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Potential effects of road proximity on zooplankton communities and water quality in lakes in the Northwest Territories

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POTENTIAL EFFECTS OF ROAD PROXIMITY ON ZOOPLANKTON COMMUNITIES AND WATER QUALITY IN LAKES IN THE NORTHWEST TERRITORIES

By

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Abstract

Studies conducted along Canada's Dempster Highway in the Northwest Territories have shown that road dust can affect water quality in roadside lakes, leading to higher calcium, conductivity, and pH levels. These water quality changes have the potential to affect important members of the lower aquatic food web, such as zooplankton.

For my thesis research, I had two main objectives: 1) To determine if changes in water chemistry caused by deposition of road dust affects zooplankton communities; and 2) To examine if the type of roadside vegetation influences the effects of road dust on aquatic habitats. To achieve these objectives, I collected biological and water quality data from 18 lakes along the Dempster and Inuvik-Tuktoyaktuk Highways in the Northwest Territories and measured the transport of dust from the highways to the surrounding landscape. I selected my study lakes using a stratified random sampling design, with distance from the road (0-300 m, 300-600 m, and > 600 m) and region of study (boreal forest, tundra) as the two factors. Transportation of dust was measured using funnel traps placed in transects from the highways. I hypothesized that zooplankton communities in lakes near the road would show significant differences in community structure, and that dense boreal forest vegetation would provide a better roadside buffer than tundra shrubs, limiting the impacts of road dust to shorter distances in the boreal forest region.

My dust measurements indicated that the majority of dust fell within 300 m from the highway, and that dust moved furthest in the tundra. However, there were no clear differences in water quality or zooplankton communities among lakes based on distance from the highway. In addition, while there were differences in communities between regions, these did not appear

to be related to the effects of the road. The lack of clear water quality differences related to the effects of road dust are contrary to results from other studies in the region. I speculate that the small sample size for my study combined with natural variability, may have masked the effects of road dust pollution. While my results suggest that gravel roads may have less of an impact on lakes than predicted, further studies with larger sample sizes and more powerful study designs are needed to better understand the issue.

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Chapter 1: Introduction

Potential effects of road proximity on zooplankton communities and water quality in lakes in the Northwest Territories

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1.1 Development in Canada's Arctic

Climate change and an increase in infrastructure development have been notable across Canada's Arctic in recent decades (Chen *et al.*, 2017). While climate change is the most geographically extensive and potentially harmful anthropogenic impact at present, resource extraction and the development of infrastructure in the north are also posing a serious challenge to Arctic biodiversity (Wrona *et al.*, 2016). In Canada's Northwest Territories, the development of new transportation infrastructure is expected to be driven by a growing population and a changing climate that may make natural resources more accessible (Government of Northwest Territories, 2017). Currently, the Dempster Highway and the Inuvik-Tuktoyaktuk Highway (ITH) are the two major gravel highways located in the northern half of the Northwest Territories. The Dempster highway, spanning from Dawson City, Yukon to Inuvik, Northwest Territories is 737 km long and officially opened in 1979, while the Inuvik-Tuktoyaktuk Highway running from Inuvik to Tuktoyaktuk is 138 km long and opened in 2017 (Government of Northwest Territories, 2017). The construction of a new highway connecting Wrigley to Norman Wells has also been planned (Government of Northwest Territories, 2019) . These highways transect delicate Arctic ecosystems underlain with permafrost and landscapes dotted with thousands of interconnected lakes and streams. The construction, maintenance, and operation of these highways likely cause significant changes to the surrounding environment, but the effects of gravel roadways are understudied, especially for aquatic ecosystems. The potential problems associated with dust contamination into nearby lakes, from the gravel road will be the focus for my thesis.

Roads are one of the most widespread forms of modification of the natural landscape (Trombulak & Frissell, 2000). During the initial construction of roadways, changes in the local environment are caused by the removal of vegetation and addition of culverts for stream and river crossings (Gill *et al.*, 2014). These actions modify the local hydrology, increasing soil erosion, temperature of run-off, soil water content, light levels, dust, metals, salts, and nutrient inputs to roadside ecosystems (Auerbach, Walker & Walker, 1997; Trombulak & Frissell, 2000; Gill *et al.*, 2014). Additionally, the development of roads can create a deeper active layer above permafrost and alter characteristics of the snowpack (Auerbach *et al.*, 1997). Once a road is built, road dust, run-off, trash, and vehicle pollution continue to affect the local area (Gill *et al.*, 2014). In the Arctic, permafrost complicates the planning, construction, and use of roads (Auerbach *et al.*, 1997). To minimize permafrost degradation, gravel roads are often built using the fill technique, which involves layering building materials over the existing ground, instead of digging trenches (Auerbach *et al.*, 1997; Government of Northwest Territories, 2017). The road is composed of a raised gravel bed, up to 1.5 m in thickness to minimize seasonal thaw penetration (Auerbach *et al.*, 1997). However, heavy traffic on these roads introduces severe, chronic dust deposition to surrounding ecosystems (Auerbach *et al.*, 1997; Chen *et al.*, 2017).

Studies have found that road dust contamination has caused changes in the abundance and diversity of local terrestrial and aquatic organisms living along roadways (Trombulak & Frissell, 2000; Gill *et al.*, 2014; Ste-Marie, Turney & Buddle, 2018). Terrestrial habitats next to the road tend to have higher soil pH, higher bulk density, lower soil moisture, altered snowpack, and deeper active-layer thaw at both sites due to the impact of dust (Auerbach *et al.*, 1997). These physical changes in the environment have been shown to cascade to plant and invertebrate communities. For example, Myers-Smith et al. (2007) found a change in the biomass of vascular plants, lichens, and mosses, adjacent to the road. This change was likely due to dust loading on plant leaves and an increase in soil pH (Myers-Smith *et al.*, 2007). The changes in vegetation can lead to changes in invertebrate communities. For example, Ste-Marie at al. (2018) observed that there was a difference in the type of terrestrial invertebrates found near compared to away from the road. Flies (order Diptera) were most commonly found near the roadway while springtails (order Collembola) were more common further away (Ste-Marie *et al.*, 2018). A recent study suggests that road dust can even influence caribou migration, forage quality & growth (Chen *et al.*, 2017). Although the impact of dust contamination decreases with distance from the road (Chen *et al.*, 2017), the expected increase in road use and construction in the north makes it important to understand the extent of the impacts of road dust on sensitive Arctic ecosystems.

While studies show clear effects of road dust on terrestrial habitats in the Arctic, less is known about the effects of roads on aquatic ecosystems. Freshwater lakes are a prominent component of the northern landscape (Sweetman, Rühland & Smol, 2010) and dust deposition from gravel highways is likely to have a negative impact on these aquatic ecosystems (Gunter, 2017; Ste-Marie *et al.*, 2018). To date, studies on aquatic ecosystems have primarily considered changes in water chemistry. Dust from roads can serve as a source of fine sediments, nutrients and contaminants to aquatic systems (Trombulak & Frissell, 2000). Gunter (2017) conducted a study that looked at the impacts of road dust on aquatic ecosystems along the Dempster Highway in the Northwest Territories. They analyzed the elemental composition of the fine surface materials from the Dempster Highway and found that potassium (K^{+}), calcium (Ca^{2+}), titanium (Ti^{3+}), iron (Fe^{2+}), strontium (Sr^{2+}), and terbium (Tb^{2+}) were the most abundant components of her samples (Gunter, 2017) . Gunter (2017) also looked at patterns in lake water chemistry in relation to proximity to the road and found that lakes within 1 km of the road had higher conductivity, pH, calcium, and magnesium content than those further away (Gunter, 2017). These changes in water chemistry are likely to influence the structure of invertebrate communities, but surprisingly no studies have been conducted to determine how these important members of aquatic food webs respond to road dust contamination of their habitat.

1.1 Lake invertebrate communities

Invertebrate communities inhabit both the lake bottom and open waters in lakes, playing an important role in freshwater food webs, transferring energy from primary producers (phytoplankton) to fish. Invertebrates living on the lake bottom are referred to as benthic invertebrates, while those swimming or drifting in the open waters are called zooplankton. While road dust contamination is likely to affect both benthic invertebrates and zooplankton, the work for my thesis will focus on zooplankton. Zooplankton communities represent an ideal study system for examining the impacts of environmental stressors on biological communities as they are abundant, diverse, easy to collect and play a vital role in aquatic ecosystems.

Zooplankton are heterotrophic, microscopic, multicellular organisms that play an important role in sustaining ecosystem services (Suthers & Rissik, 2009). Zooplankton are ubiquitous animals since they can be found in rivers, streams, lakes, reservoirs, ponds and wetlands (Suthers & Rissik, 2009). Some are termed holoplankton as they spend their entire life cycle in the water column while others, such as larval insects, only spend parts of their life cycle underwater (Suthers & Rissik, 2009). Many zooplankton are grazers in aquatic food webs, allowing for the transfer of energy from primary producers to larger organisms such as macroinvertebrates and fish (Ricci & Marie, 2000; Richardson, 2008; MacLeod, Keller & Paterson, 2018). Other zooplankton can be classified as filter-feeders or predators (Radwan, 1980; Suthers & Rissik, 2009). Zooplankton play an important role in recycling nutrients and energy back into the food web (Radwan, 1980). Due to their intermediate position in the food web, changes in zooplankton community composition may impact higher trophic levels (Loria, 2017; MacLeod *et al.*, 2018). They also play a role in regulating water clarity and standing stock of primary producers in freshwaters through top-down control of phytoplankton (Sommer & Sommer, 2006; Loria, 2017). Zooplankton themselves are often regulated by planktivorous fish species when fish communities are present (Luecke *et al.*, 1990).

Cladocerans (commonly known as water fleas) are a key group of organisms in many Arctic and subarctic lakes, occupying a variety of different habitats (Sweetman *et al.*, 2010). Most species are herbivorous filter-feeders with relatively short lifespans in comparison with copepods (Adamczuk, 2016). Those belonging to the genus *Daphnia* have shown to have an average lifespan of two months, reproducing every 2-3 days depending on temperature and average adult mass (Gillooly, 2000; Martinez-Jeronimo & Martinez-Jeronimo, 2007). In lake ecosystems, *Daphnia* are often the dominant herbivores while calanoid copepods act as primary grazers (Sommer, 2006). When conditions are favourable, cladocerans achieve their short generation times by parthenogenesis, allowing for asexual reproduction without male fertilization (LeBlanc, Taylor & Johannsson, 1997). Cladocerans are relatively tolerant to a variety of environmental conditions, allowing them to be widely distributed around the world, most often inhabiting freshwater habitats (Adamczuk, 2016).

Copepods are one of the most abundant multicellular organisms on earth and comprise approximately 95% of zooplankton abundance and biomass across all aquatic ecosystems (Richardson, 2008). Even though copepods are found in almost all freshwater habitats, the greatest diversity of copepod species is found in marine habitats (Boxshall & Defaye, 2008). These organisms have a wide range of lifestyles, from small particle feeder to predation and parasitism (Boxshall & Defaye, 2008). Most freshwater copepods are free-living and can easily be differentiated from other zooplankton due to their elongated thorax and segmented rear appendages (Boxshall & Defaye, 2008; Loria, 2017). Unlike cladocerans, copepods require both female and male individuals for sexual reproduction, producing eggs that hatch into a larval stage known as a nauplius (LeBlanc *et al.*, 1997).

Zooplankton community structure can be described in terms of the species present in a community, as well as the relative abundance of those species. There are several ways to summarize community structure, including univariate metrics, such as richness, diversity, and evenness. Species richness refers to the number of unique species present in a given community (Morris *et al.*, 2014). Rarefaction can be used to calculate values that reflect equal taxonomic/sampling effort for each lake (Hurlbert, 1971). Rarefaction accounts for differences in sampling effort by resampling abundance data for a particular site hundreds or thousands of times to determine the average number of species identified for a given number of individuals collected (Gotelli & Colwell, 2001). Species diversity considers both richness and the relative abundance or density of each species. A formula frequently used to calculate diversity is the Shannon-Wiener diversity index:

$$\mathrm{H}' = -\sum_{i=1}^{s} p_i ln p_i$$

where p_i represents the proportion of the entire population made up of species *i* and S represents the number of species encountered (Morris *et al.*, 2014). A diverse community would have a high richness and a uniform distribution in abundance for the species present. An even community has a uniform distribution of the abundance of species, whereas an uneven community will have one or a few species that dominate in abundance, while others are rare. To calculate evenness, Shannon diversity (H') is divided by the natural log of species richness. In addition to univariate metrics, there are multivariate statistical methods that allow for the visualization of differences among zooplankton communities such as Principal Component Analysis (PCA) and Nonmetric Multidimensional Scaling (NMDS). These methods produce plots (ordinations) that allow for a visual assessment of differences in the relative abundance of species in a community. Lakes that group out closer together in these plots tend to have similar assemblages of species (Morris *et al.*, 2014).

