch & Azcue, 1995).

After separation, the contents of each sieve was rinsed from the sieve and dried at 105°C for 16 hours. The relative mass of each size fraction gave the particle size distribution (in % mass).

2.4.5 Quantification of persistent organic pollutants

Sediment and tissue samples were analyzed for organochlorines pesticides and polychlorinated biphenyls at the Biotron Research Center at Western University. Analysis followed the EPA protocol 8081 and 8082, respectively (Durr, 2010, 2011b).

First, 10-20 g (wet weight) of each sample was measured out. To achieve the required weight, samples had to be pooled in the following way:

- Sediment: All samples collected on a given transect were pooled. The exception was Hippo Point, whose sediment was combined with sediment from the two nearest sites (North 1882A and North 1882B).
- Oligochaetes: All samples collected on a given transect were pooled. The invertebrates collected at Hippo Point were pooled with invertebrates from the North transect.

- Fish: No pooling of fish tissue was required.

Prior to extraction of fish samples, each dorsal muscle sample was cut into small pieces using a clean scalpel, to increase the surface area exposed to solvent during the extraction process. No mechanical alterations were required for sediment or oligochaete samples.

Three sequential hexane extractions were completed on each sample. Following each extraction, the hexane was passed through a layer of sodium sulfate to remove any water. The hexane from all 3 extractions was combined and evaporated to 1 ml. Once the desired volume was achieved, organochlorines and PCBs were quantified by Gas Chromatography-Electron Capture Detection (HP 7890 GC), with a HP-5 50 m x 0.25 mm separation column and nitrogen carrier gas. Compounds were identified by their elution time off the column. Quantities were determined by comparing peak height to the height the same peak at known concentrations.

Several quality control measures were taken. A blank sample and a duplicate were run daily. Acceptable blanks were below detection limits and acceptable duplicates within 20% of one another. A surrogate sample was added to each sample and required recoveries were 100 ± 30%. Method detection limits (MDL) are based on the variance among 10 sample spikes. Because variance is a measure of precision, not accuracy, maximum reporting limits (MRLs) for this study are 3 times the MDL to compensate for any accuracy uncertainty.

2.4.6 Quantification of mercury in fish

Mercury analysis was conducted at the Biotron Research Centre at Western University, using Direct Mercury Analysis (Durr, 2011a). First, approximately 270 mg of fish dorsal muscle was added to a weigh boat. Once in the weight boat, samples were dried at 200^{o}C for 120 seconds, then thermally decomposed at 650^{o}C for 150 seconds. Mercury vapours were then captured on a gold amalgonator and content was quantified using atomic absorption spectrophotometry at 254 nm.

For every 10 samples analyzed, a blank and a spike were also analyzed. Blanks were accepted if their concentration was < 10% of the lowest sample concentration. Spikes were accepted the recovered concentration was within 70% of the known concentration.

2.4.7 Quantification of other metals, including mercury in non-fish matrices

Metal analysis was conducted at the Biotron Research Center at Western University, on all of the same matrices as was done for POPs (sediment, invertebrate tissue and carp dorsal muscle). Analysis followed the EPA method 200.7 (Durr, 2010).

Metal concentrations in dust were also quantified, but analysis was completed at another laboratory. Unfortunately, after analyzing sediment samples at the Biotron, which had previously been analyzed at the other laboratory, it was discovered that the two labs produced dissimilar results. I had more trust in data produced at the Biotron, so I adjusted the dust data to “Biotron equivalent data” using intra-laboratory correction factors. Data were only converted if a strong linear relationship existed between sediment metal data from the 2 labs, as was the case for Ni, Pb, and Cr (Figure A3.1).

At the Biotron, samples were digested by aqua-regia digestion at 95^{o}C for 2 hours, using a 3:1 mixture of $HCl:HNO_3$. No organics removal was required for any of the samples. Following digestion, samples were analyzed for metals using a Perkin Elmer Optima 3300 Duel View ICP-OES with SeeSpray Concentric Nebulizer, a Cyclonic Spray Chamber, a peristaltic pump and a CETAC AXS-500 auto-sampler. The flame was an argon plasma flame and the carrier gas was nitrogen. Metals were identified according to the characteristic wavelength of light emitted upon ion excitation. Metals were quantified by comparison of light emission intensity with that of a known concentration of the same metal.

For every 10 samples analyzed, a blank and a spike were also analyzed.

Blanks were required to be below detection limits and the difference between duplicates was required to be < 10% of their average concentration.

2.5 Statistical analyses

As a result of sample pooling and the loss of some samples, triplicate data did not exist for all samples. In this case, trends were analyzed without statistics. The only samples for which statistics could be used were the fish body burdens. In this case, after testing for normality, a one-way ANOVA was used, followed by a Tukey’s test where necessary. If the assumption of normality was not met, the Kruskall-Wallis one-way ANOVA and the Tukey’s test were employed. All analyses were done using SigmaPlot (Systat Software Inc., 2008) at the 0.05 confidence level.

CHAPTER 3: Results

Unless otherwise noted, all concentration results for biological samples (fish and invertebrates) are given as % wet weight. Concentrations for all other samples (dust, soil and sediment) are given as % dry weight. The exception is the calculation of relative accumulation factors from sediment to fish, in which case the concentration in both matrices is based on dry weight.

3.1. Distribution of metals in airborne dust and associated health risks

No significant differences existed between land use types for any of the following variables:

- dust deposition, g/day (F=0.916, p=0.471);
- dust concentrations (ppm) of Ni (F=1.562, p=0.268), Cr (F=0.688, p=0.582), or Pb (F=0.730, p=0.560);
- deposition (g/day) of Ni (H=2.484, p=0.478), Cr (F=0.395, p=0.760), or Pb (F=1.564, p=0.265)

For this reason, trends in these variables are discussed on a site-by-site basis.

The rate of dust deposition (g/day) was variable between sites (Figure 3.1). Sites with particularly high levels of dust deposition included the settlements of Kamere (0.10 g/day), Karagita (0.03 g/day) and the Maasai community (0.04 g/day) (Table A2.1). Site LS1 and a small-scale farm in the upper catchment also had notably elevated rates of dust accumulation, at 0.07 and 0.03 g/day, respectively.

In terms of contaminant concentrations in dust, results suggest that at least 3 metals are present in detectable amounts: lead (Pb), chromium (Cr) and nickel (Ni) (Figure 3.2). Cr concentrations are the highest of the 3 metals, ranging between 5.3 and 273 ppm (Table A2.2). Cr concentrations are also the most spatially variable (Figure 3.2).

The highest Cr concentrations were found at site A3 and at a salmon farm located in the eastern most part of the catchment (Figure 3.3). These sites have Cr concentrations of 273 and 118 ppm, respectively (Table A2.2). Naivasha Town, site LS4 and LS3 also have relatively high Cr concentrations compared to other sites in the catchment.

The concentration of Ni in dust is less spatially variable than that of Cr. Like Cr, however, the concentration of Ni appears to be relatively high at site A3 (27 ppm). Other sites showing high concentrations of Ni include site A1 and a salmon farm in the remote upper catchment (Figure 3.3). These sites have Ni concentrations of 30 and 21 ppm, respectively (Table A2.2).

Pb appears to be the most spatially homogeneous of the metals. No obvious peaks in concentration exist, but concentrations are relatively low in the Maasai community, site LS1, the small-scale farm and the settlement of Kamere, with concentrations of 13, 11, 14 and 12 ppm, respectively (Table A2.2).

Because the amount of dust in the air influences rate of exposure, it was also necessary to have a proxy for overall metal exposure. This was achieved by multiplying the metal concentration in dust by the daily dust deposition rate, giving the deposition of metal per day.

Due to the high rate of dust accumulation at site LS1, deposition of Cr, Pb and Ni were each relatively high here (Figure 3.4), with metals accumulating at a rate of 1.6, 0.7 and 0.6 μg/day, respectively (Table A2.1). Cr accumulation was also high at site A3, at 1.8 μg/day, because of the high Cr concentration at that site. Pb exposure had peaks in the settlements of Kamere (1.2 μg/day), Karagita (0.6 μg/day) and the Maasai community (0.5 μg/day).

In order to compare metal concentrations in dust with guidelines set for human health by the WHO (WHO, 2005), a literature-based assumption of dust density was used. A review study that looked at total airborne particulate in cities in developing countries (Brazil, China, Mexico and India) showed that total airborne particulate varied between 200 and 1200 $\mu g/m^3$ (Panyacosit, 2000).

Based on this, a conservative density of 200 μg/m^3 was used to determine the possible risk posed by metals in dust (Figure 3.5).

Results suggest that Pb in dust not a concern for health anywhere in the catchment. Ni appears to exceed WHO guidelines at all sites in the catchment except one. Finally, total Cr exceeds the WHO guideline for Cr (VI) only at site A3. Because Cr (VI) makes up only a proportion of total Cr, this is an overestimate of risk.

To determine whether dust was derived from local or non-local sources, metal concentrations in local soil from each site were determined. The relative ratios of Cr, Ni, and Pb in dust and soil from the same site were compared to determine if the metal fingerprint was similar between the two matrices (Figure 3.6). In almost every case, Pb was found in higher proportions in the soil than in the dust. The opposite was true of Cr, which is in higher proportions in the dust. Ni exists in similar proportions in both matrices.

There are a few obvious exceptions to this trend (Figure 3.6). For the settlements of Kamere and Karagita, the dust fingerprint is very similar to the fingerprint of the local surface soil. The same is true for the salmon farm in the upper catchment. Another site that doesn’t follow the same trend as the others is site A3, where Cr makes up a much higher proportion of the metals in dust than at any other site. Finally, the soil at site LS1 appears to have a lower proportion of lead than does the soil at the other sites in the catchment (Figure 3.6).

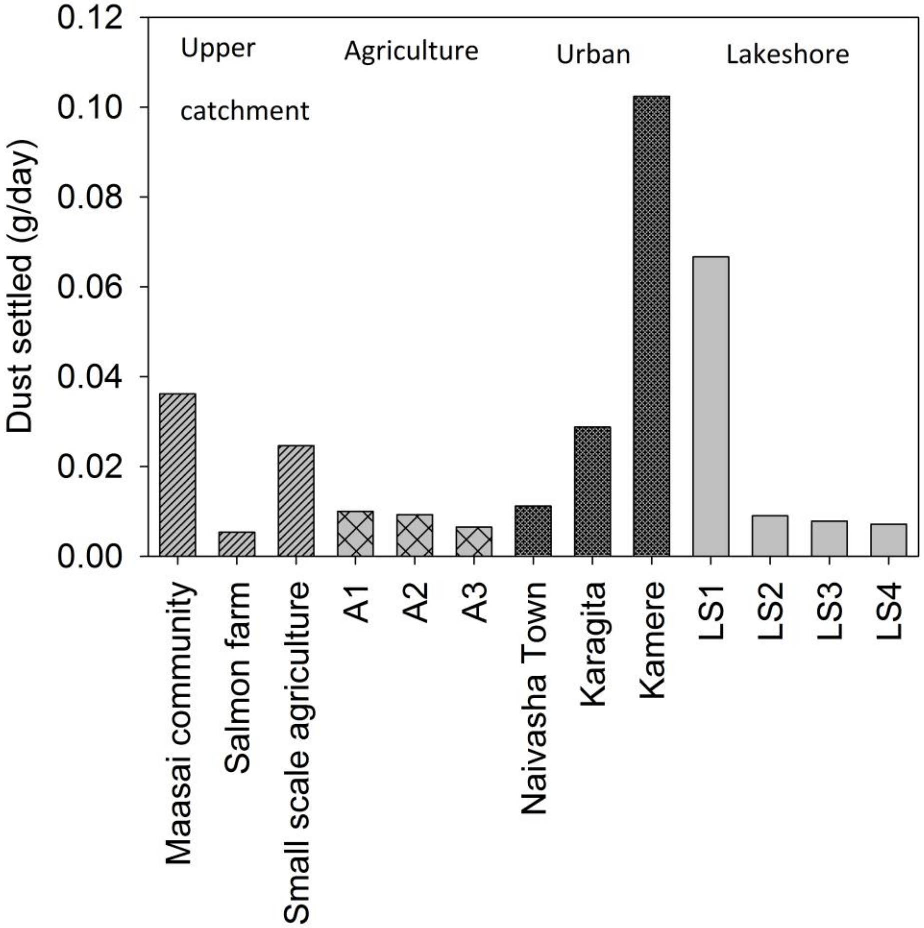

Figure 3.1: Rate of dust accumulated per day at 13 sites around the Lake Naivasha catchment. Sites are arranged in order of land use, in the following order (from the left): upper catchment, industrial agriculture, urban, and lakeshore.

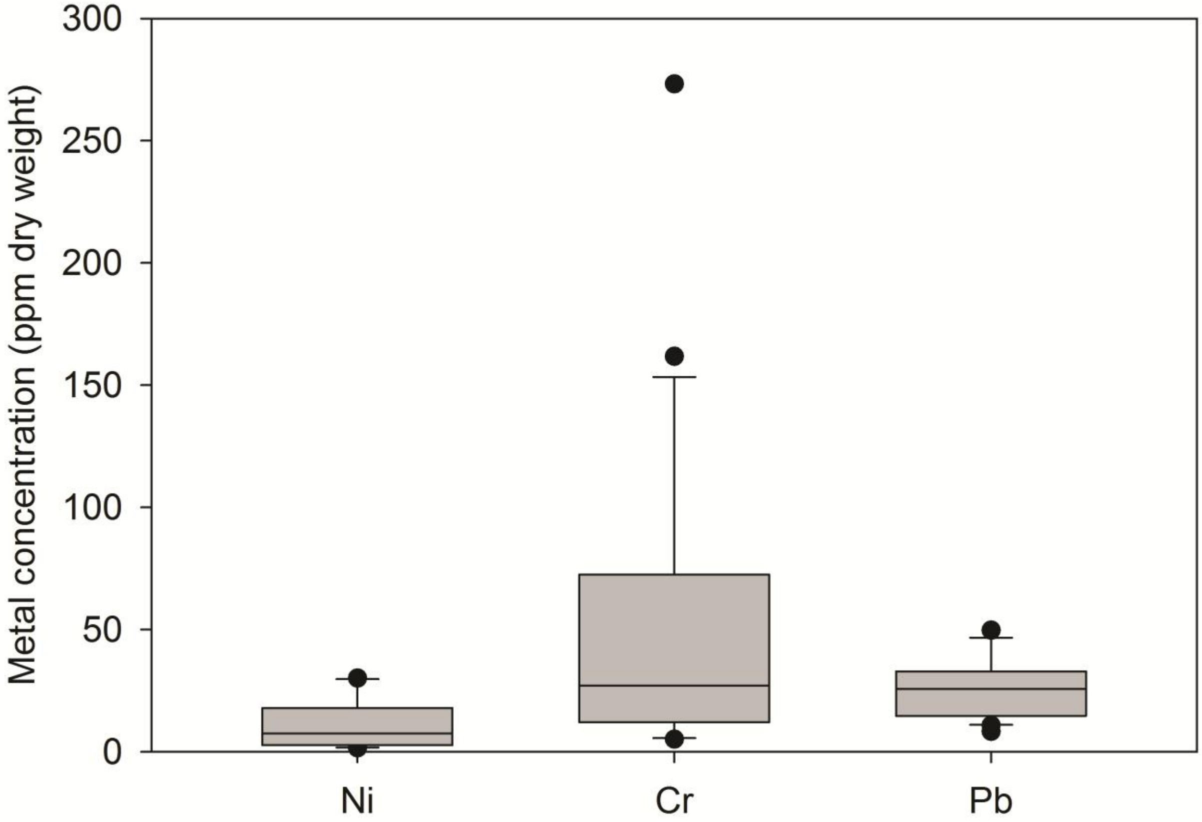

Figure 3.2: Range of concentrations of Ni, Cr, and Pb in airborne dust at various sites in the Lake Naivasha catchment (all sites combined). The middle bar within a box represents the median value. The bottom of the box and the top of the box represent the 1st and 3rd quartiles, respectively. Individual dots represent sites that fall outside the 5% and 95% confidence intervals, which are indicated by the end of the whiskers.

