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Effects of Dust Palliative Use on Roadside Soils, Vegetation, and Water Resources (2003–2016)

Denali Park Road, Denali National Park, Alaska

Natural Resource Report NPS/DENA/NRR—2018/1580

ON THE COVER
A technician collects surface water along the Denali Park Road as part of the dust palliative use monitoring program in Denali National Park and Preserve, Alaska.
NPS/SARAH STEHN

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Executive Summary

The National Park Service has been monitoring dust palliative ($CaCl_2$) applications and chloride in roadside soil solution and surface water for 13 years along the length of the Denali Park Road in interior Alaska. In this report, we describe the results of this program, focusing on the spatial and temporal patterns of chloride occurrence and its effects on the roadside environment. The most frequent and highest concentrations of $CaCl_2$ applied over this period have been concentrated along the first 30 miles of the unpaved portion of the Denali Park Road. This road section traverses mostly wide-open landscapes susceptible to long-range transport of fugitive dust, and has the heaviest traffic and the driest conditions. Spatial and temporal patterns of chloride in soil solution reflect patterns of palliative application, with high concentrations occurring where high levels of the $CaCl_2$ dust palliative have been applied.

In general, our data indicate that along much of Denali Park Road, levels of chloride in soil solution are unlikely to reach levels that would cause harm to native biota in the roadside environment in the near future. However, we detected a few ‘hot spots’ of elevated chloride levels that warrant attention and concern. Chloride in soil solution is greatly concentrated on road curves where a large surface area drains into a small area. At these locations, especially where total palliative applications are also high (e.g., milepost 15-30), chloride concentrations in soil solution are likely to exceed levels considered toxic to some plants (> 250 ppm, US EPA 1992). Further, we observed that soil solutions carry chloride well into the roadside environment (> 10 m) where steep slopes (> 25%) depart from the road edge. In locations along the road where frequent palliative applications, road curves, and steep road embankments intersect, the likelihood of potentially detrimental concentrations of chloride in soil solution extending into native soils is considerable.

In general, roadside vegetation health appears good along most of the Denali Park Road. We noted indications of tissue damage to several species of herbaceous plants and woody shrubs, but damage was inconsistent and chloride in damaged vs. healthy plant tissues was variable. We suggest this is because, at most sites, even in zones of the highest palliative application, either (1) detrimental concentrations of chloride in soil solution are not regularly reached, (2) the movement of potentially toxic concentrations is transient or spatially complex, and/or that (3) the subarctic vegetation of our region is resistant to the effects of mild chloride toxicity. However, a few ‘hot spots’ of vegetation damage have attracted our attention.

White spruce (*Picea glauca*) health in the Teklanika Forest area (milepost 27-31) is of concern. There, high foliar chloride was associated with visibly stressed trees in areas with a history of heavy palliative application. The incidence of unhealthy trees was highest near the road edge along these mileposts, with trees downslope of the road more likely affected. We believe it is very likely that the uptake of chloride in soil solution via plant roots is contributing to a high percentage of unhealthy trees in this area. When foliar chloride exceeds 3000 ppm, decline in spruce health is likely. We detected no signs of widespread plant disease contributing to decline. Our data indicate that if aggressive $CaCl_2$ application continues along this segment of the road where numerous trees are already showing signs of stress, applications may contribute to a high incidence of whole-tree death

in coming years. Conifers have demonstrated the ability to recover from salt damage (Munck et al 2010), so a change in management practice in these sensitive areas may slow or stop spruce decline.

Significant accumulation of chloride in roadside soils has apparently not occurred over the study period, but we did detect higher soil chloride at sites where the road edge drops steeply into the roadside environment, indicating a likely influence of fine-scale roadside topography on the distribution of chloride in roadside soils. The effects of $CaCl_2$ applications to soils appear to be affected by temporal or spatial factors not yet measured, emphasizing the opportunity for further study in this area, particularly if a high-resolution surface terrain model (< 5-m) of the Denali Park Road corridor were to become available to assist in analyzing spatial patterns in chloride concentrations.

The Environmental Assessment that analyzed dust abatement alternatives in Denali National Park and Preserve (NPS 1999) mandated that monitoring of these activities and their potential effects on the roadside environment must occur in tandem with any application regime. Our monitoring program has thus far provided ample information to shed light on questions management may face regarding dust abatement use along the Denali Park Road. The monitoring program has also allowed identification of natural chloride background levels and assessment of current practices with a ‘canary in the coalmine’ (leading indicator) approach for damage to plant and soil resources. In this report, we identify several areas of concern (i.e., steep and banked curves and the Teklanika Forest) that need to be considered as well as many miles where $CaCl_2$ applications appear to be causing little or no harm to the roadside environment, though we have not evaluated the effects of $CaCl_2$ on other elements of the biota such as soil or aquatic invertebrates, microorganisms, or other soil biota.