1.2 Zooplankton ecology and their response to stressors

Changes in abiotic conditions have the potential to alter the structure of zooplankton communities and cause shifts in species composition (Gannon & Stemberger, 1978; Bos *et al.*, 1996; Allen *et al.*, 1999; Swadling, Pienitz & Nogrady, 2000; Soto & De Los Rios, 2006; Dodson *et al.*, 2009; Gray & Arnott, 2009; MacLeod *et al.*, 2018). The structure of zooplankton communities is influenced by both local and regional processes (Swadling *et al.*, 2000). At a local scale, biotic and abiotic factors, including pH, ionic concentrations, productivity, and predatory-prey relationships can influence structure (Swadling *et al.*, 2000; Gray & Arnott, 2009; MacLeod *et al.*, 2018). On a regional scale, colonization and dispersal trends become important (Swadling *et al.*, 2000). Changes in abiotic and biotic factors driven by climate change and development have the potential to alter local and regional processes, thereby influencing the structure of zooplankton communities (Gray & Arnott, 2009). In northern regions, dispersal and environmental conditions already limit zooplankton diversity because of low productivity and extended periods of ice cover which allow for little movement of individuals among lakes (Swadling *et al.*, 2000).

Many variables have been identified as having an important influence on zooplankton structure and diversity, however these vary significantly among studies, and relatively few studies have been conducted on northern lakes (Aranguren-Riaño, Guisande & Ospina, 2011). A recent review by Gray et al. (2021) that considered lakes and ponds in all regions of the world, found that surface area, pH, phosphorus, nitrogen, dissolved oxygen, conductivity, chlorophyll, maximum depth and temperature were the variables most frequently correlated with zooplankton community structure. The limited number of northern studies available have identified some of the same variables. Sweetman et al. (2000), found that water temperature, dissolved organic carbon and nutrient levels significantly influenced the structure of cladoceran communities. Bos et al. (1996) found a strong relationship between the distribution of zooplankton taxa, conductivity, and ionic composition, with conductivity being the environmental variable most strongly correlated with species abundance. Swadling et al. (2000) found that zooplankton species distribution was greatly affected by the abiotic characteristics of a lake such as depth and surface area, as well as by chloride, silica, and temperature. Vucic et al. (2020) found that calcium and conductivity were both positively related with abundance, while pH was negatively affected. They also found that calcium, turbidity, and conductivity were negatively related to the diversity and evenness of communities (Vucic *et al.*, 2020). Many of the environmental variables described as important for structuring zooplankton communities in the studies summarized in this paragraph, such as conductivity and calcium, are among those influenced by road dust contamination (Gunter, 2017).

1.4 My thesis work

There are deficits in our knowledge of the ecology of many groups of organisms and monitoring in the Arctic is lagging far behind that in other regions of the world (Wrona *et al.*, 2016)**.** Fast changing environmental conditions, as well as increasing development, are bringing much needed attention to the Arctic. Understanding how sensitive northern ecosystems will react to these changes is crucial for adaptation and management efforts. Unfortunately, little is known regarding the impacts of roads on lake food webs, especially for members near the base of the food web such as invertebrates. When reviewing the published literature, there have been studies conducted that have examined how road dust can affect water chemistry, vegetation, and terrestrial animals, but aquatic organisms have been overlooked. The lack of research on impacts of dust loading on aquatic ecosystems limits the capacity for informed regulatory decisions regarding future development (Gunter, 2017).

My thesis research has two objectives outlined below. I also present the hypotheses associated with each objective below.

Objective 1: To determine if changes in water chemistry caused by deposition of road dust affects zooplankton communities. Based on reported changes in water quality characteristics associated with road dust pollution, I hypothesize that:

1) Road proximity will influence the community structure of zooplankton, with lakes closer to the road being most affected.

2) Higher calcium levels in roadside lakes will lead to increases in abundance of zooplankton that require high calcium levels, such as *Daphnia* (Vucic *et al.*, 2020).
3) Higher conductivity levels near the road will lead to increases in abundance but decreases in evenness and diversity (Vucic *et al.*, 2020).

Objective 2: To examine if the type of roadside vegetation influences the effects of road dust on aquatic habitats. Vegetation along streams and lakes plays an important role in preventing the spread of debris and disturbance from neighbouring land use, from entering the water; these strips of vegetation are known as riparian buffers. For example, Stutter et al. (2012) found that the presence of a buffer strip acted as a barrier to sediment, nutrients and pesticides that would otherwise end up in streams. Therefore, I hypothesize that:

1) Vegetation in the boreal forest region will act to limit the spread of dust away from the roadway. Therefore, dust will travel further from the highway in the treeless tundra region.
2) The effects of road dust on water quality and zooplankton will extend further from the roadway in the tundra than in the boreal forest.

Chapter 2: Materials & Methods

Potential effects of road proximity on zooplankton communities and water quality in lakes in the Northwest Territories

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2.1 Study location and site selection

The Gwich'in Settlement Area and Inuvialuit Settlement Region are located in the northern portion of Canada's Northwest Territories. Four communities are found within these settlement areas: Tuktoyaktuk, Aklavik, Inuvik and Fort McPherson (Figure 2.1). The Inuvialuit Settlement Region ranges from Tuktoyaktuk to Inuvik, where the Inuvik-Tuktoyaktuk Highway is found. The Gwich'in Settlement Area ranges from Inuvik to Fort McPherson where the most northern part of the Dempster Highway is located. For these remote communities, roads are essential. Before the Inuvik-Tuktoyaktuk Highway was completed, the only way to travel from Inuvik to Tuktoyaktuk during the summer months was by plane. The introduction of these highways has allowed for access to better healthcare and education, an increase in tourism, as well as access to remote areas for commercial vehicles and scientific research (Government of Northwest Territories, 2017, 2019).

My study included 18 lakes located along the Dempster and Inuvik-Tuktoyaktuk Highways (ITH) in the Northwest Territories (Figure 2.1). Lakes along both highways were sampled between July 30th and August 13th, 2021. Along the Dempster Highway, lakes were located in the Boreal Forest region dominated by coniferous trees, such as black spruce (*Picea mariana*), white spruce (*Picea glauca*) and jack pine (*Pinus banksiana*) (Sweetman *et al.*, 2010). In comparison, lakes along the ITH were located in the Tundra region dominated by sedges (*Carex spp*.), lichen-heath and various dwarf shrugs (Sweetman *et al.*, 2010).

The lakes selected for this study were randomly chosen using a stratified random sampling design with two different categorical variables: distance from road and region. The distance from road category was divided into three levels based on the proximity of the nearest shoreline of the lake to the road: 0-300 m, 300-600 m, or > 600 m. The categories were selected based on past studies that showed road dust had the strongest effects within 1 km from the road(Everett, 1980; Myers-Smith *et al.*, 2007; Chen *et al.*, 2017; Gunter, 2017). The region category refers to whether the lakes were located in the boreal forest or the tundra. To ensure that the lakes were randomly selected for inclusion in the study, I used Google Earth to number all lakes within 1 km of the highway in two sections: 1) Lakes in the boreal forest area along the Dempster Highway running between Tsiigehtchic and Fort McPherson between -134.6° and -133.5° longitude; 2) lakes in the tundra area along the ITH running between Inuvik and Tuktoyaktuk between 68.7°and 69.3° latitude. Next, I divided the lakes into three distance categories based on how far the closest shoreline was from the highway: 0-300 m, 300-600 m, and > 600 m. I then used the sample function in R to randomly choose nine numbers associated with the lakes I numbered in each region. In this way, I was able to randomly select nine lakes in the boreal forest region and nine in the tundra region, with three in each region at each distance category (0-300 m, 300-600 m, > 600 m). The random selection of lakes was done to prevent any bias in the selection of lakes that might occur if they were chosen for convenience or other considerations.

2.2 Field data collection

I used funnel traps to measure the movement of dust from the road to the surrounding landscape (Figure 2.2). I placed a funnel with a 160 mm diameter opening into the top of a 10 L plastic carbuoy. I added approximately 2 L of milli-Q water to each jug before deploying the funnel traps to provide weight and stability. I deployed the funnel traps in transects running out from the road in both the tundra and boreal forest for five days each. I placed the jugs at distances of 0 m, 150 m, 450 m and 750 m from the road. These distances represented halfway between our lake distance categories (0-300 m, 300-600 m & > 600 m). After collection, I filtered water from the traps through a 500 μm sieve to remove any insects or plant matter without removing dust particles. I then boiled each sample down to 1 L to ensure a consistent volume of liquid in all samples and to sterilize the sample so that biological sources of turbidity (e.g. bacterial blooms) were reduced. I measured turbidity and conductivity of the water from the dust traps using an Oakton T-100 turbidity meter and an Oakton CON150 conductivity meter, respectively. My measurements of turbidity and conductivity of the water allowed me to estimate the relative amount of dust that travelled to each funnel trap.

I collected data on lake surface area and distance of each lake from the road using the ruler function on Google Earth in preparation for fieldwork. I determined the maximum depth of each lake using a handheld depth finder (Speedtech Depthmate SM-5). I also collected water quality data including Secchi depth (water clarity), turbidity, conductivity, dissolved oxygen (DO), pH, dissolved nitrogen (DN), dissolved phosphorus (DP), dissolved organic carbon (DOC), calcium, chlorophyll-a, and water temperature. To obtain water clarity measurements, I lowered a Secchi dish over the shady side of the boat at the deepest point the lake. In the same region, I measured turbidity, conductivity, DO, pH, chlorophyll-a and temperature, using a Manta+ multiparameter probe (Eureka Water Probes) at a depth of 1 m. I also collected surface water samples to determine levels of DOC, DN, DP, calcium, and various other trace elements, at the same site. I filtered surface water samples through a 1.2 μm pore size glass fiber filter (Fisherbrand G4) and refrigerated them until they were sent off to TAIGA Laboratories in Yellowknife for analysis. I selected the aforementioned variables for measurement since they have been shown to be significantly correlated with zooplankton community structure in past studies (Gray *et al.*, 2021).

I collected zooplankton samples from each lake at the point of maximum depth and preserved them on site using 95% ethanol. For lakes greater than 3 m in depth, I collected zooplankton with a single vertical haul using a 35-cm diameter, 50 μm mesh size zooplankton net. For shallow lakes less than 3 m in depth, where a vertical tow was not possible, I collected zooplankton by performing oblique zooplankton tows with the same net by casting the zooplankton net out from the boat, allowing it to sink towards the bottom and then pulling the net toward the boat on an angle. I repeated oblique tows three times and pooled the resulting sample for preservation. In both cases, I used a mechanical flowmeter attached to the mouth of the net to determine the volume of water that passed through the net. Determining the volume of water passing through the net allowed me to calculate the density of zooplankton in each lake.

2.3 Laboratory work and analysis

In the laboratory, we identified crustacean zooplankton to the species level with the help of several keys, including Brooks (1959), Balcer et al. (1984), Witty (2004), and Haney (2013). Samples were examined under dissecting and compound microscopes at a magnification of 40x to 400x, depending on the size of the specimen. Three subsamples were taken from each sample, and a minimum of 100 individuals were counted and identified for each subsample, resulting in the identification of at least 300 individuals per lake. Copepod nauplii were excluded from all counts. During counts, the presence/absence of the phantom midge *Chaoborus americanus* was noted since their absence is often a good indicator that fish are present in the lake (Sweetman & Smol, 2006).

I calculated univariate measures of community structure to describe zooplankton communities, including Shannon diversity, rarefied richness, species evenness, and total abundance. To calculate Shannon diversity for each lake, I used the "diversity" function, found in the Vegan package (Oksanen *et al.*, 2019). I calculated species richness using rarefaction to obtain estimates that reflect equal taxonomic/sampling effort for each lake (Hurlbert, 1971). Rarefaction accounts for differences in sampling effort by resampling abundance data for a particular site thousands of times to determine the average number of species identified for a given number of individuals collected (Gotelli & Colwell, 2001). I conducted rarefaction using the rarefy function in the Vegan package for R (Oksanen *et al.*, 2019), which uses a formula from Hurlbert (1971). I calculated species evenness by dividing Shannon diversity by the log of the rarified species richness for each lake. Finally, I calculated species abundance by determining the sum of the density of all species of zooplankton present in each lake.

I examined correlations among water quality variables, lake physical characteristics, and univariate measures of zooplankton community structure using Spearman correlations. I also examined correlations among water quality variables, lake physical characteristics and specific zooplankton species. The Spearman correlation is a non-parametric technique that uses ranks to determine if there is a monotonic relationship between two variables (Daniel, 1990). I performed the correlation analysis using the rcorr function in the Hmisc package for R (Harrell & Dupont, 2019), and I used the corrplot function in the corrplot package to make the associated plot (Wei & Simko, 2017).