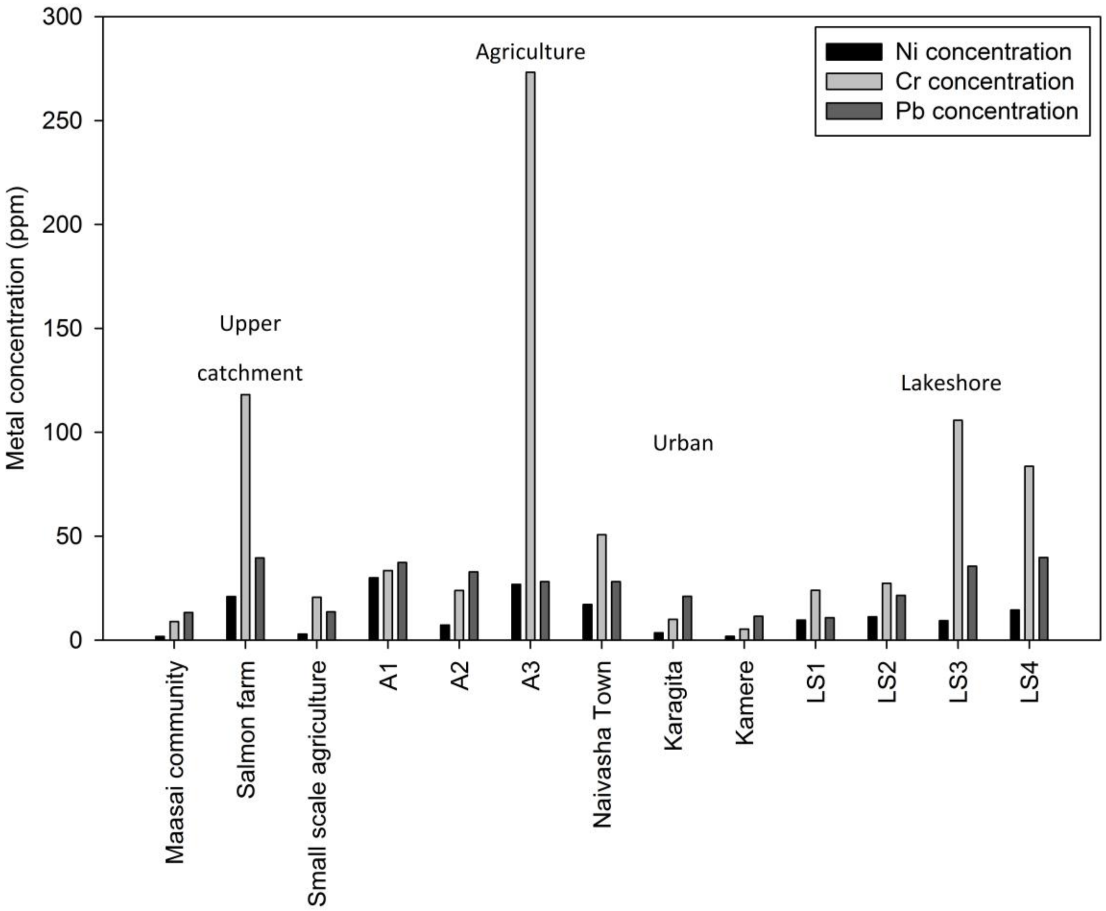

Figure 3.3: Concentrations of Ni, Cr, and Pb in dust at each of the 13 sites around the Lake Naivasha catchment. Sites are arranged in order of land use, in the following order (from the left): upper catchment, industrial agriculture, urban, and lakeshore.

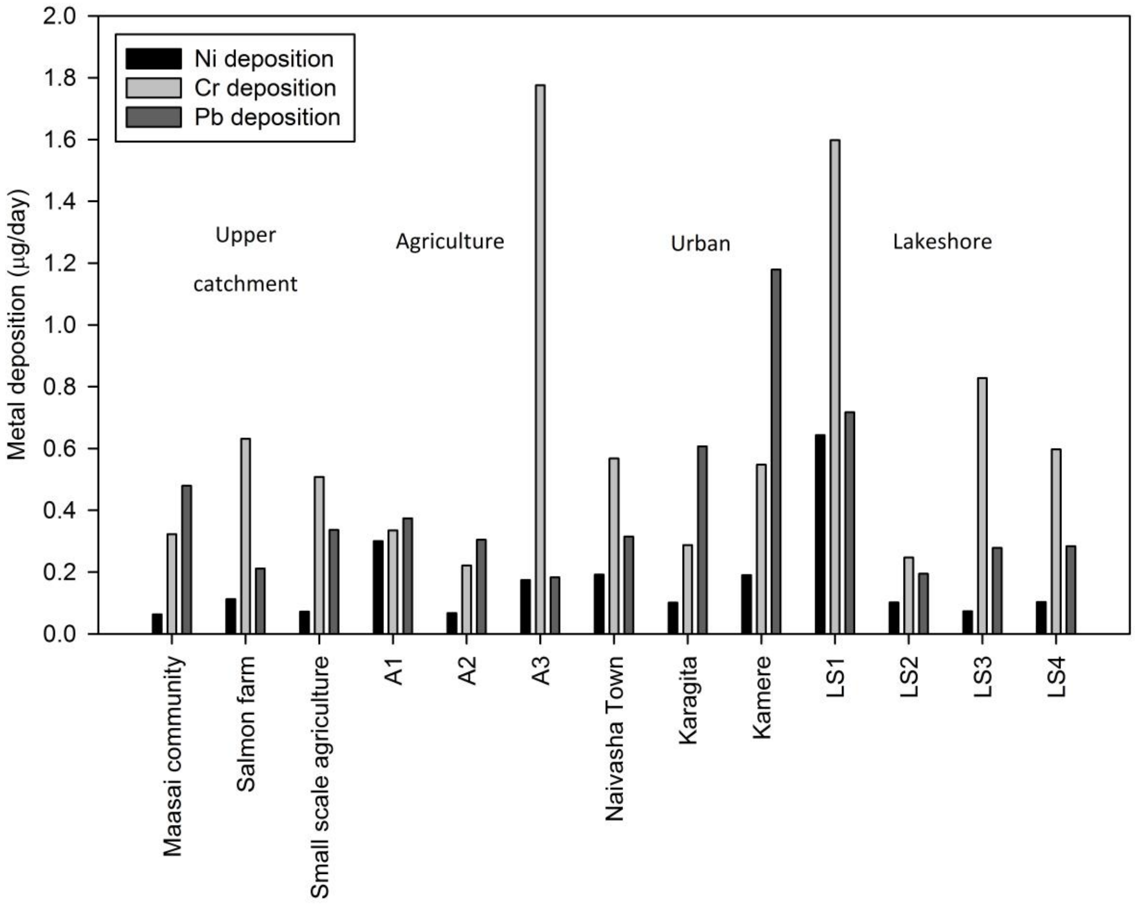

Figure 3.4: Daily deposition of Ni, Cr, and Pb in airborne dust at each of the 13 dust collection sites. Daily metal deposition is being used as a proxy for exposure risk. Sites are arranged in order of land use, in the following order (from the left): upper catchment, industrial agriculture, urban, and lakeshore.

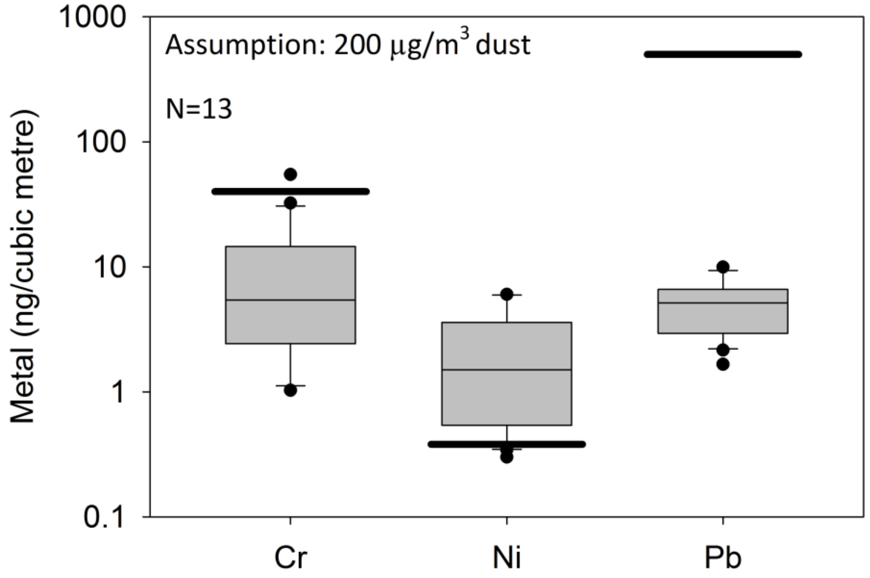

Figure 3.5: Airborne metal densities compared to WHO guidelines, assuming 200 μg/m^3 of dust in the air. The bold, black line shows the WHO guideline. The middle bar within a box represents the median value. The bottom of the box and the top of the box represent the 1st and 3rd quartiles, respectively. Individual dots represent sites that fall outside the 5% and 95% confidence intervals, which are indicated by the end of the whiskers.
Note: WHO guideline for Cr is set for Cr (VI). By comparing guideline to total Cr, actual health concern is over-estimated.

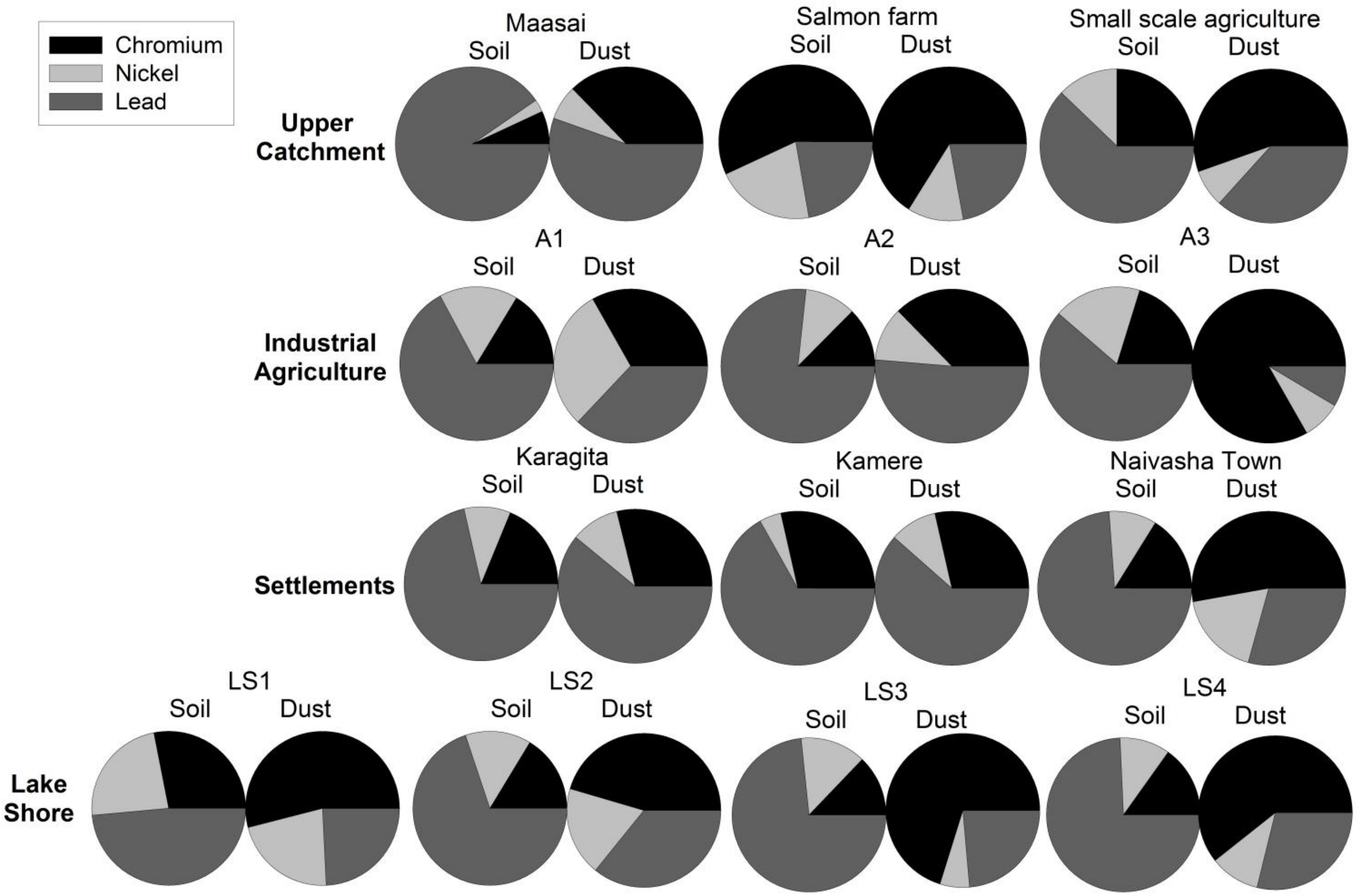

Figure 3.6: Fingerprinting of the relative ratios of Cr, Ni, and Pb in dust and surface soil from all dust sites. Where the ratios of metals are similar between dust and soil from the same site, dust is considered to be locally derived.

3.2. Distribution of persistent organic pollutants and metals in the *C. carpio* and associated health risks

Lake wide, the concentration of various metals and nutrients in *C. carpio* dorsal muscle varied over several orders of magnitude. The highest concentrations were seen for macronutrients (P, S, Ca, K and Mg) and some micronutrients (Zn and Fe) (Figure 3.7). Detectable concentrations were also seen for many non-essential metals (Si, Sn, Sr and Hg).

Variance was considerably lower for POPs, where concentrations for all fish fell between 0 and 0.08 ppm. The highest concentrations were seen for endosulfan sulfate (a breakdown product of endosulfan), endrin aldehyde, total DDT, and endrin, in that order (Figure 3.7). No PCBs were found in any samples.

To better understand the level of human health risk posed by metals and POPs in fish, body burdens were compared to guidelines set by the EPA (Figure 3.8). Note that all estimates of risk are overestimates, because samples with concentrations below detection limits were excluded from analysis. Unless otherwise noted, detection limits were as follows: mercury, 0.0005 ppm; other elements, 0.5 ppm; organochlorines, 0.001 ppm; polychlorinated biphenyls, 0.04 ppm.

For the metals and elements measured in this study, only 2 have EPA guidelines – Hg and Se (Figure 3.8). Of these, only Hg exceeded the guideline for unrestricted fish consumption in some fish. Based on the Hg median body burden of 0.039 ppm, however, fish can be safely consumed up to 16 times per month. Nearly half of all Hg concentrations are safe for unlimited consumption. These data reflect the 23 of 24 samples with detectable concentrations of Hg.

For the POPs measured in this study, only 4 have EPA guidelines: total endosulfan, dieldrin, endrin, and total DDT. Of these, only dieldrin and total DDT exceeded the guideline for unrestricted fish consumption (Figure 3.8).

Considering only the median dieldrin body burden of 0.002 ppm, fish should not be consumed more than twice per month. These data reflect only the 10 of 24 fish with detectable levels of dieldrin.

Although several individual fish exhibited total DDT concentrations above the EPA guideline for unrestricted consumption, if we consider only the median body burden of 0.006 ppm, no restrictions on fish consumption are necessary. These data reflect the 15 of 24 samples with detectable concentrations of DDTs. Even at the highest total DDT body burden, fish are safe to consume 8 times/month (Figure 3.8).

To determine if contaminant body burden was spatially variable, 4 fish from each site were analyzed, with the goal of having at least 3 with concentrations above detection limits, so statistical analysis could be performed. Results of spatial analysis suggest that no significant differences in Hg body burden exist (H=5.679, p=0.339) between sites (Table 3.1).

The number of non-detects for POPs was high enough that individual POPs could not be statistically compared between sites. This problem was circumvented by comparing the spatial variability of total POPs (Table 3.2). For total POPs (H=17.991, p=0.003), the highest concentration was found in the south of the lake, offshore from Sher flower farm. The lowest concentration was found to the north of the lake, at the Mouth of the Malewa River and the Naivasha Town sewage outflow (Table 3.2). The magnitude of difference in total POPs between the two sites was such that the median body burden in the south was over 8 times greater than that in the north (Table 3.2). To visualize the spatial distribution, the statistical results for total POPs are displayed on a map (Figure 3.9).

For all metals (Table 3.3) and POPs (Table 3.4), the biomagnification factor from oligochaetes to *C. carpio* was calculated. A relative accumulation factor from sediment to *C. carpio* was also determined. Relative accumulation factors suggest that total Hg is not accumulating in *C. carpio* (Table 3.3).

Because no Hg was detected in oligochaete samples, no BMF could be calculated.

For the POPs that were detected in the sediment, there were often only 1 or 2 sites with detectable concentrations, meaning calculated RAFs are often based on few sediment data and likely include a lot of uncertainty. With that caveat, δ-BHC, endosulfan sulfate, dieldrin, 4,4'-DDT, 4,4'-DDE and total DDTs all appear to be bioaccumulating in *C. carpio* (Table 3.4). The body burden of POPs in almost all oligochaetes from all sites was below detection limits, so no relative accumulation factors could be calculated.