Acknowledgments

The authors would like to thank E. Pullman of ABR Inc. for assistance with the design of the chloride monitoring program in 2005 and J. Walton for leading field sampling 2006-2009. G. Eckert and E. Fraley assisted with development and implementation of the plant tissue sampling plan. K. Turchick assisted with development and implementation of the soil sampling plan. J. Paynter maintained the applications database 2003-2012. P. Sousanes provided weather data. S. Bishop and A. Prichard provided review of an earlier draft of this report.

Introduction

The use of chemical dust suppressants on unpaved roads is effective and widespread (i.e., Sanders et al. 1997, Sanders and Addo 2003, Piechota et al. 2004). Use of road dust suppressants reduces maintenance costs by limiting the amount of fines lost from the road as dust, and has safety and health benefits (Sanders et al. 1997, Kerin and Lin 2010). On public lands, fugitive dust from heavily trafficked unpaved roads can contribute to undesirable changes to nearby soils and vegetation (i.e., Walker and Everett 1987, Myers-Smith 2006, Auerback et al. 1997) and thus land managers are motivated to consider palliative use. On particularly scenic public lands, use of dust palliatives has the additional benefit of improving visitor experience by allowing better visibility of landscapes and wildlife (Borg and Phillips 2014).

Although benefits are many, use of chemical dust suppressants also imposes risks to the biota. Dust palliative compounds are salting agents generally comprised of a chloride (Cl-) anion and corresponding cation of either magnesium (Mg^{2+}) or calcium (Ca^{2+}; Sanders et al. 1997). When mixed with water, the salt readily disassociates, allowing both components to enter the roadside soil water through leaching and runoff. Along roads where dust palliative use is high, or along segments of road where the palliative runoff becomes concentrated (i.e., large-area drainages), a potential for ecological impairment exists. For example, use of $MgCl_2$ as a dust palliative in the Rocky Mountains altered stream and soil chemistry (Goodrich et al. 2009a and b), and was associated with significant decline of roadside vegetation when certain threshold concentrations of foliar chloride were reached (Goodrich et al. 2008, Goodrich and Jacobi 2012). Although chloride is an essential plant micronutrient, high levels of the ion are considered toxic and can lead to significant leaf injury (Shortle and Rich 1970).

Thus, managers of unpaved road systems surrounded by native ecosystems of high ecological value (e.g., national parks and other conservation areas) must employ dust palliatives at levels that effectively limit excess fugitive dust from leaving the roadway, while minimizing negative effects on the roadside environment. Managers of Denali National Park and Preserve (henceforth, Denali) in subarctic Interior Alaska face this scenario while maintaining the 78 mile unpaved portion of the Denali Park Road, the only motorized access route into the park. Park managers have noted the negative impacts of fugitive dust along the Denali Park Road at least since the 1970s (US NPS 1979) and efforts to test the use and effectiveness of chemical dust suppressants began in 1994 (ABR, Inc. 2005). In 1999, through a formal environmental assessment process, managers selected and approved calcium chloride ($CaCl_2$) for application as a dust palliative over much of the Denali Park Road (Karle 1999, NPS 1999). With the approval of palliative use, managers specified the need to establish a monitoring program to track the long-term effects of $CaCl_2$ applications on Park resources (NPS 1999).

Ideally, a dust palliative monitoring program would detect the potential for detrimental accumulations of salts in the roadside environment before damage to native vegetation has occurred. Declining plant health has been more highly correlated to chloride levels versus other ion concentrations (i.e., Mg^{2+}; Hofstra and Hall 1971, Goodrich et al. 2009a) and a number of plant species that occur in Denali (e.g., *Picea glauca*, *Larix laricina*, *Cornus stolonifera*, *Sphagnum* spp.) have been reported to be sensitive to elevated chloride concentrations (Strong 1944; Wilcox 1982; Lumis et al. 1983; Kelsey and Hootman 1992). Accumulation of chloride in plant tissues generally occurs via root uptake of the anion in solution because chloride moves easily through the soil and is unlikely to form complexes with other ions or remain bound in the soil (although see Oberg and Bastviken 2012). Hence, Denali Park Road managers chose the monitoring of chloride in soil solution as an affordable and efficient way to review even temporary alterations to the environment as they occur (ABR, Inc. 2005). With this 'canary in the coal mine' approach, managers hope to prevent regular over-exposure of roadside resources to chloride.

However, the rate of soil pore water contamination that leads to harm to vegetation and soils is not definite (i.e., White and Broadley 2001), and the efficacy of using measures of chloride in soil solution as a 'leading indicator' for ecosystem health has yet to be tested. The uptake, use, and storage of ions in plants is complex and species specific (Chapin and Van Cleve 1992) and expected background levels or tolerance of chloride in subarctic plant species and soils are not well described (although see Wilcox 1982). A comprehensive monitoring program should thus include additional components to test for cumulative effects of dust palliative use, while also providing opportunities for increased understanding of ecosystem tolerances (i.e., toxicity thresholds).