To visualize the movement of dust from roads to the surrounding landscape, I fit negative exponential functions to the turbidity and conductivity data obtained from the funnel traps used to measure dust loads:

$$Turbidity = Turbidity_0 \, e^{-r*distance}$$

$$Conductivity = Conductivity_0 \, e^{-r*distance}$$

In these equations, $Turbidity_0$ and $Conductivity_0$ are the turbidity and conductivity levels I found in the funnel traps closest to the road, *r* is the decay rate and *distance* refers to the distance the funnel traps were placed from the road. The functions were fit using the nls function in R.

I used data collected from my dust traps to estimate the potential change in turbidity and conductivity that could be caused by road dust transportation to adjacent lakes. I did this by considering the surface area and volume of my dust traps, along with the relationships I identified between conductivity and turbidity levels in my traps versus distance from the road. To estimate the effects of road dust for a typical lake in this region, I consulted a dataset of 60 lakes along the Dempster and Inuvik-Tuktoyaktuk highway (Murdoch *et al.*, 2021) and determined the mean surface area and volume of those lakes. The mean volume of these lakes was ~704,000 m^3 and the mean surface area was ~403,000 m^2. I then determined the surface area: volume ratio for both my dust traps and the typical lake. I assumed that the only factors affecting changes in conductivity or turbidity were the ratio of surface area to volume of a lake and its distance from the road. Through cross multiplication, I could solve for the change in turbidity or conductivity (e.g. for conductivity):

$$\frac{S_{trap}}{C_{distance}} = \frac{S_{lake}}{\Delta Conductivity} \qquad \textit{Equation 1}$$

Where *C* represents the measured conductivity at a particular *distance* from the road (our traps were placed at 0 m, 100 m, 450 m, and 750 m). S_{trap} and S_{lake} represent the surface area to volume ratios of the dust trap and a typical lake in the region, respectively. $\Delta Conductivity$ represents the unknown change in conductivity for a typical lake that can be solved through cross multiplication and some algebra.

So, to calculate the effect of road dust over a five-day period (equivalent to the time my dust traps were deployed), I used the following equations based on rearrangement of Equation 1:

$$\Delta Conductivity = \frac{C_{distance} \times S_{lake}}{S_{trap}} \qquad \textit{Equation 2}$$

$$\Delta Turbidity \ \frac{T_{distance} \times S_{lake}}{S_{trap}} \qquad \textit{Equation 3}$$

Where $\Delta Turbidity$ represents the change in turbidity for a typical lake in the region, *T* represents the measured turbidity at a particular distance from the road, and all other variables definitions match those from Equation 1. According to these relationships, a lake with a larger surface area to volume ratio would be more heavily influenced by dust since S_{lake} is in the denominator of each equation. Similarly, since conductivity and turbidity values measured in my traps were higher closer to the road, lakes closer to the road would be more heavily influenced by dust. To scale up the effects of dust to one year, the $\Delta Conductivity$ and $\Delta Turbidity$ values were multiplied by 73 (365 days / 5 days = 73). This model assumes that there is no change over time, or in different weather conditions (e.g. wet vs. dry).

I obtained wind data from the weather station for Inuvik Airport located at latitude 68.19° longitude 133.31° for hourly wind speed and direction during the dates when my dust traps were deployed (Tundra 2-6 August, Boreal 9-13 August). I created a wind rose using ggplot in R to visualize how the wind speed and direction was distributed during those timeframes.

I used two-factor Analysis of Variance (ANOVAs) to determine if key water quality variables and univariate measures of zooplankton community structure differed among distance from the road categories (0-300 m, 300-600 m, > 600 m) or between regions (boreal forest, tundra). Prior to conducting ANOVAs, I tested the response variables for normality using a Shapiro-Wilks test using the shapiro.test function in R. I tested for homogeneity of variances using Levene's test as performed by the leveneTest function in the car package for R (Fox & Weisberg, 2019). All univariate response variables were normally distributed and demonstrated homogeneity of variances among categories, with the exception of total abundance. I used the bestNormalize package in R (Peterson, 2021) to identify a suitable transformation for total abundance and based on these results I used the Box.Cox transform. The transformed total abundance data met the assumptions of normality and homogeneity of variances.

I used non-metric multidimensional scaling (NMDS) ordination to compare the relative abundance of zooplankton species in different lakes. I plotted the results in two ways. The first plot showed zooplankton relative abundance in lakes based on their distance categories and the second showed zooplankton relative abundance in lakes based on the region they are found (boreal forest vs. tundra). I also ran a permutational analysis of variance (PERMANOVA) to test if there were differences in the centroid (middle position) or dispersion of zooplankton communities based on their assignment in distance categories or region. The NMDS was created using the metaMDS function, while the PERMANOVA used the adonis function and was based on the Bray-Curtis dissimilarity measure (Oksanen *et al.*, 2019).

2.4 Figures

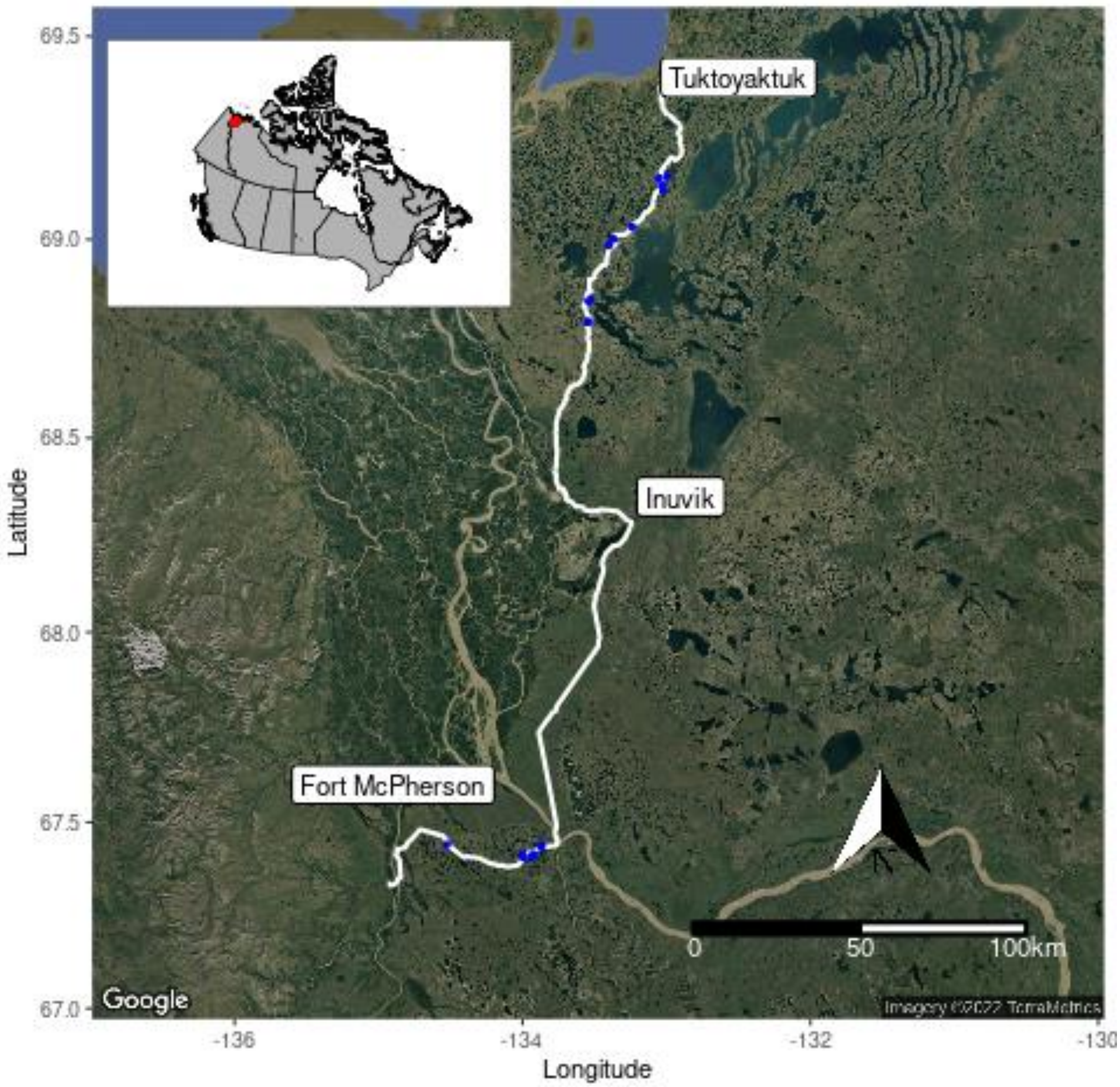

Figure 2.1. Overview of the study area. Lakes sampled along the Dempster and Inuvik-Tuktoyaktuk Highways are marked with blue circles.

Figure 2.2. Dust collection trap used to measure how far from the road dust was travelling across the landscape.

Chapter 3: Results

Potential effects of road proximity on zooplankton communities and water quality in lakes in the Northwest Territories

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3.1 Objective 1: Water quality

Negative exponential functions were good fits for the conductivity and turbidity data collected from my dust traps (Figure 3.1). In both the tundra and boreal forest, the conductivity and turbidity decreased with increasing distance from the road. Conductivity appeared to level off at around 400 m from the road, while turbidity levels levelled off at around 350 m (Figure 3.1). For both variables, the highest values were found in the tundra on the east side of the road (Figure 3.1). The predominant wind direction while my dust traps were deployed was northeast for both the tundra (Appendix 1A) and for the boreal forest (Appendix 1B).

Comparisons of our lakes in terms of their surface areas (1.11 – 10.14 ha), temperatures (12.3 – 17.58°C), and maximum depths (0.8 – 10.5 m) found that there are no significant differences in these key characteristics among the lakes distance categories (ANOVAs, $p>0.05$ in all cases; Figure 3.2). However, there were significant differences in these variables between regions, with tundra lakes having larger surface areas, higher maximum depths, and warmer surface temperatures (ANOVAs, $p<0.05$ in all cases; Figure 3.3).

There were no significant differences in the eight main water quality characteristics of our lakes (conductivity, calcium, pH, dissolved oxygen, chlorophyll, dissolved nitrogen, dissolved organic carbon and dissolved phosphorus), among distance categories (ANOVAs, $p>0.05$ in all cases; Table 3.1; Figure 3.4; Figure 3.5). Between the regions, DN and DOC were the only variables found to have significant differences (ANOVAs, p-values<0.05; Table 3.1; Figure 3.5).

My Spearman correlation analysis with water quality and physical characteristics showed that watershed area was positively correlated, and phosphorus negatively correlated with a lake's distance from the road (Figure 3.6). Distance from the road did not correlate with the lake water quality variables I expected to be influenced by road dust, such as conductivity and calcium (Figure 3.6).

3.2 Objective 2: Zooplankton

The final zooplankton data set consisted of 20 crustacean species across my 18 study lakes (Table 3.2). The rarefied richness of zooplankton communities ranged from 3.8 - 9.9 with a mean of 6.4. Shannon diversity ranged from 0.3 - 1.4, with a mean diversity of 0.9. The total abundance of zooplankton ranged from 0.3 - 108.0 individuals L^{-1}, with a mean of approximately 12.9 individuals L^{-1}. Zooplankton evenness ranged from 0.16 - 0.75 among lakes.

My Spearman correlations showed that rarified richness and diversity were not correlated with distance from the road or any of the water quality variables I measured (Figure 3.6). Abundance was not correlated with distance from the road but was positively correlated with turbidity, temperature, and phosphorus levels (Figure 3.6). Evenness was negatively correlated with distance from the road, watershed area, and pH, and positively correlated with phosphorus levels (Figure 3.6).

I found no significant differences in rarified richness, diversity, or abundance among distance categories or between regions (ANOVAs, p> 0.05 in call cases; Table 3.3; Figure 3.7). The ANOVA conducted for evenness found a significant difference based on distance from the road (p=0.032; Table 3.3; Figure 3.7). A follow-up Tukey test showed that there was a significant difference between the 0-300 m versus the > 600 m category (p=0.047) and a marginally significant difference between the 300-600 m category versus the > 600 m category (p=0.059).

Together, my nonmetric multidimensional scaling analysis with the PERMANOVA showed that the relative abundance of zooplankton did not differ based on distance from the road but did differ between the two regions (Table 3.4; Figure 3.8). On average, the tundra had higher abundances of *Heterocope septentrionalis*, *Daphnia pulicaria, Bosmina longirostris*, and *Daphnia longiremis* while the boreal forest had higher abundances of *Leptodiatomus pribilofensis, Ceriodaphnia* sp., and *Daphnia* *tenebrosa* (Table 3.2). *Spearman correlations showed that Heterocope septentrionalis* was positively correlated with maximum depth (Figure 3.9), which was significantly greater in the tundra (Figure 3.3). *Bosmina longirostris* was positively correlated with temperature (Figure 3.9), which was significantly higher in the tundra (Figure 3.3). *Bosmina longirostris* and *Daphnia longiremis* were both positively correlated with chlorophyll, turbidity and phosphorous (Figure 3.9). Chlorophyll and phosphorus are not significantly different between regions but did appear to be slightly higher in the tundra than the boreal forest (Figure 3.5). *Leptodiatomus pribilofensis* and *Ceriodaphnia sp.* are positively correlated with nitrogen and DOC which were significantly higher in the boreal forest then the tundra (Figure 3.9). Finally, *Daphnia tenebrosa* was only found in the boreal forest and was positively correlated with lake colour (Figure 3.9).