To see if contaminant concentrations were increasing with fish size, the relationship between body burden, and both fish weight and fork length was examined. Fish weight and fish fork length are strongly correlated with one another (r^2=0.905, p<0.001) (Figure 3.10). Near or above a fork length of 60 cm, there were 4 fish whose weight seems to be higher than predicted by the trend line. These 4 fish are from 3 different sites on the lake and span a range of POP and Hg concentrations.

The relationship between total body burden of POPs and the fork length (r=0.103, p=0.630) and weight (r=0.143, p=0.504) of *C. carpio*, both show no linear correlation (Figure 3.11). This lack of correlation is also true when correlations are compared individually for each site (Tables 3.5A and 3.5B). The exception is fish caught offshore from Sher flower farm, in the south of the lake. Fish from this site have a higher body burden of POPs than fish from other sites, and the relationship between total POPs and length (r=0.963, p=0.037) and total POPs and weight (r=0.955, p=0.045) is linear (Figure 3.11).

A similar trend can be seen for Hg body burdens and size. Lake-wide, there is no linear correlation between total Hg body burden and fork length (r=0214, p=0.923) or weight (r=0.137, p=0.534) (Figure 3.12). The lack of correlation is also true when fish from each site are considered individually (Tables 3.6A and 3.6B). The only exception is fish caught offshore from Nini flower farm, in the south of the lake. Fish from this site show a linear relationship between Hg body burden and both length (r=0.995, p=0.005) and weight (r=0.998, p=0.002) (Figure 3.12).

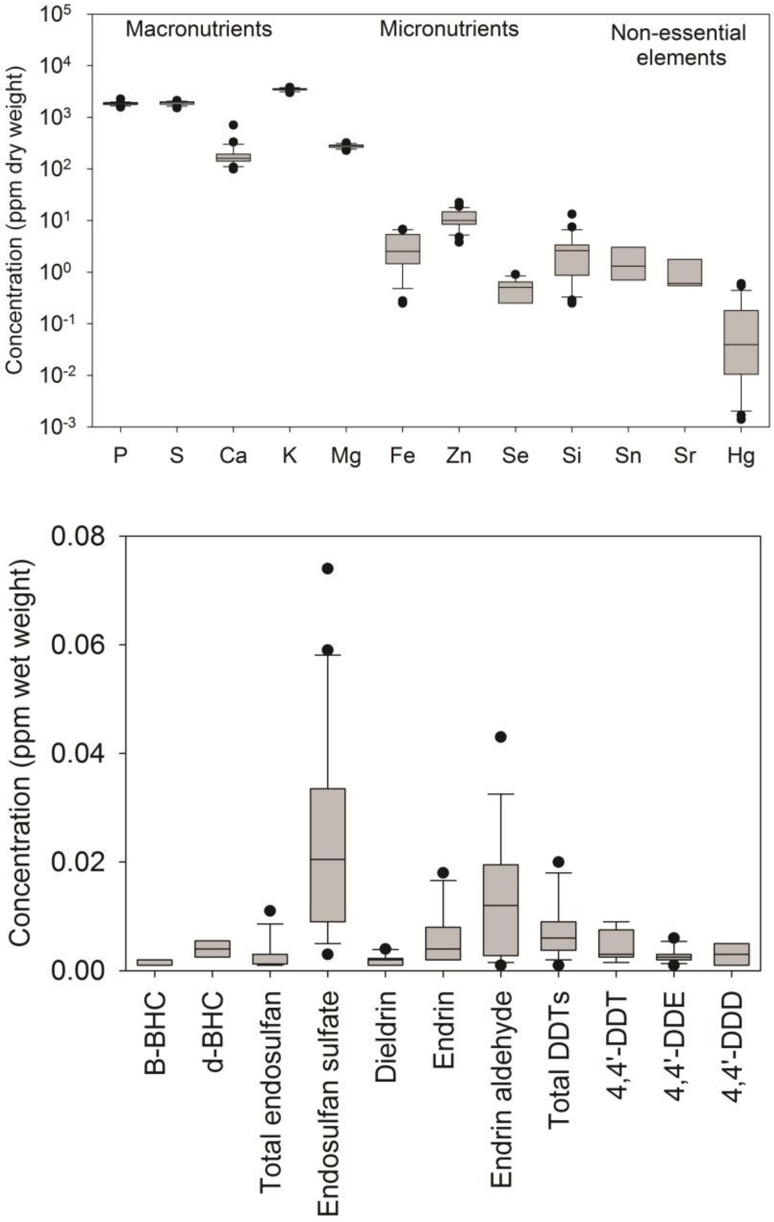

Figure 3.7: Concentrations of all detectable elements and POPs in the dorsal muscle of *C. carpio* (all sites combined). The middle bar within a box represents the median value. The bottom of the box and the top of the box represent the 1st and 3rd quartiles, respectively. Individual dots represent sites that fall outside the 5% and 95% confidence intervals, which are indicated by the end of the whiskers. Maximum reporting limits: Mercury (0.0005 ppm), other elements (0.5 ppm), organochlorines (0.001 ppm), PCBs (0.04 ppm)

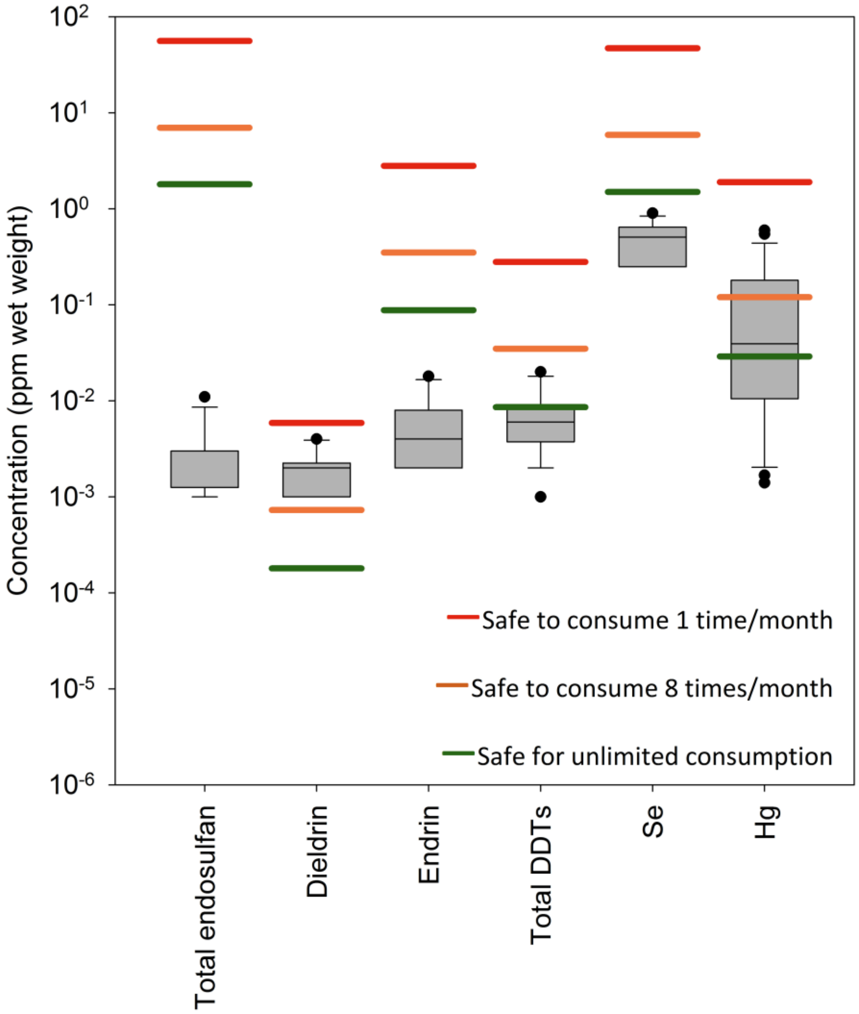

Figure 3.8: Concentrations of all POPs and elements in the dorsal muscle of *C. carpio* compared to guidelines set by the EPA. The stand-alone lines represent the concentration of each compound that is acceptable at a given frequency of fish consumption, based on single contaminant exposure risk. The middle bar within a box represents the median value. The bottom of the box and the top of the box represent the 1st and 3rd quartiles, respectively. Individual dots represent sites that fall outside the 5% and 95% confidence intervals, which are indicated by the end of the whiskers.
[Note: EPA guideline for Hg is actually for CH_3Hg, but only total Hg was measured for this study. In this case, total Hg is a reasonable approximation of CH_3Hg because CH_3Hg represents approximately 90% of the total amount of Hg in fish (Bloom, 1992)].

Table 3.1: Comparison of Hg in *C. carpio* dorsal muscle between sites. Analysis was conducted using a Kruskall-Wallis one-way ANOVA (H=5.679, p=0.339).

Site	Rank	Median	Q1	Q3
KWS annex	a	0.144	0.0241	0.430
Nini farm	a	0.106	0.0794	0.329
Sher farm	a	0.0863	0.0256	0.0936
Naivasha Town sewage	a	0.0309	0.0210	0.120
Hippo Point	a	0.0218	0.00595	0.107
Malewa Mouth	a	0.00516	0.00213	0.144

Table 3.2: Comparison of total POPs in *C. carpio* dorsal muscle between sites. Analysis was conducted using a Kruskall-Wallis one-way ANOVA and Tukey's (H=17.991, p=0.003).

Site	Rank	Median	Q1	Q3
Sher farm	a	0.0755	0.0680	0.0910
KWS annex	ab	0.0550	0.0330	0.0750
Nini farm	ab	0.0380	0.0320	0.0470
Hippo Point	ab	0.0265	0.0165	0.0355
Malewa Mouth	b	0.0207	0.0110	0.0248
Naivasha Town sewage	b	0.0090	0.0065	0.0130

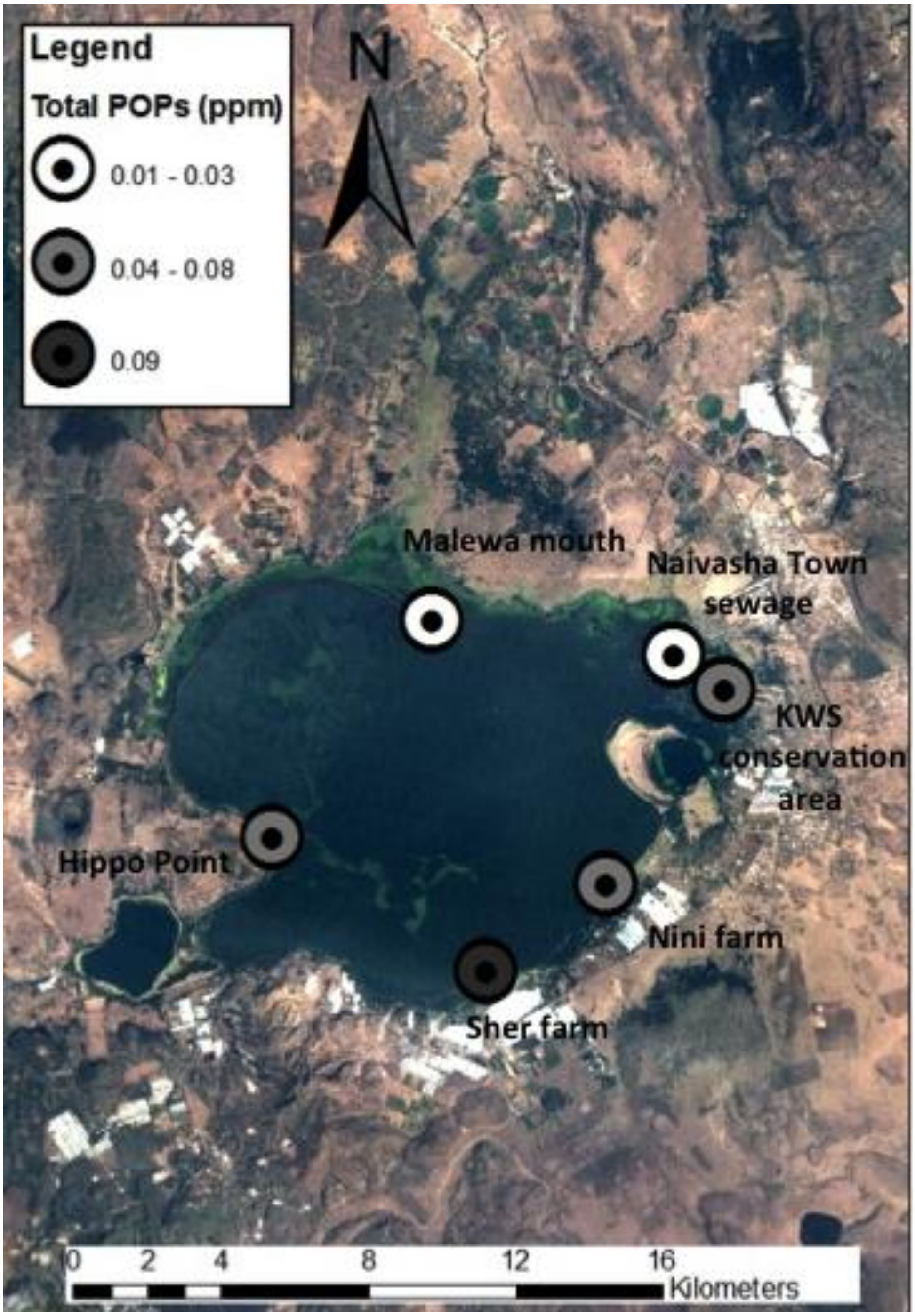

Figure 3.9: Map showing the spatial distribution of fish body burden of total POPs in Lake Naivasha. The legend shows the median body burden at a given site, in ppm (wet weight). Ranges have been set to correspond to the results of statistical analysis, where: black = a, grey = ab, and white = b.

Table 3.3: Biomagnification factor (BMF) of metals and other elements from oligochaetes to *C. carpio* and relative accumulation factors (RAF) of metals and other elements from sediment to *C. carpio*.

Metal	Sediment* (ppm d/w)	Oligochaete (ppm w/w)	*C. carpio* (ppm d/w)	*C. carpio* (ppm w/w)	*C. carpio* BMF	*C. carpio* RAF
P	670	1100	8300	1900	1.7	12
S	250	840	8300	1900	2.3	33
Ca	6700	310	700	160	0.52	0.10
K	20000	1100	15000	3500	3.2	0.75
Mg	2500	110	1200	280	2.5	0.48
Fe	25000	280	11	2.5	0.0090	0.00044
Zn	88	8.4	43	10.0	1.2	0.49
Se	ND	ND	2.2	0.51	n/a	n/a
Sb	ND	ND	2.2	0.50	n/a	n/a
Si	1300	57	12	2.7	0.048	0.0091
Sn	1.7	ND	5.7	1.3	n/a	3.3
Sr	54	4.5	2.6	0.61	0.13	0.049
Hg*	0.59	ND	0.17	0.04	n/a	0.3

*Sediments were dried at 105°C, which likely resulted in the loss of some Hg and Se

**Hg is measured as total mercury

All concentrations are given as median values from the entire lake, excluding concentrations that were below the detection limit

ND: Not Detected

n/a: Not calculable because of undetectable concentrations

BMF is calculated on a wet weight basis, from oligochaetes to *C carpio*

RAF is calculated on a dry weight basis, from sediment to *C. carpio*

Table 3.4: Biomagnification factor (BMF) of POPs from oligochaetes to *C. carpio* and relative factors (RAF) of POPs from sediment to *C. carpio*.