Based on my calculations of the effects of road dust on the typical lake in the region (Equation 2 and Equation 3), conductivity could increase by between 0.35-5.2% per year dependent on its region and distance from the road (Figure 3.10; Table 3.5). For turbidity, my calculations suggest a change between 3.3-177% per year dependent on its region and distance from the road (Figure 3.10; Table 3.5).

3.3 Tables

Table 3.1.Results of analysis of variance tests conducted to examine if water quality variables differed among distance categories or the region of study (boreal forest vs. tundra). DFn = degrees of freedom numerator, DRd = degrees of freedom denominator.

Variable	Effect	DFn	DFd	F	p
Conductivity	Distance category	2	14	0.020	0.980
	Region	1	14	0.002	0.966
	Distance category: Region	2	14	0.991	0.396
Calcium	Distance category	2	14	2.618	0.108
	Region	1	14	2.429	0.141
	Distance category: Region	2	14	0.579	0.573
pH	Distance category	2	14	0.328	0.726
	Region	1	14	0.245	0.628
	Distance category: Region	2	14	1.190	0.333
Dissolved oxygen	Distance category	2	14	0.473	0.632
	Region	1	14	0.312	0.585
	Distance category: Region	2	14	1.725	0.214
Chlorophyll-a	Distance category	2	14	0.982	0.399
	Region	1	14	0.440	0.518
	Distance category: Region	2	14	0.508	0.612
Dissolved nitrogen	Distance category	2	14	0.264	0.772
	Region	1	14	19.044	**0.000648**
	Distance category: Region	2	14	0.983	0.399
Dissolved organic carbon	Distance category	2	14	1.216	0.326
	Region	1	14	50.797	**5.11×10^{-6}**
	Distance category: Region	2	14	1.238	0.320
Dissolved phosphorus	Distance category	2	14	2.618	0.108
	Region	1	14	2.429	0.141
	Distance category: Region	2	14	0.579	0.573

Table 3.2. List of the zooplankton found in my sample lakes with their abbreviations, as well as the mean abundance and standard deviation of each species in both regions.

Zooplankton	Abbreviation	Mean abundance tundra	Std. dev	Mean abundance boreal forest	Std. dev
Bosmina longirostris	Bsmn.lng	7.921	15.661	0.006	0.015
Holopedium gibberum	Hlpdm.gb	0.050	0.150	6.430×10^{-4}	0.002
Ceriodaphnia sp.	Crdphn.	0.002	0.006	0.031	0.045
Simocephalus serrulatus	Smcphn.	0.000	0.000	0.002	0.009
Daphnia tenebrosa	Dphn.tnb	0.000	0.000	0.016	0.027
Daphnia pulicaria	Dphn.plc	0.555	0.703	0.000	0.000
Daphnia longiremis	Dphn.lng	4.110	10.116	9.440×10^{-4}	0.002
Macrothrix laticornis	Mcrthr.l	0.002	0.005	0.000	0.000
Streblocerus serricaudatus	Strblcr.	0.000	0.000	6.410×10^{-4}	0.002
Chydorus sphaericus	Chydrs.s	0.028	0.066	0.018	0.021
Alona sp.	Alon.sp	0.001	0.003	0.018	0.054
Acroperus harpae	Acrprs.h	0.000	0.000	7.880×10^{-4}	0.002
Calanoid copepodids	Clnd.cpp	3.601	6.547	1.346	2.136
Epischura copepodids	Epschr.c	0.000	0.000	0.006	0.015
Epischura lacustris	Epschr.l	0.000	0.000	0.002	0.006
Heterocope septentrionalis	Htrcp.sp	0.089	0.231	0.003	0.005
Hesperodiaptomus eiseni	Hsprdpt	0.011	0.033	0.000	0.000
Leptodiaptomus pribilofensis	Lptdptm	0.271	0.292	1.391	1.573
Cyclopoid copepodids	Cyclpd.c	5.647	10.954	0.524	0.804
Eucyclops agilis	Ecyclps	0.010	0.031	0.003	0.009
Cyclops scutifer	Cyclps.s	0.168	0.498	0.000	0.000
Acanthocyclops sp.	Acnthc.	0.133	0.399	0.010	0.023

Table 3.3. Results of a two factor analysis of variance tests for univariate measures of zooplankton community structure. DFn= degrees of freedom, numerator, DFd=degrees of freedom denominator

Metrics	Effect	DFn	DFd	F	p
Rarefied richness	Region	1	12	1.023	0.332
	Distance category	2	12	0.257	0.778
	Region: Distance category	2	12	1.967	0.182
Shannon diversity	Region	1	12	0.007	0.933
	Distance category	2	12	2.311	0.142
	Region: Distance category	2	12	0.652	0.538
Evenness	Region	1	12	0.214	0.652
	Distance category	2	12	4.632	**0.032**
	Region: Distance category	2	12	0.438	0.655
Total abundance	Region	1	12	3.274	0.095
	Distance category	2	12	1.584	0.245
	Region: Distance category	2	12	2.072	0.169

Table 3.4. Results of permutational analysis of variance to test for differences in the dispersion of species abundances among distance categories and regions. Df= degrees of freedom; SS= sum of squares; MS= mean square.

Source	**Df**	**SS**	**MS**	**F**	**R^2**	**p**
Region	1	0.675	0.675	2.412	0.126	0.013
Distance category	2	0.756	0.378	1.352	0.141	0.160
Residuals	14	3.917	0.279	n/a	0.732	n/a
Total	17	5.349	n/a	n/a	1.000	n/a

Table 3.5. Predicting the potential impact of road dust on the conductivity and turbidity of lakes based on their region, side of the road and distance from the road.

Region	**Distance from road (m)**	**Conductivity**		**Turbidity**	
		Impact in 1 year	**% increase in 1 year for typical lake**	**Impact in 1 year**	**% increase in 1 year for typical lake**
Boreal Forest North	0	4.99	2.16	1.69	33.01
	100	0.83	0.36	0.23	4.52
	450	0.83	0.36	0.32	6.19
	750	0.83	0.36	0.23	4.52
Boreal Forest South	0	6.66	2.88	1.19	23.36
	100	3.54	1.53	0.61	12.01
	450	1.46	0.63	0.60	11.68
Tundra East	0	12.06	5.21	9.09	177.88
	100	1.46	0.63	0.48	9.44
	450	0.83	0.36	0.26	5.04
	750	1.04	0.45	0.33	6.55
Tundra West	0	4.78	2.07	1.29	25.20
	100	2.08	0.90	0.23	4.52
	450	0.83	0.36	0.17	3.38
	750	0.83	0.36	0.21	4.11

3.4 Figures

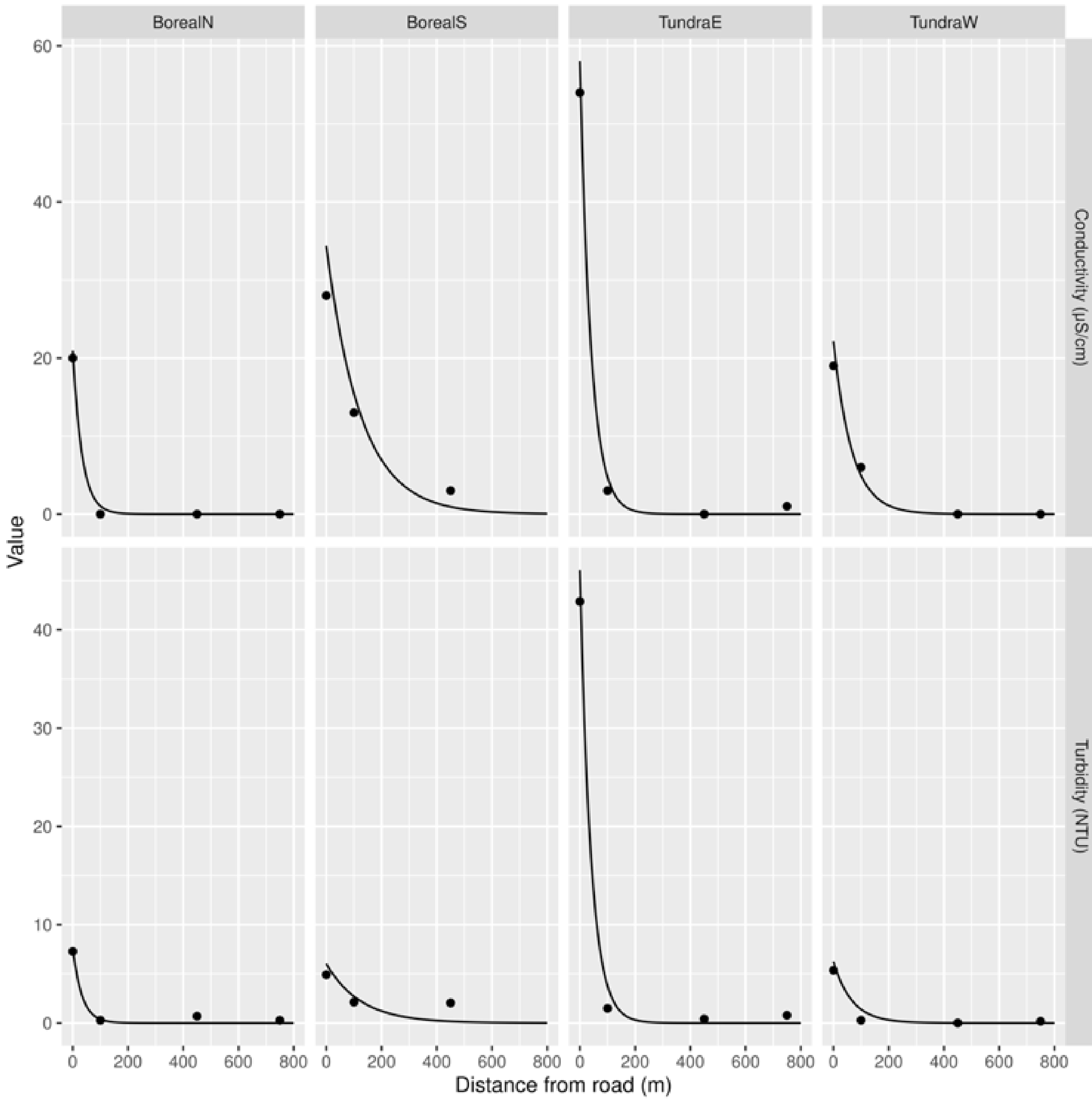

Figure 3.1. Conductivity (top panels) and turbidity (bottom panels) measured in the water found in our dust traps in either the boreal forest or tundra region. Traps were set on the East and West side of the road in the tundra (TundraE, TundraW) or, North or South of the highway in the boreal forest region (BorealN, BorealS). Points represent measurements and the lines show a negative exponential function fit to the data.

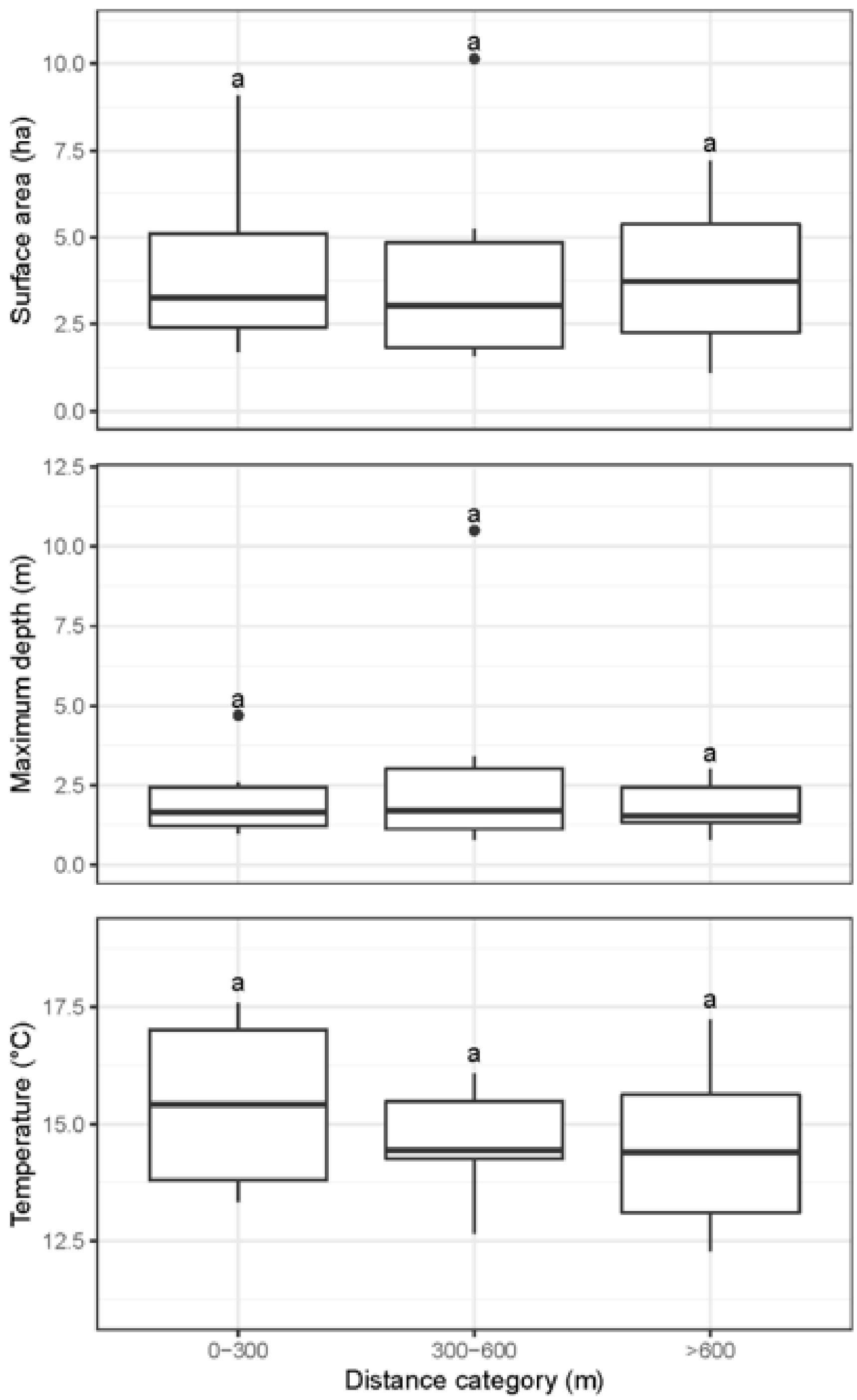

Figure 3.2. Physical characteristics of our study lakes based on their assigned distance categories based on their distance from the road. Bolded line = median, lower end of box = first quartile, upper end of box = third quartile, whiskers = range of data, dots = outliers.

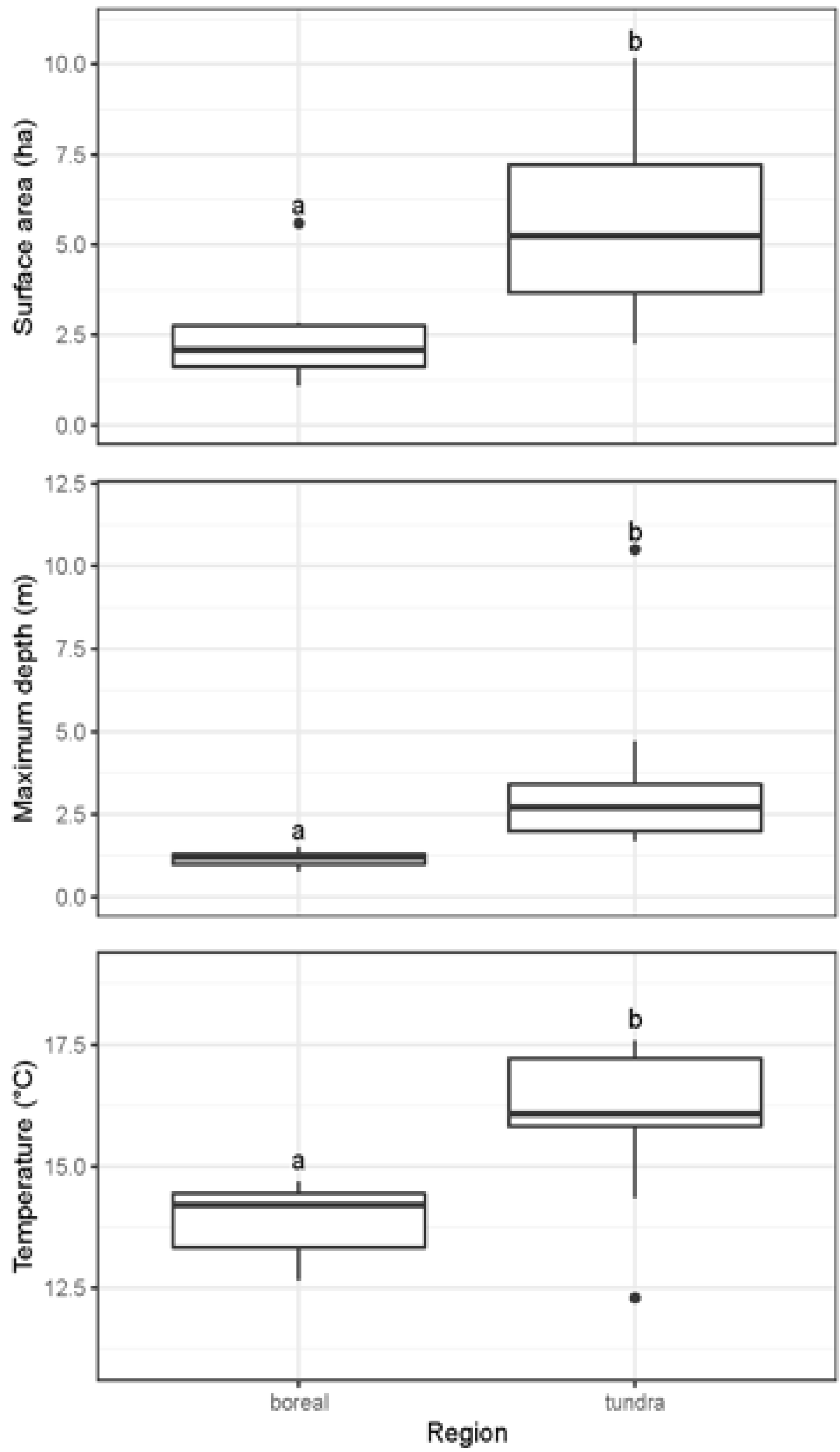

Figure 3.3. Comparison of surface area, maximum depth, and temperature in our study lakes in the boreal forest and tundra.

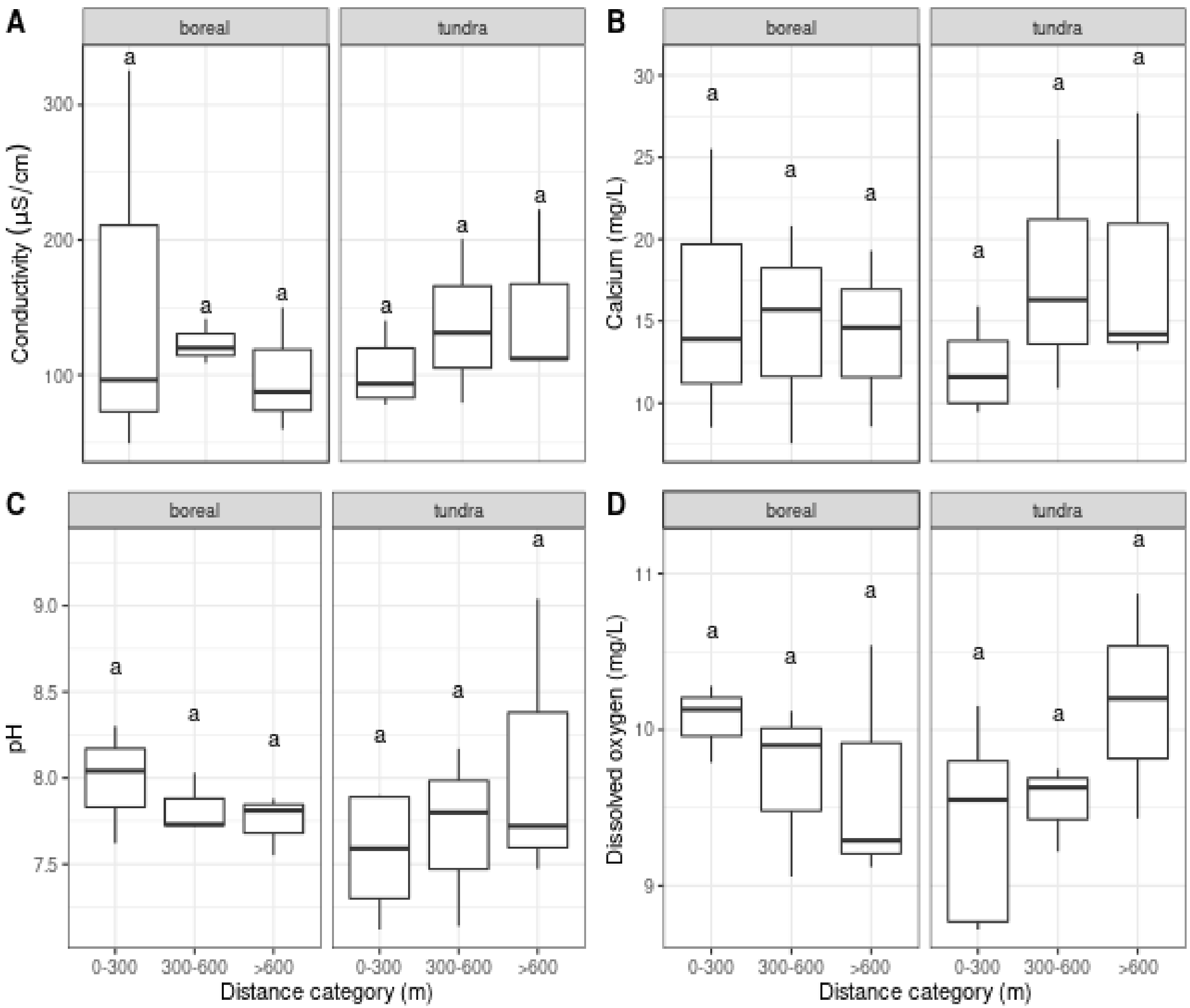

Figure 3.4. Values of conductivity (A), calcium (B), pH (C), and dissolved oxygen (D) based on lakes categorized by distance from the road and region (boreal forest versus tundra). Letters above bars indicate the results of our ANOVAs. Matching letters indicate no difference, while differing letters indicate a statistically significant difference.

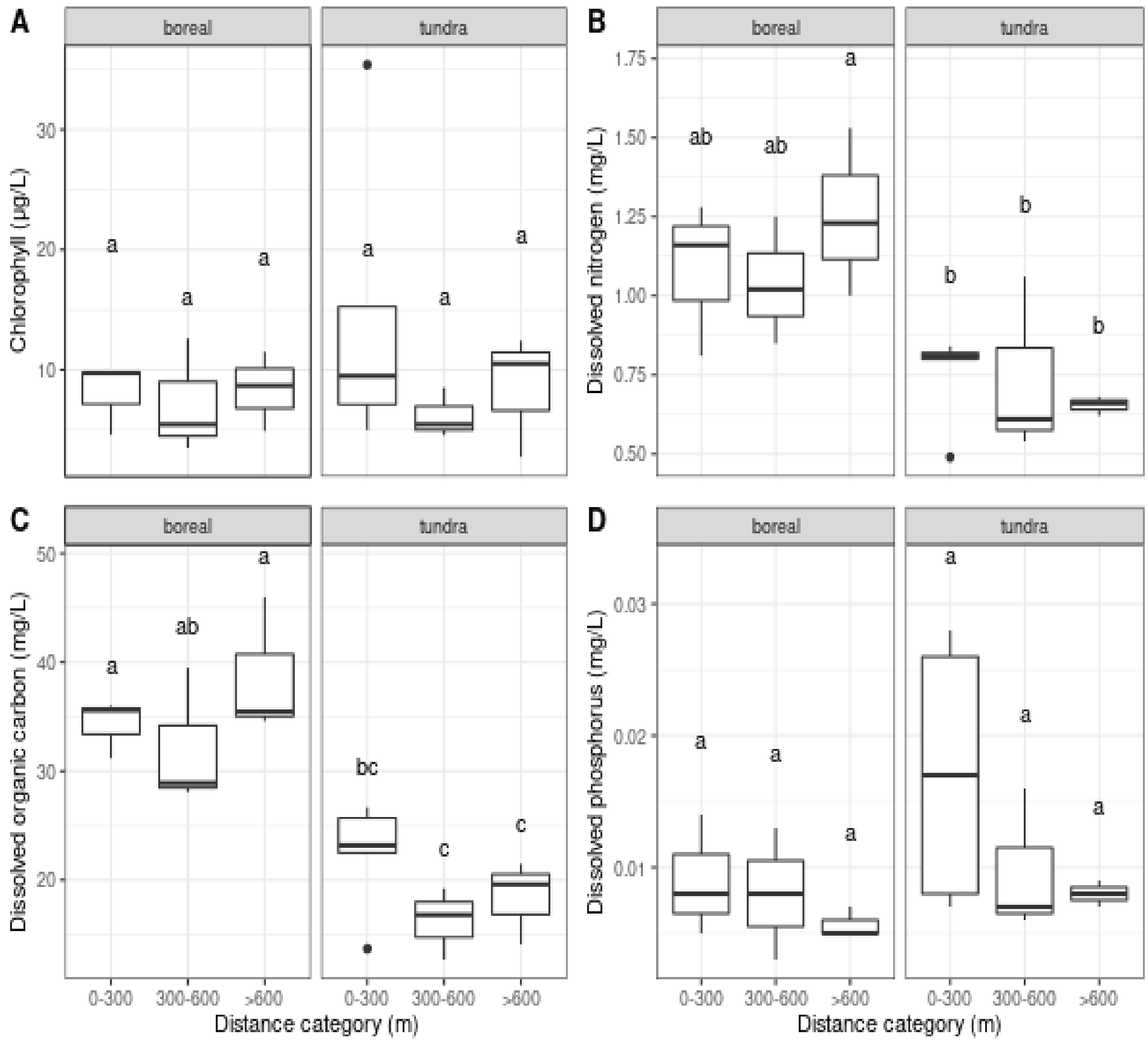

Figure 3.5. Values of chlorophyll-a (A), dissolved nitrogen (B), dissolved organic carbon (C), and dissolved phosphorus (D) based on lakes categorized by distance from the road and region (boreal forest versus tundra). Letters above bars indicate the results of our ANOVAs. Matching letters indicate no difference, while differing letters indicate a statistically significant difference.