Chemical	Sediment* (ppm d/w)	Oligochaete (ppm w/w)	*C. carpio* (ppm d/w)	*C. carpio* (ppm w/w)	*C. carpio* BMF	*C. carpio* RAF
β-BHC	0.005	ND	0.004	0.001	n/a	0.9
δ-BHC	0.001	ND	0.02	0.004	n/a	20
Endosulfan I	ND	ND	0.02	0.004	n/a	n/a
Endosulfan II	ND	ND	0.01	0.003	n/a	n/a
Total Endosulfan	ND	ND	0.01	0.003	n/a	n/a
Endosulfan sulfate	0.002	ND	0.09	0.02	n/a	40
Dieldrin	0.002	ND	0.01	0.002	n/a	4
Endrin	ND	ND	0.02	0.004	n/a	n/a
Endrin aldehyde	ND	ND	0.05	0.01	n/a	n/a
4,4-DDT	0.002	ND	0.01	0.003	n/a	7
4,4'-DDE	0.002	ND	0.01	0.003	n/a	5
4,4'-DDD	ND	ND	0.01	0.003	n/a	n/a
Total DDTs	0.002	ND	0.03	0.006	n/a	10

*Sediments were dried at 105^{o}C, which likely resulted in some POP volatilization
All concentrations are given as median values from the entire lake, excluding concentrations that were below the detection limit
ND: Not Detected
n/a: Not calculable because of undetectable concentrations
BMF is calculated on a wet weight basis, from oligochaetes to *C carpio*
RAF is calculated on a dry weight basis, from sediment to *C. carpio*

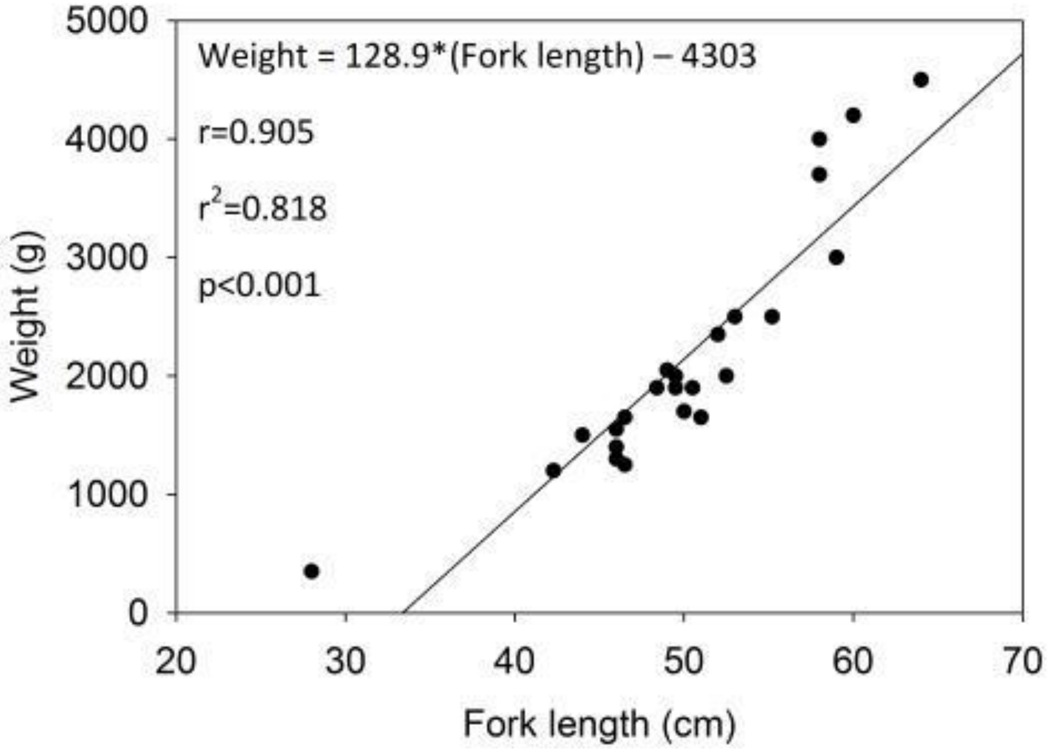

Figure 3.10: Correlation between the weight (g) and fork length (cm) of *Cyprinus carpio* from Lake Naivasha. Weight and fork length are strongly correlated ($r=0.905$, $p<0.001$)

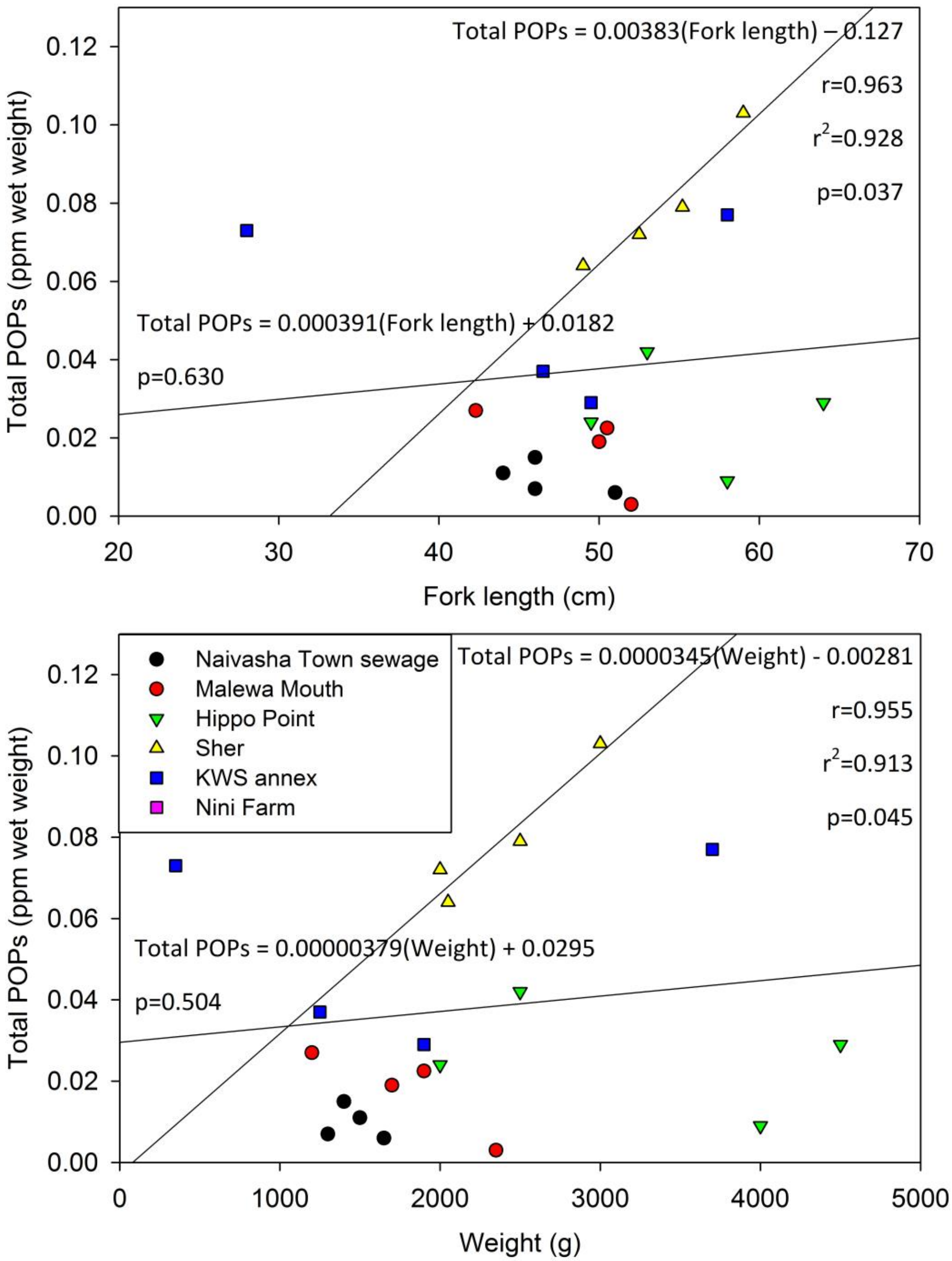

Figure 3.11: Correlation between the body burden of total POPs in *Cyprinus carpio* dorsal muscle and the weight and fork length of the fish. Neither fork length (r=0.103, p=0.630) nor weight (r=0.0143, p=0.504) shows a strong linear correlation with body burden of total POPs.

Table 3.5A: Statistics for the correlation between the weight (g) of *C. carpio* and the dorsal muscle concentration of total POPs (ppm): Equation of the line, r, r^2, and p values is given.

Site	Linear equation	r	r^2	p
Naivasha Town Sewage	POPs = -0.00000804(Weight) + 0.0215	-0.292	0.0851	0.708
Malewa Mouth	POPs = -0.0000195(Weight) + 0.0528	-0.891	0.794	0.109
Hippo Point	POPs = -0.00000435(Weight) - 0.0401	-0.38	0.144	0.620
Sher farm	POPs = 0.0000345(Weight) - 0.00281	0.955	0.913	0.045
KWS annex	POPs = 0.00000382(Weight) + 0.0471	0.221	0.0487	0.779
Nini farm	POPs = 0.00000161(Weight) + 0.0358	0.198	0.0391	0.802

N=4 for all sites

Table 3.5B: Statistics for the correlation between the fork length (cm) of *C. carpio* and the dorsal muscle concentration of total POPs (ppm): Equation of the line, r, r^2, and p values is given.

Site	Linear equation	r	r^2	p
Naivasha Town Sewage	POPs = -0.000794(Length) + 0.0469	-0.577	0.333	0.423
Malewa Mouth	POPs = -0.00172(Length) + 0.102	-0.717	0.514	0.283
Hippo Point	POPs = -0.000378(Length) + 0.0472	-0.174	0.0304	0.826
Sher farm	POPs = 0.00383(Length) - 0.127	0.963	0.929	0.037
KWS annex	POPs = -0.000338(Length) + 0.0694	-0.174	0.0303	0.826
Nini farm	POPs = 0.000369(Length) + 0.0210	0.237	0.0564	0.763

N=4 for all sites

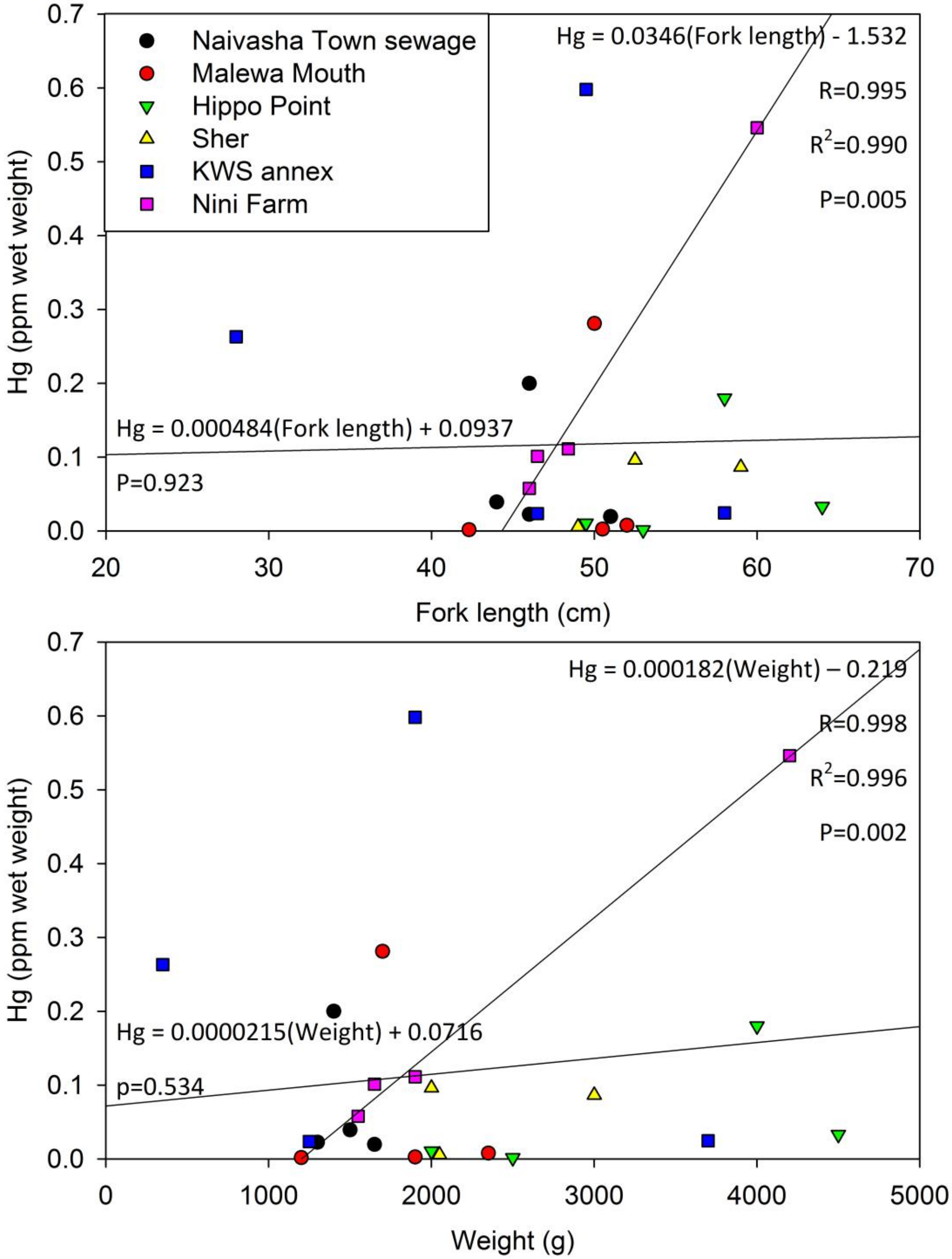

Figure 3.12: Correlation between the body burden of mercury in *Cyprinus carpio* and the fork length (r=0.120, p=0.923) and weight (r=0.683, p=0.521) of the fish. Detection limit was 0.5 ppm. Twenty-one non-detect values are not shown.

Table 3.6A: Statistics for the correlation between the weight (g) of *C. carpio* and the dorsal muscle concentration of total mercury (ppm): Equation of the line, r, r^2, and p values is given.

Site	Linear equation	r	r^2	p
Naivasha Town Sewage	Hg = -0.000165(Weight) + 0.311	-0.283	0.0800	0.717
Malewa Mouth	Hg = -0.0000307(Weight) + 0.128	-0.106	0.0112	0.894
Hippo Point	Hg = 0.0000381(Weight) - 0.0677	0.543	0.295	0.457
Sher farm	Hg = 0.0000329(Weight) - 0.0147	0.372	0.139	0.757
KWS annex	Hg = -0.0000478(Weight) + 0.313	-0.245	0.0622	0.751
Nini farm	Hg = 0.000182(Weight) - 0.219	0.998	0.996	0.002

N=4 for all sites

Table 3.6B: Statistics for the correlation between the fork length (cm) of *C. carpio* and the dorsal muscle concentration of total mercury (ppm): Equation of the line, r, r^2, and p values is given.

Site	Linear equation	r	r^2	p
Naivasha Town Sewage	Hg = -0.00716(Length) + 0.405	-0.246	0.0607	0.754
Malewa Mouth	Hg = 0.00678(Length) - 0.257	0.213	0.0453	0.787
Hippo Point	Hg = 0.00439(Length) – 0.190	0.331	0.110	0.669
Sher farm	Hg = 0.00688(Length) - 0.305	0.702	0.493	0.505
KWS annex	Hg = -0.00392(Length) + 0.406	-0.183	0.0333	0.817
Nini farm	Hg = 0.0346(Length) – 1.532	0.995	0.990	0.005

N=4 for all sites

CHAPTER 4: Discussion

4.1 Interpretation and implications of metals in dust

The findings of this study partially support the hypothesis that persistent organic pollutants and metals are a risk for human health in the Lake Naivasha catchment. In airborne dust, Ni is over WHO health guidelines at every site except one, but Cr and Pb do not appear to exceed guidelines. Additionally, no contaminants in fish are at high enough concentrations that fish should not be consumed.

Findings also support the hypothesis that risk caused by these contaminants is spatially variable.

In the terrestrial system, exposure risk takes the form of metal contaminated dust. Although there were spatial differences in the amount of dust and the concentrations of metals in dust, these differences were not explained by land use. This is likely because dust at most sites is not locally derived, as shown by the dissimilar fingerprints of metals in the dust as compared to metals in local soils.

Despite the lack of difference in dust between land use types, spatial variability in the amount and the content of dust did still exhibit trends. Cr is the metal that shows the most spatial variability. Interestingly, areas of high Cr concentrations do not correspond with urban centers, as may have been predicted given that the primary sources of anthropogenic Cr are urban activities, such as coal and oil combustion, chrome plating and other industrial activities (Baird & Cann, 2005). This could suggest that Cr is actually coming from spatially variable, but natural sources, such as steam released from geothermal vents (Arnórsson, 1970; USEPA, 1980).

Ni was mixed more homogeneously in the catchment than Cr, and the sites where Ni concentrations were relatively high were natural areas. This suggests Ni in dust may be arising largely from natural sources, such as weathering soil and bedrock. This conclusion supports previous literature, which suggest that the geogenic concentration of Ni in the Naivasha basin is high (Tarras-Wahlberg, et al., 2002).

Pb in the dust is also fairly homogeneous, with relatively low concentrations occurring at sites isolated from major roads, such as site LS1 (a conservation area), the Maasai community (located in a National Park) and Kamere settlement (where dust collector was in an area of town very difficult to access by car). This is likely because Pb in in the system has resulted from its use as a gasoline additive in Kenya, making its concentration higher near major roads (Li, Poon, & Liu, 2001).

It is important to note that the amount of dust can be just as important in determining exposure risk from chemicals in dust as the concentration of chemicals themselves. It is for this reason that the WHO sets their human heath guidelines in terms of the mass of metal per unit volume of air (WHO, 2005). For this reason, it is concerning that 3 human communities, Kamere, Karagita and the Maasai community, are among the dustiest sites. This is likely because high levels of human, animal, and vehicular traffic, construction, and industrial activities increase the suspension of locally derived dust (Australian Department of Environment and Conservation, 2008).