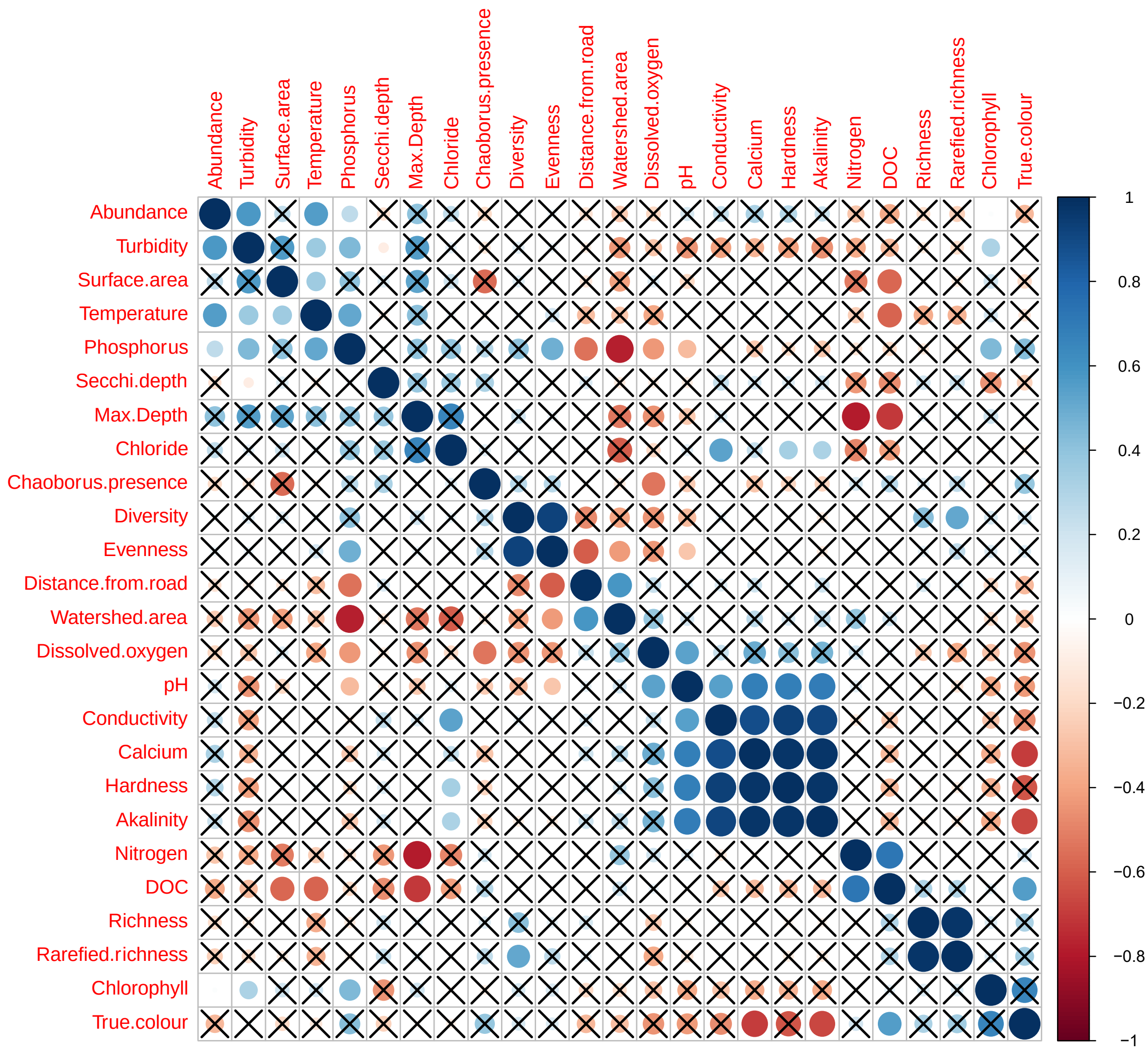

Figure 3.6. Correlation plots showing Spearman correlations among physical, water quality, and zooplankton community characteristics (richness, rarefied richness, diversity, evenness, abundance). Cells that have an X through them indicate those correlations were not significant. The strength of the correlation is indicated by both the size of each circle, as well as the intensity of the colour, with dark red colour indicating a strong negative correlation, and a dark blue colour indicating a strong positive correlation.

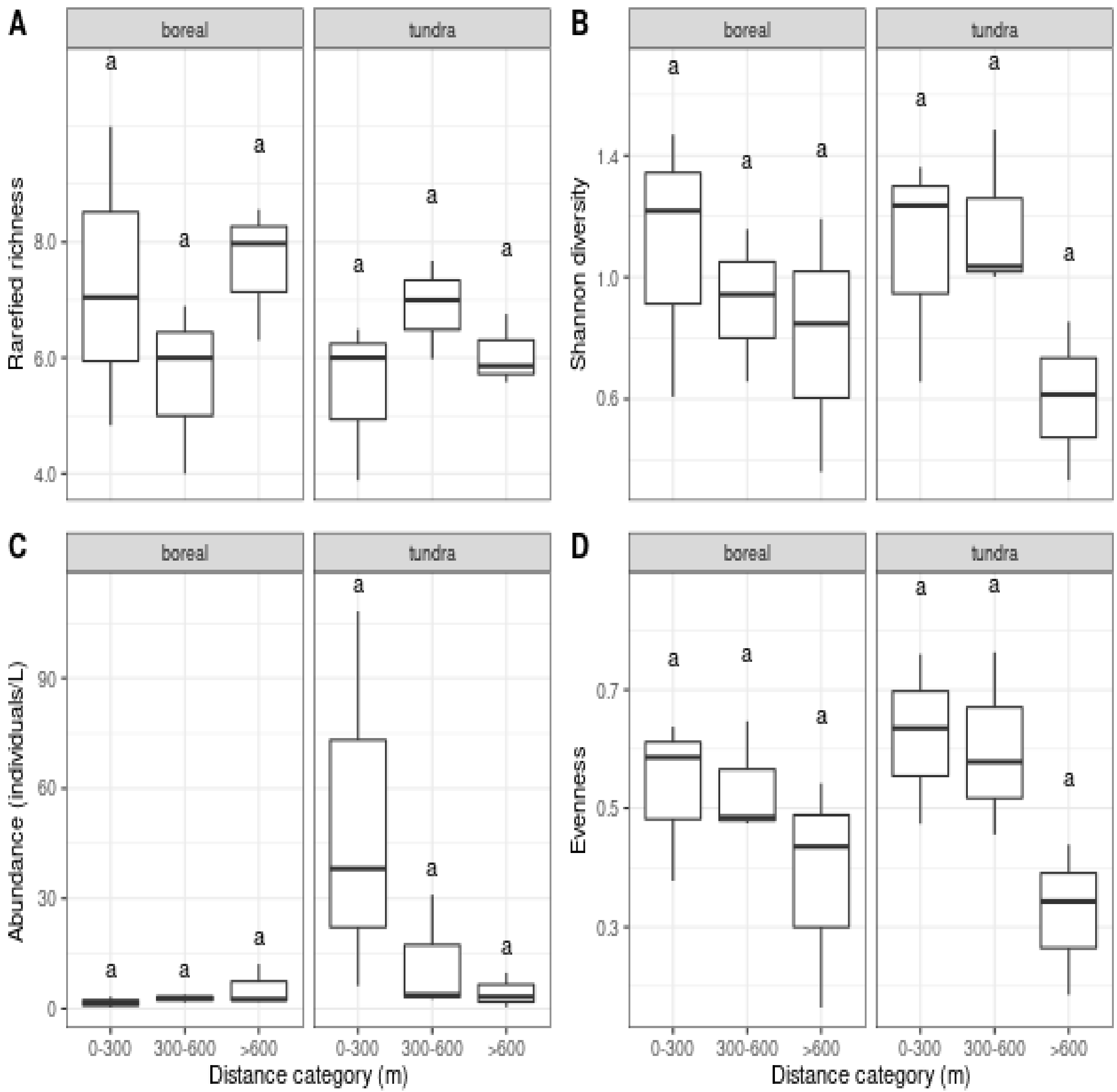

Figure 3.7. Values of rarefied richness (A), Shannon diversity (B), total abundance (C) and evenness (D) for zooplankton communities in lakes categorized by distance from the road and region (boreal forest versus tundra). Letters above bars indicate the results of our ANOVAs. Matching letters indicate no difference, while differing letters indicate a statistically significant difference.

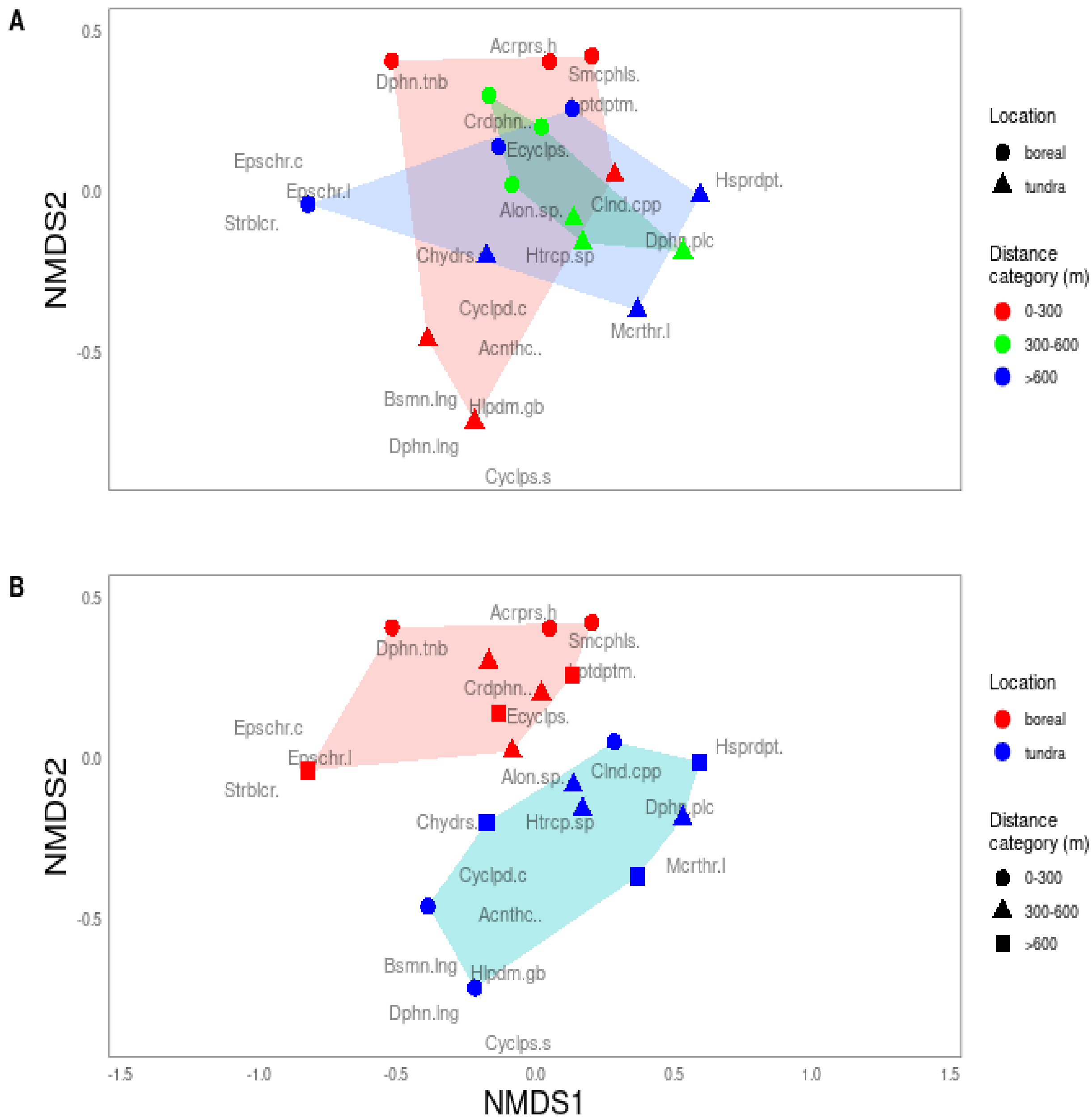

Figure 3.8. Nonmetric multidimensional scaling plots with shading by distance category (A) and location (region) (B). Each dot represents one of the study lakes and text represents zooplankton species names. Dots closer to a species name indicates that lake contains a higher relative abundance of that species.