In order to estimate the level of risk posed by metals in dust, a dust density of 200 $\mu g/m^3$ was assumed for each site across the catchment (Panyacosit, 2000). This allowed the comparison of concentration data with guidelines set by the WHO. Using this approach, Pb concentrations were safe at all sites and Cr was only over recommended guidelines at one site. It should be noted, however, Cr risk here is overestimated, as WHO guidelines for Cr (VI) are being compared to the concentrations of total Cr measured in this study. Literature on the oxidation state of Cr in the atmosphere suggests that Cr (VI) may account for approximately 1/3 of total atmospheric Cr (Nusko & Heumann, 1997). Assuming Cr (VI) to be 1/3 of total Cr, Cr is not a health risk at any sites in the Naivasha catchment.

Ni was the only metal that exceeded guidelines set by the World Health Organization, but it did so at all sites in the catchment except one (WHO, 2005). This could make Ni exposure an important ecological determinant of health in the Naivasha catchment. Because the source of airborne Ni in this system is likely natural, it is unlikely that anthropogenic activities, such as fossil fuel combustion, could be targeted to reduced Ni loading. In this context, the best exposure mitigation strategy may be the implementation of a dust management plan to reduce the amount of airborne dust.

4.2 Interpretation and implications of POPs and metals in *C. carpio*

Of relevance to all body burden results in this study, is the systematic overestimation of risk imparted by the handling of non-detects. For most contaminants, there were some fish with body burdens below method reporting limits (unless otherwise noted, detection limits are as follows: mercury, 0.0005 ppm; other elements, 0.5 ppm; organochlorines. 0.001 ppm; polychlorinated biphenyls, 0.04 ppm.). These non-detects are acknowledged, but the discussion focuses on data from samples that were above detection limits. Although this approach is common in the literature (Mugachia, et al., 1992), it inherently overestimates risk.

Of the contaminant body burdens measured in this study, only 3 were high enough to exceed EPA guidelines for unlimited fish consumption: dieldrin, DDT, and Hg. No PCBs were found in any samples.

In the case of Hg, 23 of the 24 fish analyzed had concentrations greater than the maximum reporting limit of 0.5 ppb. Even at the maximum Hg body burden, fish are still safe to consume once per month. It is highly unlikely, however, that an individual consuming fish will be exposed to fish only at the highest body burden. It may therefore be more relevant to consider the median body burden. In the case of Hg, the median body burden of 0.039 ppm makes fish save to consume up to 16 times per month, or approximately 4 times per week. Because most Naivasha citizens do not consume fish this often (Keriko, et al., 2010), Hg is not a health risk to the majority.

The highest Hg concentrations found in this study are also approximately 80-fold higher than the highest Hg body burdens found in tilapia in a previous Naivasha study, where body burdens were between 3.7 and 6.6 ppb (Campbell, et al., 2003). Although the data presented by Campbell are for tilapia, and interspecific differences in Hg accumulation can occur as a result of feeding at different trophic levels (Zhou & Wong, 2000; Campbell, et al., 2003), this is not likely the sole explanation for the increase in Hg. Both carp and tilapia feed at the similar trophic levels and both have been shown to exhibit similar body burdens of Hg (Zhou & Wong, 2000; Campbell, et al., 2003).

Possible anthropogenic sources of Hg in the Naivasha catchment include urban centers, where Hg is used in electrical switches, batteries, and could be released during the burning of coal, fuel oils and municipal waste (Selin, 2009). Mercury can also be deposited from regional, or even global sources, as it is known to have an atmospheric residence time on the order of 1 year (Slemr, et al., 1985; Lindqvist & Rhodhe, 1985) and is capable of traveling tens of thousands of kilometers (Schroeder & Munthe, 1998). It is also known to be released from natural sources, especially volcanic activity (Selin, 2009). For Naivasha, being located in a rift valley, next to Mount Longonot, a dormant volcano, natural Hg cycling may be an important driver of Hg in Naivasha's fish. It is unlikely, however, that an increase in any of these sources is the sole cause of the observed magnitude of Hg increase.

Another possible explanation for the increase in body burden is increased bioavailability of Hg already in the sediment (Carrasco et al., 2011), perhaps as a result of anoxic conditions in 2010. In 2009-2010, Naivasha experienced a prolonged drought, which resulted in water levels being lower than the lake had seen since the 1940s (Harper, et al., 2011). Heavy rains in 2010 quickly washed large amounts of organic matter into the lake and decomposition resulted in decreased oxygen levels (Morara, 2010). Because Hg is methylated in anoxic conditions and methylation increases bioavailability (Kelly, et al., 1997; Morel, et al., 1998), perhaps this phenomenon allowed for an increase in Hg bioavailability, the signature of which is now being seen.. If a portion of the increase in Hg body burden is due increased bioavailability in 2010, it is likely that median mercury concentrations will drop in the future, as older fish die and are replaced by fish born after 2010.

To follow up on these findings, it would be of value to determine the levels of mercury in the blood or hair of humans from the Naivasha catchment.

Aside from Hg, dieldrin and DDT are the other two contaminants were above EPA health guidelines in some cases. Both are organochlorine pesticides. DDT was introduced for use in Kenya in 1947, but has been banned for agricultural use since 1986 (International POPs Elimination Project, 2005). Despite the ban, a 2005 investigation found that DDT was still being held in storage at many agricultural sites in Kenya and its use is suspected to be ongoing in some areas (International POPs Elimination Project, 2005). A study by Gitahi (2002) revealed that concentrations of DDT in Naivasha's fish were actually higher than those of its breakdown product, DDE. This provided evidence that DDT use was recent in the Naivasha catchment. These facts align well with the findings of this study, which suggest that median body burden of DDT is equal to that of DDE (Table 3.3).

Detectable concentrations of total DDTs were found in 14 of 24 fish. Of the 14 fish with detectable concentrations, only 4 fish had concentrations that exceeded concentrations safe for unlimited consumption. The highest observed body burden was from a fish caught offshore from KWS annex, although even the body burden in this fish was low enough to allow safe consumption at a rate of 12 meals per month. In this light, it does not seem likely that DDT is a concern for human health in Naivasha.

Dieldrin is the final contaminant above EPA health guidelines in fish, although detectable levels of dieldrin were found in only 10 of the 24 fish analyzed. The dieldrin body burdens in these fish were between 0.001 and 0.004

ppm wet weight. According to these concentrations, fish consumption should be limited to 1-3 times per month, however, over half of the fish did not have detectable concentrations of dieldrin. This means that it like probably safe to consume fish more frequently than 1-3 times/month.

We can conclude that for single contaminant exposure via fish consumption, it is not likely that metals or organochlorines pose a risk to human health. However, in addition to those single contaminants that exceed EPA guidelines, there were also other contaminants for which no guideline exists. One example is endosulfan sulfate, which is a toxic breakdown product of the insecticide endosulfan (USEPA, 2000). Although no guideline exists for endosulfan sulfate, its concentration is approximately 4 times greater than that of its precursor. In combination, it's possible that the presence of more than one contaminant may act synergistically to harm human health (Carpenter et al., 1998). Additionally, the EPA guidelines used in this study are set for healthy adults, but high-risk groups in society, such as children, pregnant women or those who are already ill, may be particularly vulnerable to exposure.

The only discernable spatial trend in fish body burdens was a statistically greater concentration of total POPs in fish caught in the south of the lake, as opposed to those fish caught in the north. One possible explanation for this could be the loading of POPs in runoff from the widespread industrial agriculture on the south shore of the lake. Interestingly, however, previous studies have shown that sediment originating from the upper catchment and entering the lake via the rivers in the north, settles primarily in the southern, eastern and central basin (Tarras-Wahlberg, et al., 2002). This upper catchment derived sediment could also be the source of the higher level of POPs in the south of the lake.

Total mercury does not appear to be accumulating between trophic levels. This is likely because most of the mercury in the sediment is not bioavailable. Methylmercury is the most bioavailable form of mercury and likely accounts for only a small proportion of total mercury in the sediment.

Dieldrin and DDT both displayed an increase in concentration between the sediment and the tissue of *C. carpio*. This is perhaps not surprising, given that organic contaminants are known to accumulate in the fatty tissue of organisms. Contrary to what is typically seen (Borgå, Fisk, Hoekstra, & Muir, 2004), however, neither the weight nor the length of the fish appears to be good predictor of body burden, except in the south of the lake. The same trend exists for Hg body burden.

Comparison of organochlorines body burdens with those found in previous research suggests that all have decreased in concentration except for endosulfan, which was only banned for use in 2011. This is encouraging and suggests that exposure risk through fish consumption may continue to decrease as time from banning increases.

4.3 Future research

The first area in which more research is needed is the exposure risk caused by contaminants in dust. This research should focus on addressing the 3 primary limitations of the current study:

- Inter-laboratory correction factors could only be applied to 3 metals in this study: Ni, Cr, and Pb. Future research should focus on expanding analysis to include other metals of potential concern to human health, including As, Cd, Mn, and Hg.
- Analysis of POPs in dust was not possible because of the insufficient mass of dust collected. Future research should focus on collecting a greater mass of dust (≥ 20 g dry weight) for this analysis, perhaps through the use of active samplers.
- Because the present study lacks data on site-specific densities of airborne dust, an assumption of dust density was applied to all sites. This likely does not accurately represent the actual dust density at a given site, or the

spatial heterogeneity of density between sites. The limitation could also be addressed through the use of active samplers.

In addition to dust, future research could focus on better understanding the risks posed by fish consumption in the Naivasha catchment. These could include some of the following components:

- Increasing the number of sites sampled to better understand the spatial variability of contaminant body burden in fish. To reduce non-detects, at least 50 g (wet weight) of muscle tissue should be analyzed from each fish.
- Determining the concentration of Hg and POPs in sediment at the same sites where fish are sampled, according to EPA standards. One of my many lessons learned in this study was that oven-drying sediments could lead to loss of volatile compounds.

4.4 Management implications

Given the Ecosystem Health framework from which this research was developed, the first step in improved management should be community consultation (Charron, 2012). Findings from this study should be shared with community members in an accessible manor, and the potential courses of action should be discussed. Community involvement will ensure that new management practices are socially and culturally appropriate and will increase the likelihood that the recommendations are accepted and supported by the community.

The findings of this study have several implications for managers. Firstly, exposure to dust and the contaminants in dust may be an important determinant of health, although metals may be derived largely from natural sources. Elevated levels of dustiness in many of the settlements may be particularly relevant for human health. For these reasons, I am suggesting that a dust management plan in settlements would be useful. Such a plan might include context appropriate adaptations (Department of Environment and Conservation, 2008), including:

- The use of dust barriers, such as improved vegetation, especially along the sides of unpaved roads.
- The paving of a single, major road in all settlements.
- Reduction of speed limits on unpaved roads.

Better monitoring of pesticide use is also suggested, both for small-scale farming in the upper catchment and industrial horticulture operations in the lower catchment. Although industrial farms are currently subject to regular inspection, all inspections are arranged in advance (Kinyua, pers. comm.). I am suggesting that a more effective means of monitoring and enforcement would be unannounced visits to farms, to ensure that best practices are being followed all the time.

In the upper catchment, enforcement of regulations surrounding pesticide use could be more challenging and resource intensive. I propose that unannounced site visits be used in conjunction with a farmer-training program in these areas. Such a training program could focus on best practices in pest control, erosion prevention, and the potential health effects associated with pesticides in the environment. If resources were available, a reward system or public recognition system could also be put in place to recognize farmers with good agricultural practices.

A third management option to mitigate contaminant exposure risk is the protection and rehabilitation of the papyrus fringe around the lake. Riparian vegetation, such as papyrus, slows down the movement of incoming water allowing sediment to settle out of the water before reaching the lake. The papyrus currently experiences many anthropogenic insults, including clearing for agricultural land, and grazing by cattle and displaced wildlife (Morrison & Harper, 2009). Interventions to improve the papyrus at the mouth of Lake Naivasha’s two inflowing rivers have been deemed feasible and are described by Morrison and colleagues (2009). Fringe rehabilitation, however, should go beyond improving the filtration of inflowing river water. Improved shoreline vegetation around the entire lake, and along rivers in the upper catchment would also help reduce inflow of contaminants.

CHAPTER 5: Conclusions

This study examined concentrations of metals and persistent organic pollutants in dust and fish in the Naivasha catchment, to better understand exposure risk through inhalation and consumption.

Of the 3 metals found in dust (Cr, Ni and Pb), concentrations of Cr were the highest. Cr concentrations also exhibited greater spatial variability than Ni and Pb. It is speculated that this occurs because Ni is naturally derived from substrate found throughout the catchment. The primary source of Pb is the use of leaded gasoline, which is also widespread in the catchment. .

Three settlements appeared to have relatively high rates of dust deposition compared to the other sites, with dust in these sites being largely locally derived. This is significant because settlements are also sites with high densities of people, increasing human exposure to contaminants in dust.

The only metal of concern for human health through airborne exposure was Ni. Based on an assumed dust density of 200 μg/m^3, it appears that airborne Ni is above WHO health guidelines at all sites in the catchment except one. Management efforts should focus on minimizing the amount of airborne dust at all sites, especially human settlements.

Both metals and persistent organic pollutants were examined in the dorsal muscle of *Cyprinus carpio*. Mercury was the only metal that exceeded WHO guidelines for unlimited fish consumption, although the median body burden of Hg is still safe to consume 16 times per month.

Organochlorine pesticides were the only POPs detected, as PCBs were below detection limits in every sample. Only dieldrin and DDT exceed concentrations safe for unlimited fish consumption in any fish. The median concentration of dieldrin in fish was safe to consume 1-3 times per month, however, given the non-detect rate 58%, actual risk posed by dieldrin is much lower than this. DDT is also unlikely to be a health risk. Even at the highest observed DDT concentration, fish is safe to consume 8 times per month.

It was not possible to determine the exact source of the incoming POPs in this study, but regardless of how they enter the lake, the POPs seem to be accumulating in *C. carpio* to the greatest extent in the south of the lake. Comparison of results with previous literature suggests that body burdens of all POPs except endosulfan, are decreasing, likely because of pesticide bans.

Management efforts should focus on reducing loading of POPs at their source, by increasing monitoring of all farms and providing additional training for farmers in the upper catchment. Efforts should also be made to improve the filtering capacity of natural fringe vegetation.