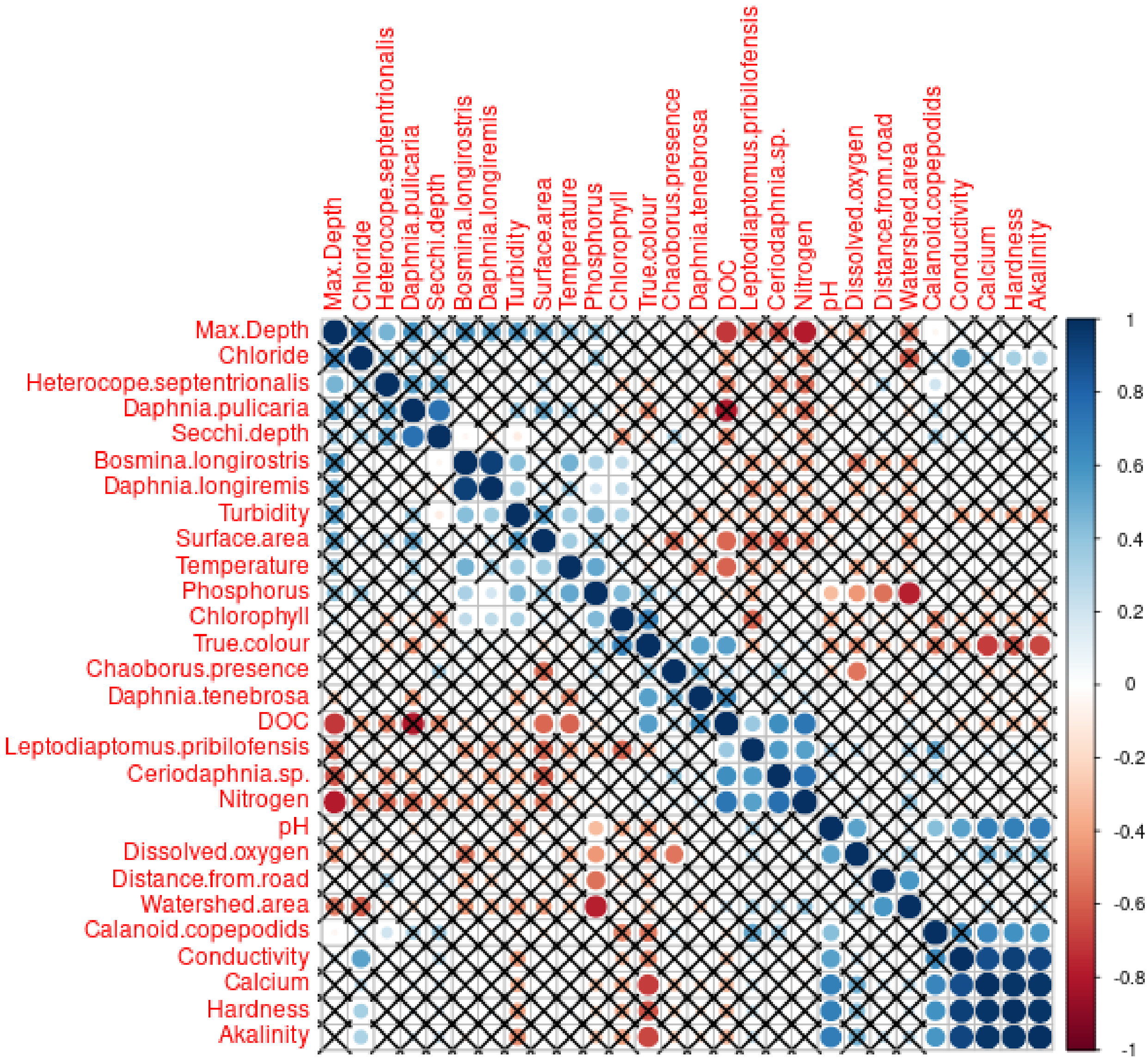

Figure 3.9. Correlation between selected zooplankton taxa (Heterocope septentrionalis, Daphnia pulicaria, Bosmina longirostris, Daphnia longiremis, Leptodiaptomus pribilofensis, Ceriodaphnia sp., Daphnia tenebrosa, calanoid copepodids) and physicochemical variables.

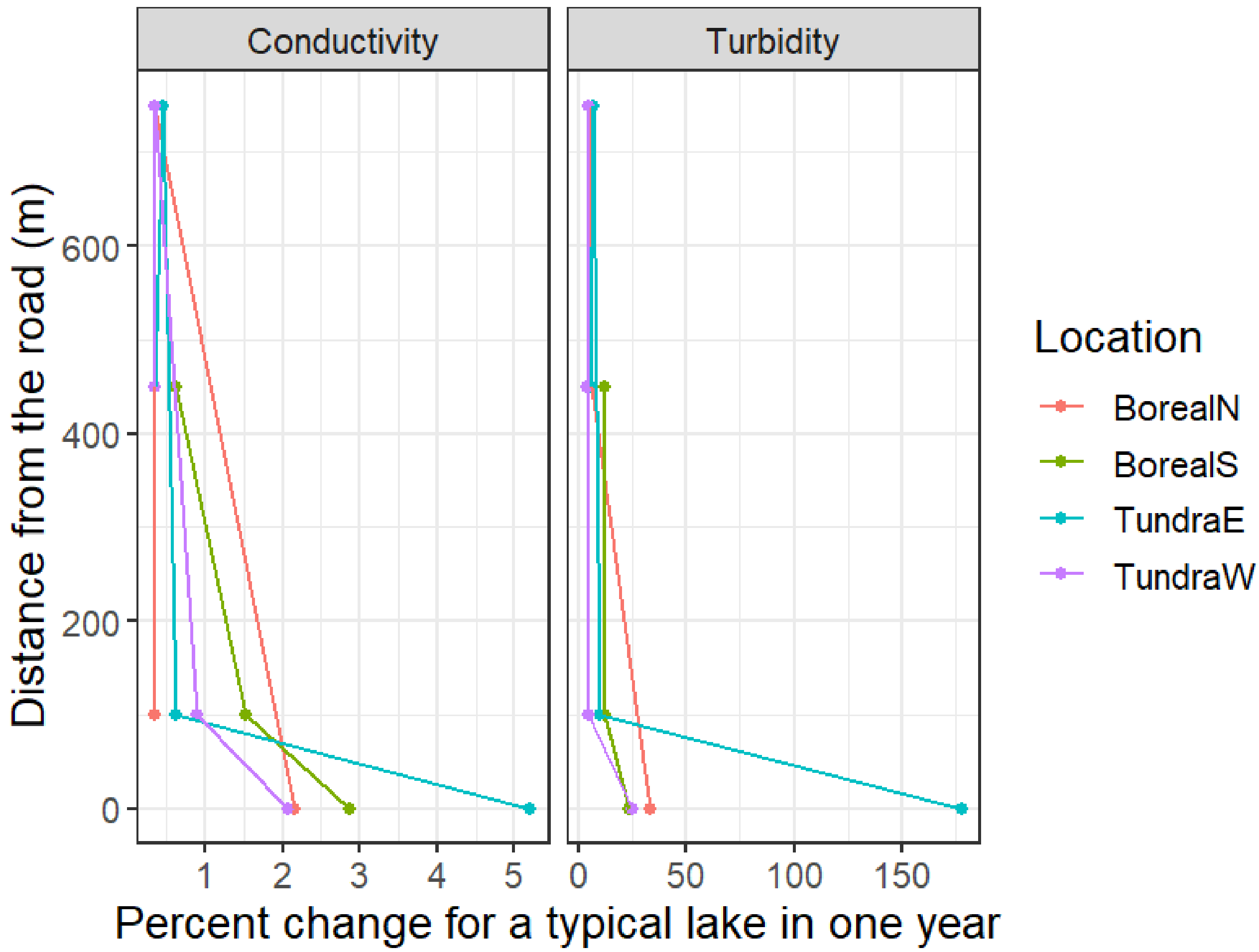

Figure 3.10. Forecasted percent change over one year in conductivity and turbidity for a typical lake, based on the lake's region and side of the road.

Chapter 4: Discussion

Potential effects of road proximity on zooplankton communities and water quality in lakes in the Northwest Territories

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4.1 Dust Movement

My dust traps confirmed that dust was moving from the highways out to a distance of at least 300 m across the landscape. The effects of dust were measured through changes in conductivity and turbidity of the water in my dust traps. Therefore, it is possible that if I left the traps out for a longer than five days in each region, I might have detected elevated conductivity or turbidity at distances greater than 300 m from the highway. The dust traps also showed that the movement of dust was not uniform across the landscape. Traps located downwind of the highway in both the boreal forest and tundra areas had higher conductivity and turbidity levels than those upwind of the highway (Appendix 1A; 1B). The conductivity and turbidity of dust traps in the tundra were highest, and I speculate that this might relate to a lack of tree cover. Trees and shrubs, like those found in the boreal forest, act as wind breaks, and are known to reduce the amount of particulate matter (dust) from the atmosphere, acting as natural filters (Łukowski, Popek & Karolewski, 2020). However, more data will be needed to test this hypothesis. Increasing sampling effort by adding more replicates along both highways would allow for a more accurate measurement of dust movement away from the road. This would help account for differences in dust deposition caused by wind direction, elevation, and differing traffic volumes, improving our ability to model dust movement. Measurements of wind speed at each site would also be helpful in identifying the causes of variation in dust movement. Overall, my dust trap results are largely consistent with past studies that have suggested dust influences terrestrial and aquatic habitats within 1000 m from the road (Chen *et al.*, 2017; Gunter, 2017; Zhu *et al.*, 2019).

4.2 Water Quality

There were no differences in water quality related to distance of a lake from the road. I hypothesized that conductivity and calcium would be elevated in lakes closer to the road due to the transportation of calcareous dust and materials across the landscape. Given that our dust traps confirmed the movement of dust from the highway, these results were unexpected. Compared to the literature, these results are not consistent with previous studies in the region (Chen *et al.*, 2017; Gunter, 2017; Zhu *et al.*, 2019). There are several potential reasons for the apparent lack of effects of road dust on our study lakes. First, the random selection of study lakes may have underrepresented the effects of road dust on lakes in the region. Zhu et al (2019), found that there was some evidence for elevation of conductivity and nutrients near the road, but the 28 lakes they studied showed a high degree of variability in these characteristics. Therefore, it is possible that, by chance, the eighteen study lakes selected were not reflective of the true effects of road dust on lakes in this region, and others might have shown more obvious changes related to distance from the road. Second, I may not have sampled lakes far enough from the road to see a clear pattern. Gunter (2017) found an elevation in calcium and conductivity of lakes within 1 km from the road compared to lakes further away. It is possible that all of my study lakes were equally affected by road dust since they were within 1 km from the road. However, this seems unlikely given the measurements obtained from my dust traps. A future study that includes lakes further than 1 km from the road would help to determine if my results underestimated the effects of road dust due to the small distance range covered. Third, it is possible that the flushing rate of the lakes is high enough to dilute road dust pollution, leading to little change in calcium and conductivity levels in our study lakes. Even lakes without obvious stream connections can experience inputs from groundwater, which may be enough to dilute this type of pollution. Unfortunately, we do not have hydrological data for our study lakes to evaluate this hypothesis.

Based on results from my dust traps and my extrapolation for a typical lake, both conductivity and turbidity should have been higher in lakes closer to the road. As discussed above, I did not observe this in my actual lake data. However, if this did occur, increases in conductivity and turbidity could have negative impacts on zooplankton diversity (Vucic *et al.*, 2020). Increased conductivity in freshwater ecosystems is often linked to lower population growth rates, reduced diversity, and changes in zooplankton community composition (Arnott *et al.*, 2020). My calculations also predicted large increases in turbidity, but I am skeptical that those predictions would be borne out in the real world. I speculate that particles in the water column would likely settle to the bottom of the lake rather than remaining in suspension. Therefore, the turbidity measurements from my dust traps should be viewed as a measurement of dust movement rather than a reflection of the actual effects of road dust on lake turbidity. Additional study would be needed to determine if road dust can cause any long-term changes in the turbidity of roadside lakes.