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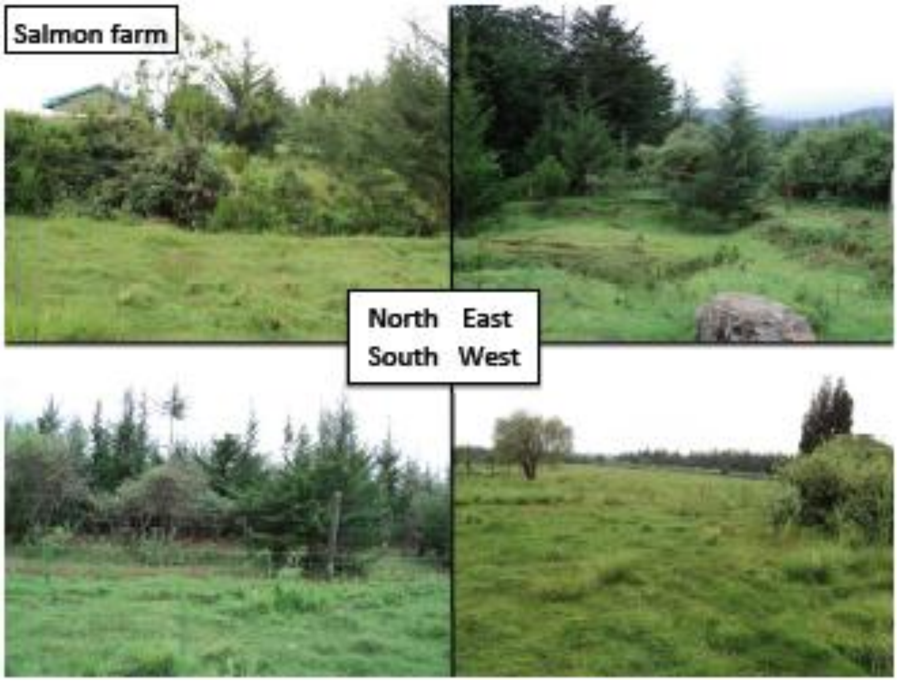
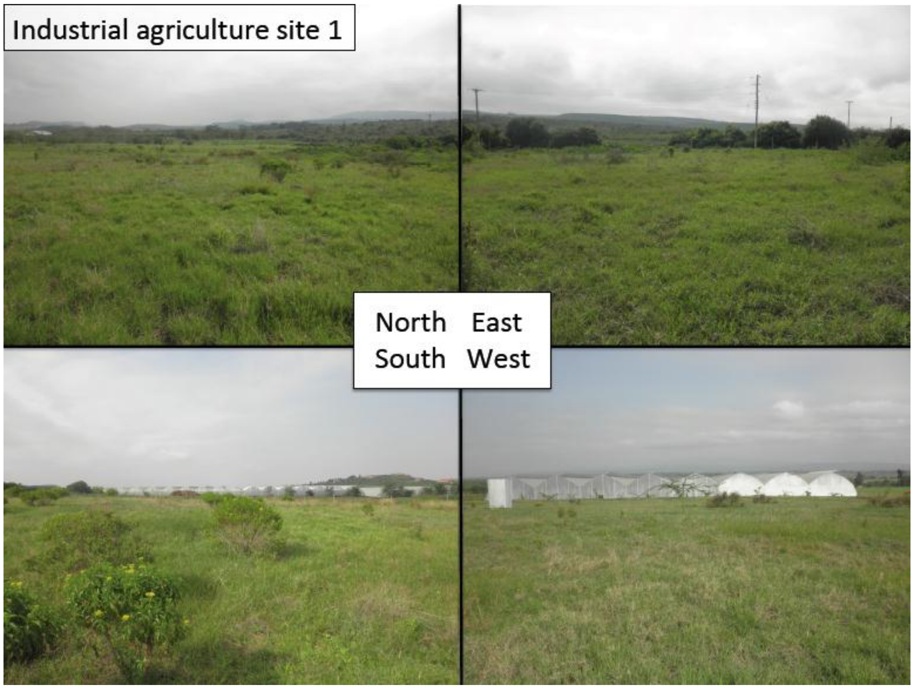
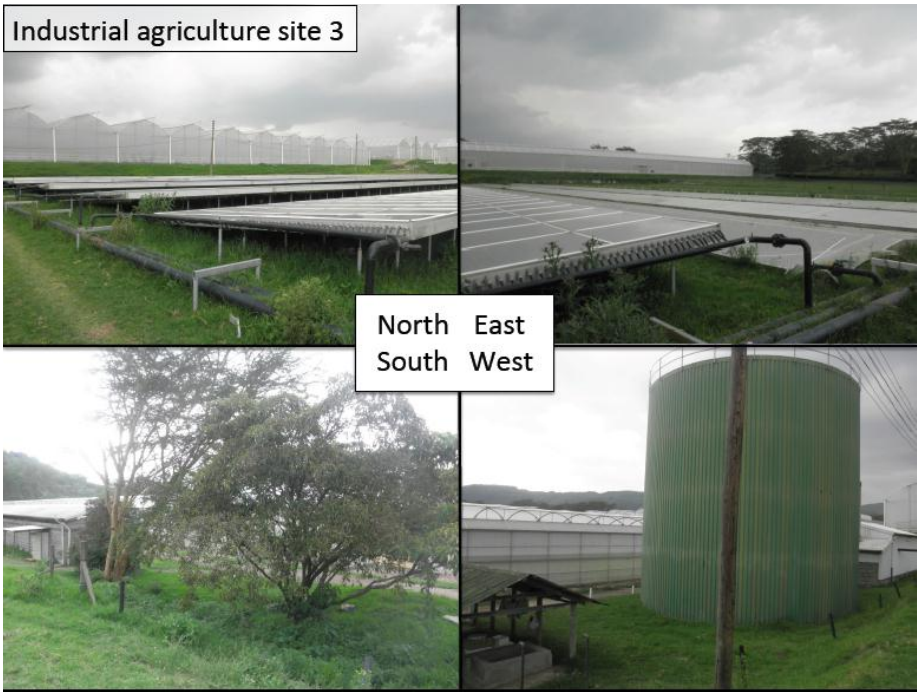
APPENDIX 1: Dust site photo library




Small-scale farm
North
East
South
West


Industrial agriculture site 1
North
East
South
West


Industrial agriculture site 2
North East
South West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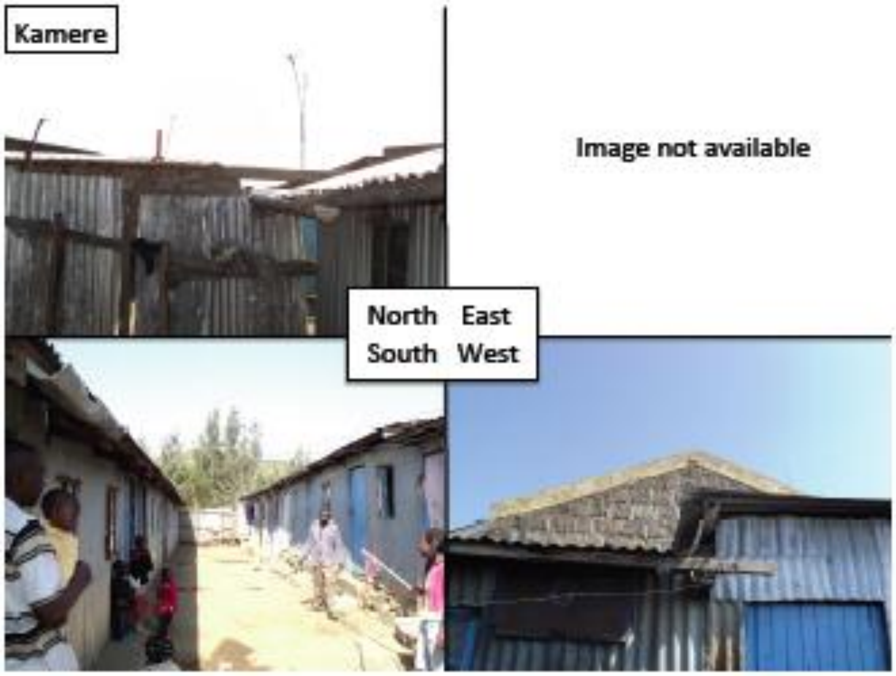
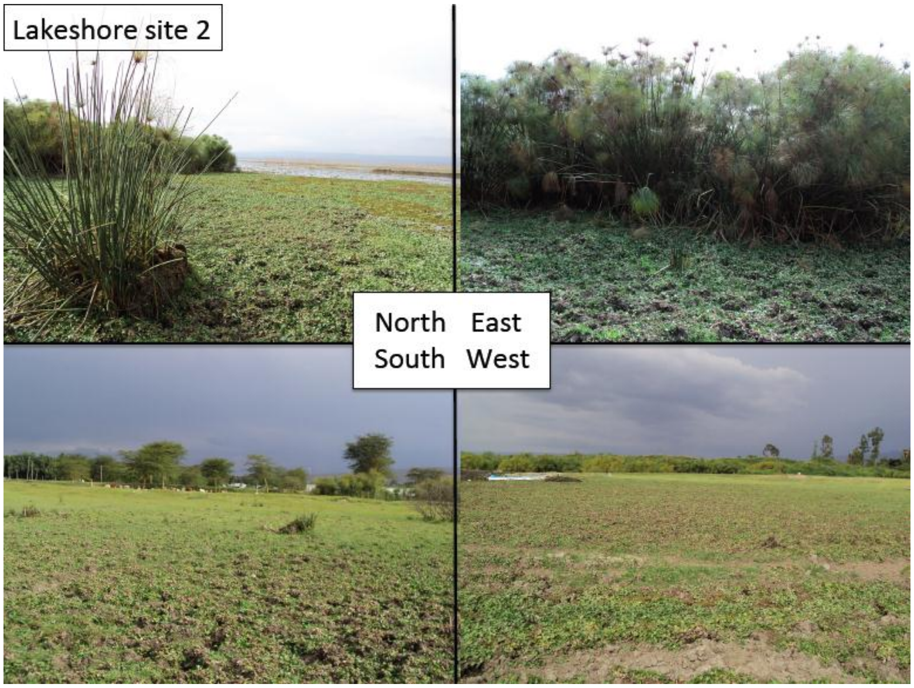
North East
South West


Kamere
Image not available
North East
South West


Naivasha Town
North East
South West


Lakeshore site 1
North East
South West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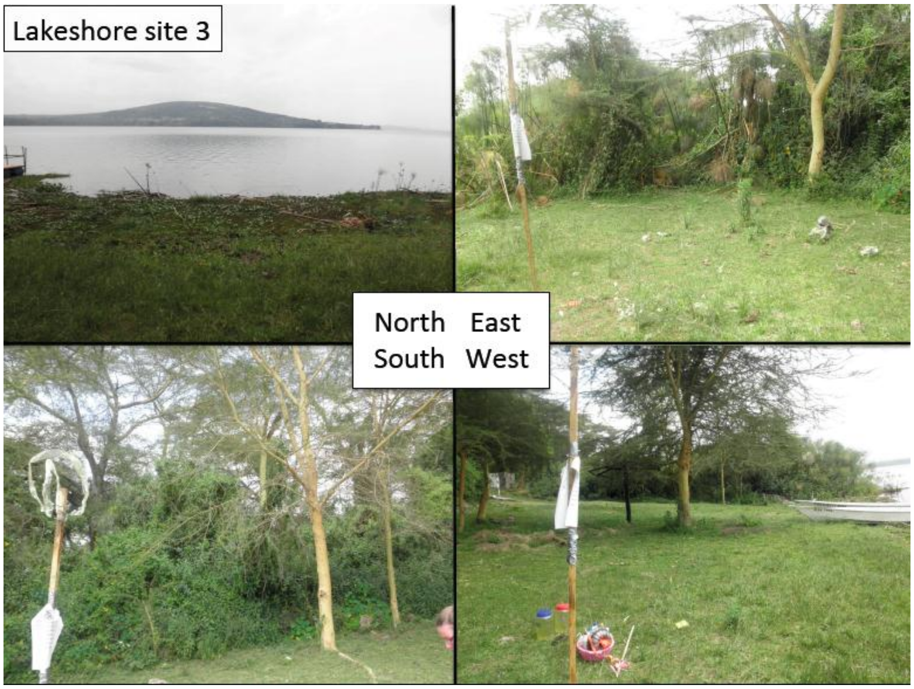
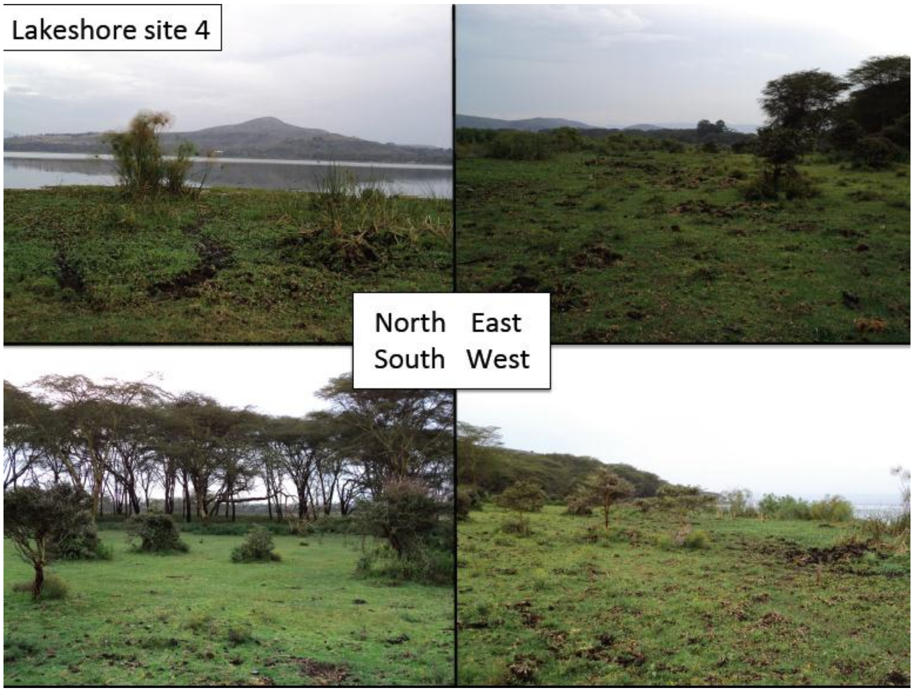
North East
South West


Lakeshore site 3
North East
South West


Lakeshore site 4
North East
South West

APPENDIX 2: Summarized data

Table A2.1: Rate of dust accumulation (g/day) and metal accumulation (µg/day) at various sites around the Lake Naivasha catchment. Dust accumulation values were multiplied by the concentration of metal at a given site to calculate exposure risk, as µg metal/day

Site name	Rate of dust settling (g/day)	Metal deposition (µg metal/day)		
		Ni	Cr	Pb
Maasai community	0.036	0.063	0.323	0.479
Salmon farm	0.005	0.113	0.632	0.212
Small scale farm	0.025	0.072	0.508	0.337
A1	0.010	0.300	0.335	0.374
A2	0.009	0.067	0.222	0.305
A3	0.007	0.174	1.776	0.183
Karagita	0.029	0.101	0.288	0.607
Kamere	0.102	0.190	0.548	1.179
Naivasha Town	0.011	0.192	0.568	0.315
LS1	0.067	0.643	1.598	0.718
LS2	0.009	0.102	0.247	0.195
LS3	0.008	0.073	0.828	0.278
LS4	0.007	0.103	0.597	0.284

Table A2.2: Concentration of metals (ppm dry weight) in dust from various sites around the Lake Naivasha catchment.
Maximum reporting limit: 0.5 ppm

Site name	Metal concentration in dust (ppm dry weight)		
	Ni	Cr	Pb
Maasai community	1.743	8.920	13.248
Salmon farm	21.036	118.112	39.571
Small scale agriculture	2.930	20.615	13.652
A1	30.027	33.518	37.381
A2	7.271	23.905	32.878
A3	26.810	273.175	28.152
Karagita	3.519	9.994	21.084
Kamere	1.858	5.347	11.511
Naivasha Town	17.158	50.733	28.152
LS1	9.652	23.973	10.764
LS2	11.260	27.318	21.528
LS3	9.372	105.804	35.586
LS4	14.477	83.625	39.744

Table A2.3: Concentration of various metals in the surface soil at the 13 sites where dust was collected around the Lake Naivasha catchment.
Maximum reporting limits: 0.01 ppm for all metals except As, Mo and Cr where MRL=0.1 ppm

	Metal (ppm dry weight)								
Site name	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu
Maasai community	5412	0.06	3.43	7.91	1.06	4121	2.21	1.67	0.64	3.44
Salmon farm	46615	< 0.1	< 0.01	203.3	4.74	3948	17.05	28.8	95.9	11.09
Small scale agriculture	18232	0.61	0.90	20.64	2.72	3385	3.34	3.33	6.77	< 0.01
A1	23805	1.29	3.95	56.46	4.47	5492	6.25	5.46	4.72	0.44
A2	16864	2.75	2.55	34.91	3.64	3210	4.90	4.62	3.83	< 0.01
A3	15844	0.83	6.54	48.37	2.38	10773	3.21	3.95	3.77	1.66
Karagita	17885	1.01	1.12	40.69	2.65	10650	3.83	3.89	3.68	< 0.01
Kamere	10298	0.36	2.66	14.13	1.93	6071	3.12	2.03	5.13	0.64
Naivasha Town	11892	< 0.1	1.00	19.42	2.19	2830	4.60	3.64	2.26	< 0.01
LS1	30132	< 0.1	3.15	80.01	4.13	10131	6.74	6.88	9.42	6.39
LS2	19087	< 0.1	4.12	59.05	2.71	7401	3.61	3.51	3.75	1.78
LS3	12002	< 0.1	3.58	39.67	1.80	6387	2.45	2.88	2.42	0.02
LS4	16908	< 0.1	0.93	65.63	2.24	4488	2.95	3.22	2.97	< 0.01

Table A2.3 cont'd: Concentration of various metals in the surface soil at 13 sites where dust was collected around the Lake Naivasha catchment.
Maximum reporting limits: 0.01 ppm for all metals except As, Mo and Cr where MRL=0.1 ppm

	Metal (ppm dry weight)									
Site name	Fe	Hg	K	Li	Mg	Mn	Mo	Na	Ni	P
Maasai community	11554	0.08	9329	7.95	743	364	0.34	481	0.24	424
Salmon farm	87727	2.21	6373	11.02	1519	1368	< 0.1	64	35.1	734
Small scale agriculture	20060	0.32	8546	8.55	1503	218	< 0.1	283	3.46	188
A1	32113	0.25	26545	15.99	2586	1225	0.62	177	4.78	427
A2	26920	0.40	17636	9.71	1541	808	0.35	483	3.27	326
A3	17439	0.42	21192	14.46	2631	390	< 0.1	529	3.44	542
Karagita	22513	0.04	19343	12.38	2045	553	< 0.1	790	1.92	362
Kamere	16646	0.21	18775	9.83	1114	485	< 0.1	4849	0.82	318
Naivasha Town	24199	0.38	13522	8.96	1181	663	< 0.1	420	1.40	184
LS1	33967	0.38	31141	25.45	4381	421	< 0.1	402	7.82	433
LS2	19886	0.44	19843	11.07	2420	447	< 0.1	1222	3.17	563
LS3	13769	0.35	9700	7.59	1911	252	< 0.1	298	2.59	606
LS4	17659	0.07	13682	8.71	1671	311	< 0.1	294	2.07	373

Table A2.3 cont'd: Concentration of various metals in the surface soil at 13 sites where dust was collected around the Lake Naivasha catchment.
Maximum reporting limits: 0.01 ppm for all metals except As, Mo and Cr where MRL=0.1 ppm

	Metal (ppm dry weight)									
Site name	Pb	S	Sb	Si	Sn	Sr	Ti	Tl	V	Zn
Maasai community	8.31	74.4	< 0.01	132	0.47	10.26	555	< 0.01	1.51	57.68
Salmon farm	37.48	117.5	< 0.01	832	4.81	43.71	3621	0.30	110.5	82.46
Small scale agriculture	16.82	52.6	< 0.01	2659	1.52	19.58	1036	< 0.01	9.31	47.35
A1	19.41	83.2	< 0.01	902	3.51	25.03	1206	2.90	10.09	80.94
A2	23.37	64.3	< 0.01	1035	3.24	24.63	1216	< 0.01	9.02	79.88
A3	11.44	88.3	< 0.01	540	0.76	69.46	950	< 0.01	9.07	58.60
Karagita	13.99	82.4	< 0.01	2064	0.27	35.17	1160	< 0.01	6.21	70.66
Kamere	12.00	222.6	< 0.01	276	1.49	18.66	566	< 0.01	2.52	80.91
Naivasha Town	10.35	30.6	< 0.01	999	1.65	12.31	1079	0.38	5.69	71.06
LS1	16.27	89.2	< 0.01	447	3.35	71.85	999	< 0.01	22.09	79.70
LS2	16.03	282.8	< 0.01	1542	1.37	54.52	882	< 0.01	9.02	85.15
LS3	13.78	163.0	0.04	1398	1.48	42.62	726	< 0.01	5.60	57.06
LS4	14.55	168.9	0.13	3385	0.75	34.09	952	< 0.01	6.79	61.25

Table A2.4: Concentration of persistent organic pollutants in *C. carpio* from 6 sites on Lake Naivasha. The following POPs were analyzed for, but were below detection limits for every site: α-BHC, γ-BHC, heptachlor, aldrin, heptachlor epoxide, γ-chlordane, α-chlordane, endrin ketone, methoxychlor, total PCBs. Maximum reporting limit: 0.001 for organochlorines, 0.04 for PCB congeners

Fish ID	Persistent organic pollutant concentration (ppm wet weight)						
	β-BHC	δ-BHC	Endosulfan I	Endosulfan II	Endosulfan sulfate	Dieldrin	Endrin
NTS 1	ND	0.006	ND	ND	0.008	0.001	ND
NTS 2	ND	ND	ND	ND	0.009	0.002	ND
NTS 3	ND	ND	ND	ND	0.005	0.001	ND
NTS 4	0.001	ND	ND	ND	0.005	0.001	ND
MM 1	0.002	0.004	ND	ND	0.014	0.001	ND
MM 2	0.001	0.004	ND	ND	0.014	ND	ND
MM 3	ND	0.002	ND	ND	0.014	0.002	ND
MM 4	ND	ND	ND	ND	0.003	ND	ND
HP 1	ND	ND	ND	ND	0.023	0.003	ND
HP 2	ND	ND	ND	ND	0.009	ND	ND
HP 3	ND	ND	ND	ND	0.022	0.002	ND
HP 4	ND	ND	ND	0.001	0.034	ND	0.002
SHER 1	ND	ND	ND	0.003	0.059	ND	ND
SHER 2	ND	ND	ND	0.003	0.05	ND	0.004
SHER 3	ND	ND	0.004	0.007	ND	0.004	0.018
SHER 4	ND	ND	ND	0.003	0.074	ND	0.004
KWS 1	ND	ND	0.003	ND	ND	ND	0.011
KWS 2	ND	ND	ND	ND	ND	ND	0.002
KWS 3	ND	ND	ND	0.003	ND	ND	ND
KWS 4	ND	ND	ND	0.003	0.032	ND	0.008
Nini 1	ND	ND	ND	0.001	0.025	ND	0.002
Nini 2	ND	ND	ND	0.002	0.04	0.002	0.003
Nini 3	ND	ND	ND	0.002	0.019	ND	0.004
Nini 4	ND	ND	ND	0.001	0.023	ND	0.002

Table A2.4 cont'd: Concentration of persistent organic pollutants in *C. carpio* from 6 sites on Lake Naivasha.

Maximum reporting limit: 0.001 for organochlorines, 0.04 for PCB congeners

Fish ID	Persistent organic pollutant concentration (ppm wet weight)					
	Endrin aldehyde	4,4-DDT	4,4'-DDE	4,4'-DDD	Total POPs	Total DDTs
NTS 1	ND	ND	ND	ND	0.015	ND
NTS 2	ND	ND	ND	ND	0.011	ND
NTS 3	ND	ND	ND	ND	0.006	ND
NTS 4	ND	ND	ND	ND	0.007	ND
MM 1	ND	ND	ND	ND	0.021	ND
MM 2	ND	ND	ND	ND	0.019	ND
MM 3	0.002	0.007	ND	ND	0.027	0.0070
MM 4	ND	ND	ND	ND	0.003	ND
HP 1	ND	0.003	ND	ND	0.029	0.0030
HP 2	ND	ND	ND	ND	0.009	ND
HP 3	ND	ND	ND	ND	0.024	ND
HP 4	0.002	ND	0.002	0.001	0.042	0.0030
SHER 1	0.013	ND	0.002	0.002	0.079	0.0040
SHER 2	0.01	ND	0.003	0.002	0.072	0.0050
SHER 3	0.022	ND	0.004	0.005	0.064	0.0090
SHER 4	0.016	ND	0.003	0.003	0.103	0.0060
KWS 1	0.043	0.009	0.006	0.005	0.077	0.0200
KWS 2	0.019	0.008	0.003	0.005	0.037	0.0160
KWS 3	0.018	0.003	0.002	0.003	0.029	0.0080
KWS 4	0.021	0.003	0.003	0.003	0.073	0.0090
Nini 1	0.001	0.003	0.002	0.001	0.035	0.0060
Nini 2	0.005	ND	0.001	ND	0.053	0.0010
Nini 3	0.011	0.002	0.002	0.001	0.041	0.0050
Nini 4	0.003	ND	ND	ND	0.029	ND

Table A2.5: Concentration of metals found in *C. carpio* from 6 sites on Lake Naivasha (4 fish per site). The following metals were also analyzed for, but were below detection limits for every site: Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Li, Mn, Mo, Na, Ni, Pb, Ti, Tl, V. Maximum reporting limit: 0.0005 for Hg, 0.5 for all other elements

Fish ID	Metal concentration (ppm wet weight)					
	Ca	Fe	Hg	K	Mg	P
NTS 1	238	< 0.5	0.200	3760	295	1980
NTS 2	152	2.54	0.0393	3480	311	1810
NTS 3	162	2.04	0.0196	3440	287	1830
NTS 4	183	4.17	0.0225	3490	274	1860
MM 1	144	0.82	0.00257	3520	286	1790
MM 2	158	2.91	0.281	3630	273	1900
MM 3	204	ND	0.00168	3400	289	1880
MM 4	267	0.93	0.00775	3570	290	1960
HP 1	175	1.54	0.0330	3530	291	1870
HP 2	108	1.76	0.180	3190	277	1770
HP 3	196	6.60	0.0105	3230	250	1630
HP 4	120	6.52	0.00140	3000	228	1700
SHER 1	331	5.34	<0.0005	3570	268	1930
SHER 2	175	6.74	0.0960	3530	259	1860
SHER 3	177	6.62	0.00541	3510	270	1910
SHER 4	704	5.49	0.0863	3580	288	2250
KWS 1	154	3.71	0.0245	3700	289	1980
KWS 2	146	2.52	0.0236	3800	275	1930
KWS 3	137	2.43	0.598	3440	318	1770
KWS 4	182	0.28	0.263	3430	236	1770
Nini 1	141	1.46	0.0577	3520	309	1870
Nini 2	115	2.59	0.111	3470	246	1770
Nini 3	98.8	0.78	0.546	3070	244	1570
Nini 4	160	2.27	0.101	3400	288	1810

Table A2.5 cont'd: Concentration of metals found in *C. carpio* from 6 sites on Lake Naivasha (4 fish per site). The following metals were also analyzed for, but were below detection limits for every site: Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Li, Mn, Mo, Na, Ni, Pb, Ti, Tl, V.

Maximum reporting limit: 0.0005 for Hg, 0.5 for all other elements

Fish ID	Metal concentration (ppm wet weight)						
	S	Sb	Se	Si	Sn	Sr	Zn
NTS 1	2110	ND	ND	13.23	ND	ND	14.8
NTS 2	1980	ND	0.7	3.20	0.7	ND	14.5
NTS 3	1960	ND	ND	4.44	ND	ND	16.3
NTS 4	1970	ND	0.5	4.51	ND	ND	8.89
MM 1	2020	0.5	0.9	0.43	3.03	ND	6.80
MM 2	1950	ND	0.5	0.60	1.3	ND	6.84
MM 3	2080	ND	ND	0.29	ND	0.52	5.70
MM 4	2010	ND	ND	1.27	ND	0.57	9.92
HP 1	1990	ND	0.54	1.20	ND	ND	9.73
HP 2	1920	ND	< 0.5	0.95	ND	ND	22.3
HP 3	1600	ND	< 0.5	7.49	ND	0.61	3.80
HP 4	1680	ND	0.68	2.73	ND	ND	11.0
SHER 1	1730	ND	0.52	2.27	ND	1.02	18.8
SHER 2	1760	ND	< 0.5	2.38	ND	ND	9.00
SHER 3	1930	ND	0.52	2.72	ND	ND	8.36
SHER 4	1910	ND	< 0.5	2.50	ND	2.51	12.1
KWS 1	2000	ND	ND	3.84	ND	ND	11.8
KWS 2	1910	ND	ND	3.13	ND	ND	14.8
KWS 3	2000	ND	ND	3.17	ND	ND	9.44
KWS 4	1520	ND	ND	3.06	ND	ND	4.77
Nini 1	2000	ND	ND	0.62	ND	ND	10.1
Nini 2	1770	ND	ND	< 0.5	ND	ND	13.8
Nini 3	1860	ND	ND	ND	ND	ND	16.8
Nini 4	1900	ND	ND	ND	ND	ND	8.71

Table A2.6: Concentration of metals found in oligochaetes from various sites on Lake Naivasha. The following metals were also analyzed for, but were below detection limits for every site: As, B, Be, Cd, Co, Cr, Cu, Hg, Li, Mo, Na, Ni, Pb, Sb, Se, Sn, Tl, V. Maximum reporting limit: 0.0005 for Hg, 0.5 for all other elements

Site	Metal concentration (ppm wet weight)					
	Al	Ba	Ca	Fe	K	Mg
Hippo Point	13.7	2.55	371	297	1190	118
N1884	86.1	1.62	264	204	865	93
N1883	31.7	2.27	370	262	1070	118
N1882	27.9	4.28	282	206	1300	125
NE1884	113	1.90	315	308	1010	132
NE1883	28.4	1.77	307	264	992	103
NE1882	30.1	2.81	299	279	1070	103
E1885	70.8	3.14	382	286	1110	125
E1884	49.1	1.84	315	247	957	110
E1883	14.6	1.17	279	214	885	87.8
E1882	30.6	2.76	298	279	1040	101
SE1885	29.3	1.79	304	278	966	103
SE1884	22.0	2.08	310	267	1120	113
SE1883	34.1	3.47	264	295	1040	112
SE1882	22.5	2.64	247	264	1010	105
S1885	87.5	2.21	413	353	1050	128
S1884	29.5	2.39	325	305	1220	125
S1883	86.1	2.06	356	373	1180	128
S1882A	25.1	2.85	345	276	1110	113
S1882B	5.49	1.53	251	205	1010	98.2

Table A2.6 cont'd: Concentration of metals found in oligochaetes from various sites on Lake Naivasha. The following metals were also analyzed for, but were below detection limits for every site: As, B, Be, Cd, Co, Cr, Cu, Hg, Li, Mo, Na, Ni, Pb, Sb, Se, Sn, Tl, V. Maximum reporting limit: 0.0005 for Hg, 0.5 for all other elements

Site	Metal concentration (ppm wet weight)						
	Mn	P	S	Si	Sr	Ti	Zn
Hippo Point	6.94	1240	931	41.9	4.98	0.74	8.38
N1884	8.78	860	653	108	2.53	5.57	4.55
N1883	14.4	1150	933	78.6	4.66	1.52	11.3
N1882	6.64	1220	944	76.4	3.52	1.19	8.53
NE1884	15.5	1130	830	120.0	4.55	6.28	6.34
NE1883	11.3	1050	838	56.8	4.28	1.50	5.75
NE1882	8.25	1100	826	49.9	4.53	1.55	10.2
E1885	9.94	1150	906	56.5	5.31	3.88	11.7
E1884	9.05	1020	815	71.9	4.45	2.50	8.34
E1883	5.56	939	708	39.6	3.96	0.76	5.35
E1882	5.80	1080	809	51.7	4.24	1.69	10.6
SE1885	10.6	1020	753	58.4	4.18	1.54	9.87
SE1884	11.2	1100	869	42.2	4.36	0.99	9.16
SE1883	11.6	1130	850	64.2	4.63	1.58	7.76
SE1882	9.49	1080	831	53.8	4.52	0.85	6.37
S1885	22.9	1110	929	64.5	6.30	3.80	12.4
S1884	11.8	1190	966	53.8	5.05	1.19	10.3
S1883	14.5	1180	994	136	4.95	3.77	3.09
S1882A	8.0	1140	940	46.5	5.19	1.29	8.08
S1882B	6.2	953	788	27.6	3.60	< 0.5	6.49

Table A2.7: Concentration of persistent organic pollutants found in oligochaetes from various sites on Lake Naivasha. The following POPs were also analyzed for, but were below detection limits for every site:
Maximum reporting limit: 0.001 for organochlorines, 0.04 for PBC congeners

	POP concentration (ppm wet weight)				
	North	North East	East	South East	South
α-BHC	< 0.005	< 0.005	< 0.005	ND	ND
β-BHC	< 0.005	< 0.005	< 0.005	0.01	ND
γ-BHC (Lindane)	< 0.005	< 0.005	< 0.005	ND	ND
δ-BHC	< 0.005	< 0.005	< 0.005	ND	ND
Heptachlor	< 0.005	< 0.005	< 0.005	0.007	ND
Aldrin	< 0.005	< 0.005	< 0.005	< 0.005	ND
Heptachlor epoxide	< 0.005	< 0.005	< 0.005	< 0.005	0.007
γ-Chlordane	ND	ND	ND	ND	ND
Endosulfan I	< 0.005	< 0.005	< 0.005	< 0.005	ND
α-Chlordane	< 0.005	< 0.005	< 0.005	< 0.005	ND
Dieldrin	< 0.005	< 0.005	0.02	< 0.005	ND
4,4'-DDE	< 0.005	< 0.005	< 0.005	< 0.005	ND
Endrin	< 0.005	< 0.005	< 0.005	< 0.005	0.006
Endosulfan II	< 0.005	< 0.005	< 0.005	< 0.005	ND
4,4'-DDD	< 0.005	< 0.005	< 0.005	< 0.005	ND
Endrin aldehyde	< 0.005	< 0.005	< 0.005	< 0.03	ND
Endosulfan sulfate	< 0.005	< 0.005	< 0.005	< 0.03	< 0.005
4,4-DDT	< 0.005	< 0.005	< 0.005	< 0.03	< 0.005
Endrin Ketone	< 0.005	< 0.005	< 0.005	< 0.03	< 0.005
Methoxychor	< 0.005	< 0.005	< 0.005	< 0.03	< 0.005
Total PCBs as Aroclors	ND	ND	ND	ND	ND

Table A2.8: Concentration metals found in sediment in various sites on Lake Naivasha. The following metals were also analyzed for, but were below detection limits for every site: Ag, Sb, Se.
Maximum reporting limits: 0.01 ppm

Sample	Metal concentration (ppm dry weight)									
	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu
Hippo Point	26573	0.99	5.37	78.4	4.48	7655	4.52	6.87	10.17	2.94
N1884	23298	0.80	4.10	88.7	4.66	5439	4.74	9.33	11.21	2.64
N1883	25650	0.74	4.75	94.5	4.74	7259	4.78	9.33	11.14	1.40
N1882	24328	0.46	3.80	75.0	4.12	7357	4.41	6.32	9.76	3.01
NE1884	24671	1.30	3.03	99.7	5.74	7574	3.95	8.56	10.17	2.90
NE1883	23145	0.86	2.79	116.0	4.69	6440	4.83	9.56	9.94	< 0.01
NE1882	28525	< 0.01	3.84	86.9	4.71	7047	5.06	7.70	11.04	2.30
ESHORE	5276	0.22	0.87	28.1	0.90	1781	1.01	1.62	0.79	< 0.01
E1885	18357	< 0.01	3.86	69.8	3.00	6685	2.80	4.39	5.36	0.38
E1884	20601	0.99	4.00	87.2	3.56	6049	3.56	5.03	6.91	3.47
E1883	27081	0.54	4.82	86.9	4.44	8086	4.69	6.95	9.61	1.70
E1882	30710	< 0.01	4.78	81.5	4.95	6499	5.27	7.29	11.52	2.67
SE1885	25670	0.37	4.18	80.4	4.25	7564	4.53	6.11	8.92	2.92
SE1884	28397	< 0.01	4.63	83.6	4.46	6534	4.96	6.32	9.84	3.21
SE1883	24809	0.44	3.68	76.1	4.24	6289	4.33	6.07	9.30	2.60
SE1882	28679	0.95	4.28	79.8	4.76	7378	5.03	6.81	10.89	3.39
S1885	17605	0.76	3.85	70.1	3.67	6872	3.34	4.48	5.58	1.67
S1884	25903	0.33	3.44	81.9	4.51	7133	4.52	6.03	9.17	3.41
S1883	25469	0.76	3.59	78.8	4.32	6818	4.44	5.61	9.18	4.68
S1882 A	24972	0.65	3.85	77.5	4.51	6826	4.62	6.54	9.60	4.28
S1882 B	27731	0.69	2.53	76.5	4.54	7142	5.66	6.34	10.45	5.24

Table A2.8 cont'd: Concentration metals found in sediment in various sites on Lake Naivasha.