4.3 Zooplankton Community

There were no differences in zooplankton richness, diversity, and total abundance of communities among road distance categories or between regions. Based on the relationships between conductivity, calcium and the structure of zooplankton communities in a recent study by Vucic et al. (2020), I hypothesized that communities in roadside lakes would diverge from those not subjected to road dust contamination. However, as described above, water quality did not differ based on distance of a lake from the road, and therefore, the lack of differences in zooplankton communities at different distances from the road was not unexpected. These results are also consistent with studies on other organisms which also showed no effect of road pollution on algal communities or diatoms in particular (Gunter, 2017; Zhu *et al.*, 2019).

Zooplankton community evenness was significantly higher in lakes closer to the road. The difference in evenness between lakes close to the road and those further away seems to have been at least partially caused by the abundance of calanoid copepodids, which were very abundant in lakes at intermediate and far distances compared to other organisms in those lakes. There did not appear to be any significant correlations between calanoid copepodid abundance and environmental variables that would explain why they were more abundant at lakes further from the road. Further investigation is needed to determine why evenness is higher closer to the road and why calanoid copepodids were so abundant at lakes further from the road.

My analyses of the relative abundance of zooplankton using an NMDS and a PERMANOVA showed that there were differences based on region (boreal forest vs. tundra) but not based on distance from the road. The differences were largely due to the tundra having higher abundances of *Heterocope septentrionalis*, *Daphnia pulicaria, Bosmina longirostris*, and *Daphnia longiremis* while the boreal forest had higher abundances of *Leptodiatomus pribilofensis, Ceriodaphnia sp.,* and *Daphnia tenebrosa (Table 3.2).* My correlation analysis showed that the species more abundant in tundra lakes were correlated with maximum depth, temperature, chlorophyll, turbidity, and phosphorus (Figure 3.9). Since maximum depth and temperature were significantly higher in lakes located in the tundra, this may explain the differing species compositions (Figure 3.3). In the boreal forest, positive correlations with nitrogen, dissolved organic carbon (DOC) and lake colour may account for the abundance of *L. pribilofensis, Ceriodaphnia sp.,* and *D. tenebrosa* in that region. Colour was positively correlated with DOC (Figure 3.6), and nitrogen and DOC were both found to be significantly higher in the boreal forest than the tundra (Figure 3.5). The size and water clarity differences between tundra and boreal forest lakes were also found in a recent study by Cohen et al. (2021) who found road-accessible lakes in the boreal forest tended to be smaller, shallower, and had higher dissolved organic carbon levels. Many of the boreal forest lakes along the Dempster Highway might be described as bog lakes due to the shallow, high DOC environments with an abundance of sphagnum moss on the bottom (Cohen, 2017; Vucic *et al.*, 2020).

Of the 22 different species of zooplankton found in my study lakes, 10 were only found in one of the two regions (Table 3.1). When found, most of these species had low abundances and were only found in a small number of lakes (less than half of the lakes in a region). The rarity of these species makes it difficult to explain why they were located in one region or the other. The exception to this was *Daphnia* *pulicaria*, which was only found in the tundra and was present in seven of the nine lakes sampled. This large-bodied species of *Daphnia* is often found in large, deep lakes (Stich & Maier, 2007). This may explain why this species was only found in the tundra, as my boreal forest lakes were significantly smaller in surface area and maximum depth when compared to those in the tundra (Figure 3.3).

4.4 Study Limitations

In designing my study, one desirable feature would have been to select lakes with similar physical characteristics in the different distance categories and regions (boreal forest, tundra). This would have allowed me to have confidence that any differences in water quality or zooplankton communities I detected among lakes were driven by the effects of roads and vegetation rather than pre-existing differences in lake morphometry or water quality. Unfortunately, my ability to select lakes with similar physical properties was hindered by a lack of data on lake depths, so I opted to randomly select lakes in an effort to average out any differences in physical properties that might have existed among categories. Figure 3.2 shows that this strategy worked for road distance category, as there were no significant differences in surface area, maximum depth and temperature based on the distance of my study lakes from the road. On the contrary, lakes did differ in these characteristics between regions (Figure 3.3). Lakes located in the boreal forest had a smaller surface area, shallower maximum depth and colder temperatures. These differences could be a concern, since a lake with a greater surface area has the capability of receiving more dust deposition from the road, potentially leading to a greater impact on its water quality. Differences in temperature can also affect zooplankton communities, although the differences were relatively minor with lakes in the tundra having an average temperature 2°C warmer than lakes in the boreal forest. The warmer surface temperatures in the tundra lakes were unexpected, and likely corresponded to the time of sampling, as they were sampled July 30th-August 7th, 2021, while the boreal forest lakes were visited August 8th – 13th, 2021.

Although I believe my study design was sound for testing my hypotheses about the effects of road dust on lakes, there were several limitations to my study. First, my sample size of 18 lakes was relatively small, leading to only three replicates per factorial combination (e.g. three lakes at 0-300 m in the tundra). Larger sample sizes produce better parameter estimates. In our case, a larger number of lakes would likely have produced better estimates for water quality parameters, as well as for zooplankton richness, diversity, evenness, and abundance for lakes in each distance category and in each region. Smaller sample sizes combined with sampling error can lead to poor parameter estimates, and low statistical power, which may lead to erroneous conclusions. We had planned to sample more lakes for this project, but the cancellation of the 2020 field season due to COVID made this impossible. Another limitation to our study was our decision to sample lakes only within 1 km of the road. We accessed our study lakes on foot and the terrain made it very difficult to hike more than 1 km to access lakes. If we had access to a helicopter or float plane, sampling distant lakes would have been more feasible. We suggest that future studies consider sampling lakes further from the highway to determine if the lack of significant differences found in our study are an artefact of the sampling design. Finally, natural variability in the properties of our study lakes may have been an issue. Ideally, we would have chosen lakes with identical physical properties, such as surface area and maximum depth. While there were not statistically significant differences in these properties among our distance categories, there was variability in these parameters both within and among regions and distance categories. Variability in physical characteristics can lead to natural differences in water quality and zooplankton communities, complicating efforts to determine if a stressor is affecting the lake, or if differences are simply a product of differing environments. Unfortunately, we did not have prior data on key properties, such as lake depth. Our solution was to select lakes randomly for inclusion in the study, but we suggest that a future study more carefully consider how to compare the effects of road dust on lakes with similar physical properties.

Chapter 5: Final Thoughts

Potential effects of road proximity on zooplankton communities and water quality in lakes in the Northwest Territories

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5.1 Conclusions

My thesis research had two main objectives. The first was to determine if changes in water chemistry caused by deposition of road dust affects zooplankton communities. I hypothesized that road proximity would influence the community structure of zooplankton, with lakes closer to the road being most affected. In addition, I expected that higher calcium levels in roadside lakes would lead to increases in abundance of zooplankton that require high calcium levels. Furthermore, I hypothesized that higher conductivity levels near the road that would lead to increases in abundance but decreases in evenness and diversity. Unfortunately, all my hypotheses were refuted. Although my dust traps showed that there was potential for road dust movement to increase conductivity and turbidity in lakes near the road, I found no differences in water quality among lakes at various distances from the road. Since my hypotheses for this objective were built on the assumption that water quality would be influenced by the road, it was not surprising that I did not identify the patterns in zooplankton communities that I was expecting.

My second objective was to examine if the type of roadside vegetation influenced the effects of road dust on aquatic habitats. I hypothesized that vegetation in the boreal forest region would act to limit the spread of dust away from the roadway. Therefore, dust would travel further from the highway in the treeless tundra region. I also hypothesized that the impacts of road dust on water quality and zooplankton would extend further from the roadway in the tundra than in the boreal forest. My dust traps seemed to support my hypothesis, as I found that dust moved further away from the road in the tundra compared to the boreal forest. However, water quality data from my study lakes did not exhibit the expected pattern. I found that there were differences in water quality between lakes located in the boreal forest and tundra but these differences were not related to the types of changes I expected due to road dust (e.g. conductivity, calcium). Although the lack of tree cover in the tundra likely allows for a greater amount of dust to reach local lakes, the differences that I found in dissolved organic carbon and nitrogen are likely a natural result of the differing landscapes in which these lakes are found (Cohen et al. 2021).

In the end, my study did not detect any significant effects of road dust on water quality or zooplankton communities for lakes within 1 km of the Dempster and Inuvik-Tuktoyaktuk Highways. While this is welcome news, I am concerned that our water quality results differ from other recent studies that have suggested a significant effect of road dust (Gunter, 2017; Zhu *et al.*, 2019). The current increase in construction of new gravel highways in the Northwest Territories and worldwide means that a better understanding of this potential environmental problem is urgently needed.

5.2 Contributions to the field

Previously, no study had looked at the potential impact that dust from gravel roads may have on zooplankton communities. Not only does my research fill in gaps in our knowledge on the potential effects of gravel roads on zooplankton, but it also contributed to our knowledge on the community structure of zooplankton in small arctic lakes.

Due to the remoteness of our study region, it is likely that some lakes that were sampled had never been studied before. This meant there was a lack of reference data needed to examine potential temporal changes before and after the roads were constructed. The ITH, found in the tundra, is a relatively new (2017) highway and it is possible that not enough time has passed for the lakes and their zooplankton communities to show effects of road dust contamination, which may be cumulative. The data collected for my thesis can serve as a point of comparison for future studies examining the long-term effects of these gravel highways.

My results may also make an important contribution toward environmental management. There were concerns that future road development could have significant deleterious effects on roadside lakes. This is especially important for lakes valued by communities, such as those supporting lake trout

(*Salvelinus namaycush*). While my study is not the definitive work on this subject, it suggests that concerns about road dust harming lakes may be exaggerated. Since my results differ from previous studies, it will be interesting to follow future work on this topic that may inform environmental impact assessments for these large infrastructure projects.

5.3 Remaining gaps and future directions

Although valuable data was gathered for this project, there are still some gaps in our knowledge. Future studies should consider sampling a larger number of lakes to increase precision of estimates and statistical power. The lack of significant water quality results conflicted with past studies on the subject of road dust. Therefore, before reaching a definitive conclusion on this question, I believe that a follow up study that increases the number of lakes sampled and considers reducing inter-lake variability in physical characteristics would be helpful. In addition, the hydrology of lakes needs to be better studied to determine residence time of water. If lakes have short residence times, dust contamination would be flushed out before causing any significant changes in water quality. Finally, my study only considered zooplankton, and I believe it would be good to consider a broader range of organisms by looking at other trophic levels.

5.4 How is this project integrative?

My project had a primarily ecological foundation but contains aspects from various disciplines, not limited to biology. This project integrated biology with other sciences through the collection of environmental variables that include water quality and lake physical characteristics. Chemistry was used in analyzing water quality as well as dust samples. Data from the field of physical geography was used in the selection of my study lakes and the construction of maps (Google Earth, R maps packages). The discipline of limnology was used to understand the interactions between zooplankton, the lakes they inhabit, and the watersheds where those lakes are located.

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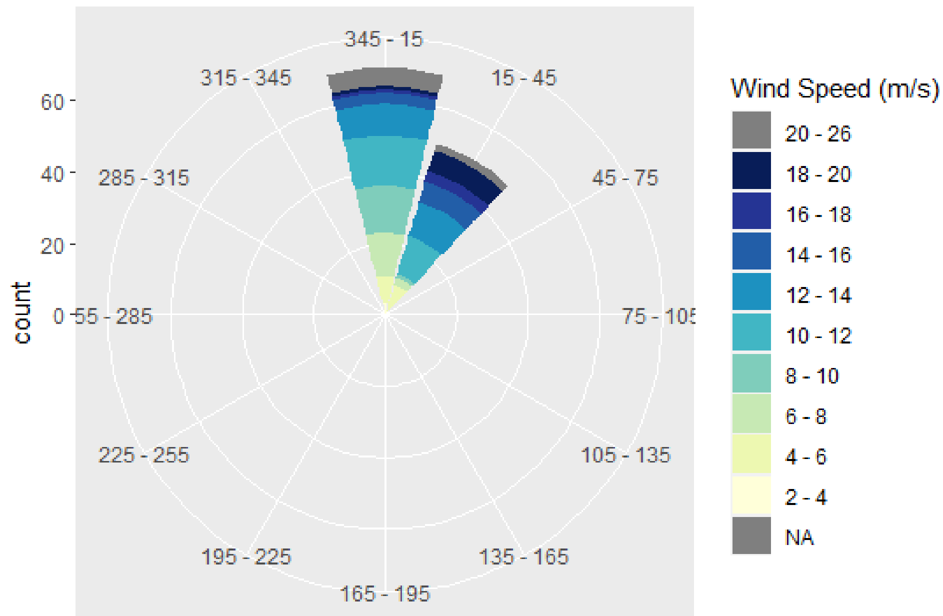
Appendices

Appendix 1. Wind rose representing the hourly wind speed and direction during the dates when my dust traps were deployed. A- Tundra during 2-6 August; and B- boreal forest during 9-13 August.

A



B