Maximum reporting limits: 0.01 ppm

Sample	Metal concentration (ppm dry weight)								
	Fe	Hg	K	Li	Mg	Mn	Mo	Na	Ni
Hippo Point	25663	0.84	19181	13.3	2485	763	ND	324	8.25
N1884	25662	0.37	17433	10.6	2405	880	ND	266	8.18
N1883	28705	1.00	19728	11.8	2650	1137	ND	223	8.21
N1882	24463	0.53	17957	12.1	2365	778	ND	279	7.60
NE1884	22711	1.04	20001	10.1	2709	1069	ND	270	9.08
NE1883	27767	0.82	19178	9.5	2466	1147	ND	244	7.43
NE1882	28968	0.57	20321	13.2	2669	886	ND	257	8.53
ESHORE	5258	0.14	5843	2.2	590	122	ND	243	0.48
E1885	17452	0.86	15888	7.4	2047	875	ND	315	4.49
E1884	19721	0.29	17365	10.4	2230	942	ND	280	6.01
E1883	27203	0.17	21235	11.8	2776	1093	ND	305	8.12
E1882	29985	1.05	21274	14.1	2830	860	ND	326	9.26
SE1885	26189	0.37	20538	12.5	2668	1101	ND	389	7.39
SE1884	27751	0.43	20538	14.5	2636	1248	ND	293	8.13
SE1883	25092	0.57	18676	11.2	2497	849	ND	233	7.70
SE1882	27747	0.68	20877	13.8	2743	868	ND	286	8.84
S1885	18741	0.53	15096	10.0	2085	1076	ND	435	4.88
S1884	25228	1.15	20068	13.0	2597	843	ND	353	7.56
S1883	23532	0.77	19821	14.5	2487	731	0.10	471	7.56
S1882 A	24746	0.40	19137	12.5	2527	797	0.06	358	7.93
S1882 B	25358	0.61	20434	15.1	2629	740	0.50	411	8.39

Table A2.8 cont'd: Concentration metals found in sediment in various sites on Lake Naivasha.

Maximum reporting limits: 0.01 ppm

Sample	Metal concentration (ppm dry weight)									
	P	Pb	S	Si	Sn	Sr	Ti	Tl	V	Zn
Hippo Point	724	21.1	221.7	909	1.79	51.6	1502	32.8	24.0	91.3
N1884	703	25.5	250.2	1294	0.99	58.5	1866	15.6	23.4	91.2
N1883	700	24.6	204.3	1339	0.41	60.4	1949	22.0	25.7	92.4
N1882	580	17.9	198.0	658	1.81	51.4	1237	16.6	22.7	76.4
NE1884	478	23.3	105.2	1826	1.49	72.3	1653	13.3	21.2	85.0
NE1883	601	22.1	130.1	2297	0.95	56.0	2000	20.3	24.6	85.3
NE1882	689	22.0	213.4	1016	1.70	53.1	1649	18.3	25.5	89.3
ESHORE	230	8.1	23.8	605	0.25	19.0	597	4.3	2.0	35.3
E1885	526	17.6	247.1	1381	< 0.01	51.4	1199	13.7	12.7	83.1
E1884	542	18.8	281.5	1478	1.13	49.3	1177	15.8	14.7	88.2
E1883	697	21.2	300.5	2339	0.58	56.0	1533	15.5	22.3	92.9
E1882	788	21.3	245.6	2501	1.88	50.4	1596	20.5	27.6	94.8
SE1885	705	19.0	278.8	1129	1.70	57.8	1300	21.1	20.6	87.7
SE1884	694	19.8	248.8	1359	2.53	50.8	1368	19.2	21.0	90.0
SE1883	680	19.4	245.8	748	1.72	49.3	1302	14.4	22.5	81.5
SE1882	720	21.3	242.7	2134	2.15	53.9	1460	15.2	25.2	90.4
S1885	536	19.3	263.6	1614	0.91	60.0	1060	13.1	13.0	75.3
S1884	682	19.6	277.4	2096	1.92	56.7	1234	19.4	22.2	88.0
S1883	603	19.4	267.1	1179	2.33	53.1	1110	15.1	22.1	83.2
S1882 A	659	21.0	320.9	520	2.03	56.6	1245	13.9	23.2	85.8
S1882 B	588	20.5	276.5	451	3.03	55.1	1203	16.8	23.7	87.3

Table A2.9: Concentrations of persistent organic pollutants in sediment from various locations on Lake Naivasha. Concentrations for the following POPs were also determined, but were below detection limits for every site: α-BHC, heptachlor, aldrin, heptachlor epoxide, γ-chlordane, α-chlordane, endosulfan I and II, endrin, endrin aldehyde, endrin ketone, 4,4'-DDD, total PCBs.

Maximum reporting limit: 0.001 for organochlorines, 0.04 for PBC congeners

Sites	Concentration of persistent organic pollutant (ppm dry weight)							
	β-BHC	γ-BHC	δ-BHC	Endosulfan sulfate	Dieldrin	4,4'-DDE	4,4-DDT	Total DDTs*
HP & S1882	0.006	0.003	0.001	0.002	ND	ND	ND	ND
N 1882 - 1884	ND	ND	ND	0.002	ND	0.002	ND	0.002
NE 1882 - 1884	0.005	ND	ND	ND	ND	ND	ND	ND
E 1882 - 1884	0.002	ND	ND	0.001	0.002	ND	0.002	0.002
SE 1882 - 1884	0.005	0.004	ND	0.002	ND	ND	ND	ND
S 1883 - 1884	0.003	0.002	ND	0.003	ND	ND	ND	ND

*Total DDTs is a value calculated from the sum of 4,4'-DDE, 4,4'-DDD and 4,4'-DDT.

Table A2.10: Physico-chemical data from all lake sites where sediment was collected.

				Pore water parameters			
Site	Lake depth (m)	Bulk density (g/m3)	Organic matter (%)	pH	ORP (mV)	Conductivity (μS/cm)	% of particles <63μm
Hippo Point	4.23672	87244.24	12.43	7.33	-123.00	304.33	37.05
N1884	1.524	124729.33	16.87	6.74	-72.33	263.33	32.75
N1883	2.62128	107657.18	21.53	6.94	-75.00	210.33	24.87
N1882	3.68808	92447.99	25.00	7.09	-77.00	231.67	26.29
NE1884	1.6764	456421.89	8.73	7.41	-140.67	233.50	29.24
NE1883	2.7432	221486.43	17.60	7.29	-151.00	282.00	63.61
NE1882	3.5052	114393.67	21.27	7.27	-131.67	275.00	24.39
Eshore	0.015	629421.73	1.47	7.49	-109.33	129.53	7.05
E1885	1.58496	128312.79	21.60	7.29	-119.00	276.33	38.95
E1884	1.85928	88837.97	17.13	7.33	-123.00	265.00	34.97
E1883	3.01752	82653.84	25.93	7.22	-112.00	292.67	18.30
E1882	3.56616	73785.74	19.80	7.25	-119.33	327.00	25.18
SE1886	1.3716	160881.48	23.67	6.83	-53.33	238.57	35.95
SE1885	2.1336	83642.67	25.27	7.03	-69.00	303.33	15.93
SE1884	2.37744	70615.20	38.27	7.21	-100.33	316.00	15.66
SE1883	2.98704	74554.83	24.27	7.28	-110.67	312.33	26.85
SE1882	3.6576	75888.97	23.87	7.23	-110.67	315.67	16.71
S1885	1.61544	127025.74	26.40	6.98	-60.33	393.33	14.64
S1884	2.71272	91223.72	24.27	7.10	-80.67	442.00	22.87
S1883	2.95656	82010.31	24.47	7.53	-80.33	221.77	15.53
S1882B	3.5052	80252.39	24.73	7.13	-85.67	329.17	17.63
S1882A	3.6576	78180.55	25.67	6.99	-75.33	415.00	14.67

APPENDIX 3: Correction factors applied to metal data from SGS

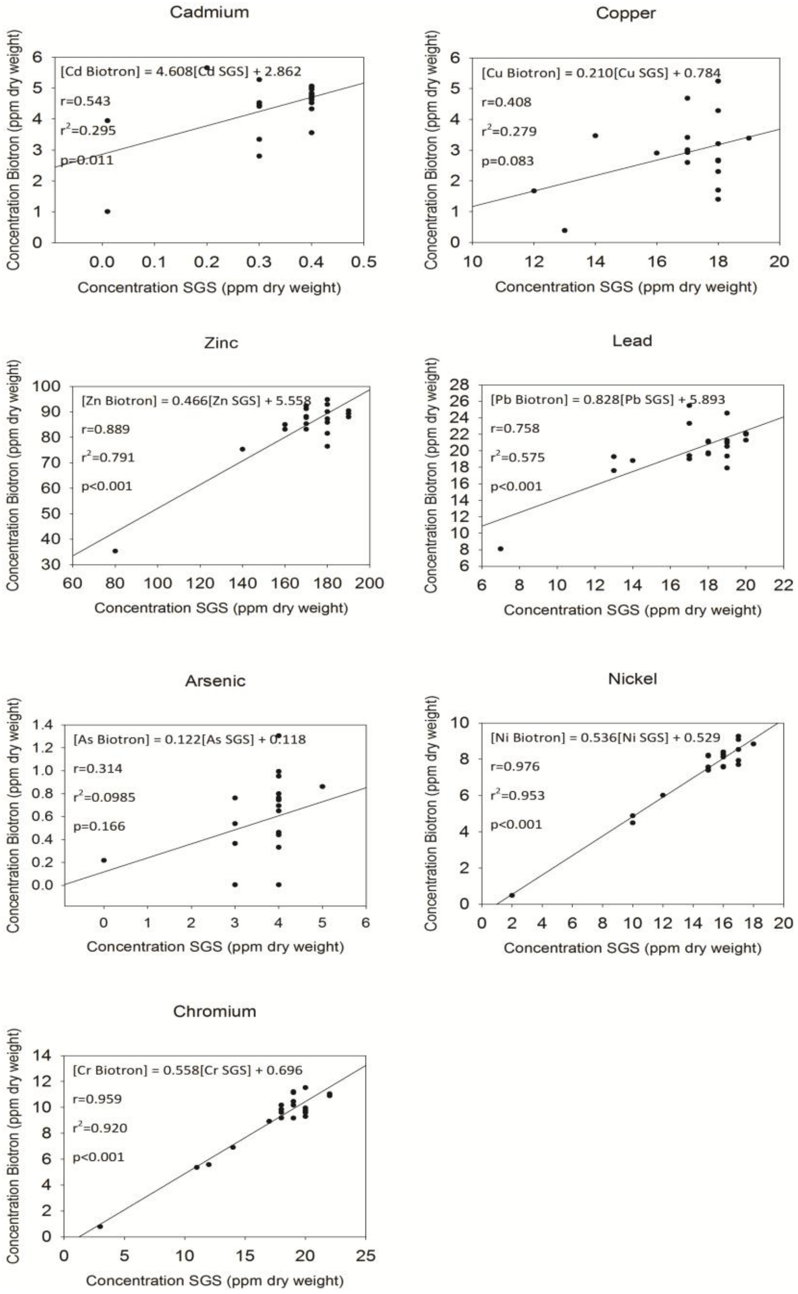


Figure A3.1: Regressions showing the linear correlation of metal data from the Biotron and SGS laboratories. The metals showing strong enough correlation for data conversion were Pb (r=0.758, p<0.001), Ni (r=0.976, p<0.001), and Cr (r=0.959, p<0.001). Zinc was not used, despite having a strong correlation (r=0.889, p<0.001), as an outlier drove its slope.

Chelsea Rae Hicks

CAREER SUMMARY

Experienced in teaching and interdisciplinary research and communication, with a diverse range of skills in:

- Oral and written communication
- University and school age teaching
- Team leadership
- Experimental design
- Fieldwork and laboratory analyses
- Literature review

EDUCATION

MSc in Biology w/ Environment and Sustainability September 2010 – Present
Western University, London, Ontario

- Studying the spatial distribution of human pollutants in Lake Naivasha, Kenya
- Providing new information to an Ecosystem Health research team, to develop a better understanding of the connection between human and environmental health
- Developing strong interdisciplinary communication skills through participation in several interdisciplinary courses and seminars
- Delivered guest lectures on aquatic ecology and on effective teaching strategies

Certificate in University Teaching and Learning September 2010 – Present
Western University, London, Ontario

- Participated in a series of skills based workshops for effective teaching
- Currently designing a novel course for teaching sustainability to the public

Honors BSc in Environmental Sciences and French September 2004 – 2010
University of Western Ontario, London, Ontario

- Developed a firm understanding of chemical and biological processes related to the environment
- Gained laboratory and field work experience
- Developed proficiency in French grammar and translation
- Participated in an exchange to France
- Achieved Dean’s Honor Roll every year

WORK EXPERIENCE

Teaching Assistant September 2010 – Present
Western University, London, Ontario

- Run tutorials to support the learning of material taught in class
- Supervise students conducting field based and lab based experiments
- Developed and implemented a series of team development activities to help increase the productivity of student project teams

Water Quality Research Assistant May 2009 – August 2010
Agriculture and Agri-Food Canada, London, Ontario

- Quantified fecal bacteria in environmental samples
- Conducted toxicity testing on bacteria found in environmental samples
- Proactively maintained laboratory stores of media and other consumables

Plant Pathology/Soil Microbiology Technical Assistant May 2008 – April 2009
Agriculture and Agri-Food Canada, London, Ontario

- Conducted field based research and laboratory analyses to determine the efficacy of novel bio-control and bio-fertilizer technology
- Spearheaded the initiation of bi-weekly lab meetings to increase staff communication
- Showcased a novel technology to thousands of visitors at the Royal Agricultural Winter Fair

Server August 2006 – January 2010
The Alibi Roadhouse Inc., London, Ontario

Water Park Manager February 2005 – October 2006
Wally World at East Park, London, Ontario

- Designed a detailed training manual, used as a training aid for over 60 lifeguards
- Provided daily support for staff and took charge in emergency situations
- Performed semi-annual staff evaluations
- Tested and regulated pool chemicals and ensured consistent conformance with government standards

VOLUNTEER EXPERIENCE

Conference Organizing Committee September 2011 – Present
Earth Day Colloquium, Western University, London, Ontario

Facilitator for hands-on science activities September 2010 – Present
Let’s Talk Science, Western University Chapter, London, Ontario

Student Buddy September 2004 – Present
Best Buddies, Brescia Chapter, London, Ontario

Chapter Coordinator September 2005 – October 2006
Best Buddies, Brescia Chapter, London, Ontario

AWARDS AND SCHOLARSHIPS

Great Ideas For Teaching Award	2011 & 2012
Dean’s Honor Roll	2004 – 2010
Scholarship of Distinction	September 2004