A report by ABR, Inc. (2005) summarizes the intermittent monitoring of dust palliative applications from 1994 to 2004. In this report, we summarize data from the most recent 13 years of annual monitoring related to $CaCl_2$-based dust palliative use along the 78 mile unpaved portion of the Denali Park Road, Denali National Park, Alaska. Specifically, we summarize spatial and temporal patterns of dust palliative application (2003-2016; Chapter 1), annual measurement of chloride in ground and surface waters (2005-2016; Chapter 2), and an analysis of roadside vegetation health and soil chemistry after 13 years of sustained palliative use (Chapters 3 and 4). Additionally, we evaluate efficacy of the established dust palliative monitoring program 11-years hence, particularly with respect to whether the annual monitoring methods currently in use (soil solution and surface water sampling) provide adequate warning of detrimental effect of palliative applications on roadside vegetation and soils.

Chapter 1: Patterns of Dust Palliative Use Along the Denali Park Road

1.1 Chapter Objectives

In this chapter, we summarize 13 years of dust palliative application data along a 73-mile unpaved road in Denali National Park and Preserve, Alaska as important context and background for assessing the effects of dust palliative use on roadside water, vegetation, and soil resources (Chapters 2-4). Specifically, our objectives were to (1) identify spatial or temporal patterns of dust palliative application that may have emerged over the study period (2003-2016), (2) quantify cumulative $CaCl_2$ loads to determine road sections most at risk of detrimental effects, and (3) investigate the relationship of regional weather trends to palliative application.

1.2 Methods

Study Area

The Denali Park Road, constructed between 1922 and 1938, runs for 92 miles (148-km) from the George Parks Highway (Alaska Route 3) to the unincorporated community of Kantishna in subarctic Interior Alaska. Road traffic is restricted between mile 15 and 92, where current park management practice allows for 160 vehicles per day as monitored under the Vehicle Management Plan (NPS 2012). The majority of road traffic derives from commercial bus tours and transportation services, as well as private lodge traffic, government vehicles and various other permitted vehicles. Because of the routine and familiar usage of 'mileposts' by those who manage the road, we report our findings and reference locations in English units rather than metric. The first 15 miles of the road is paved; the remainder (miles 15-92) is surfaced with gravel and fine material (soils) mined in borrow pits scattered along the length of the road. Maintaining the road for optimal safety and comfort is a formidable challenge and requires constant work throughout the summer season.

Dust Palliative Application

Calcium chloride ($CaCl_2$) is applied to the Denali Park Road on an as-needed basis when staff resources are available and weather conditions permit (i.e., non-windy, non-precipitating days with a relative humidity > 30%, Techman Engineering 1982). The primary circumstance defining need for palliative application is dusty conditions along the road observed by maintenance personnel or reported to roads staff. $CaCl_2$ is bought in pellet form, mixed with water to a desired concentration, and then added to a water truck modified with an application trailer for spraying onto the road surface (Marshall 1997). Palliative applications generally occur on a freshly graded road surface to reduce immediate loss of the compound from the road surface via runoff. Initial applications occur early in the season, and are repeated as necessary. There are several sections of road where $CaCl_2$ applications are prohibited due to safety or environmental concerns, for example where the road grade exceeds 10-12 percent or is adjacent to wetlands (NPS 1999). $CaCl_2$ in high concentrations can create a slippery road surface, as the dust particles bind into a slurry, and so reports of slippery corners may also affect application sites or rate as well (Riley Tingue, Denali Roads Division Supervisor, pers. comm.).

Concordant with the environmental assessment for dust abatement activities along the Park Road (NPS 1999), roads division staff recorded the application date, starting mile, ending mile, and concentration of palliative for each application. This information is submitted to vegetation management staff yearly. An application event consists of one pass with a 16-foot wide spray wand. During particularly dry spells, and/or when $CaCl_2$ has been recently applied, straight water applications can be applied to the road surface without any concentration of chloride included. These water applications are not mapped or monitored, and are meant to temporarily reduce dust as a local precipitation event would. Although there is potential for water applications to affect the concentration of $CaCl_2$ in soil solution via run-off or dilution, tracking the fine-scale impacts of this management activity is beyond the scope of this study.

Data Analyses

To summarize the spatial distribution and cumulative concentration of $CaCl_2$ applications, we used the reported starting and ending locations (accurate to 0.1 mile) and concentration of each application event to create route events along the Denali Park Road layer in a geographic information system (GIS). We then divided the road into one-mile sections to compute cumulative applications, summing the concentration of $CaCl_2$ applied for each mile over the study period (2003-2016). By examining cumulative $CaCl_2$ loads, we aimed to identify sections of road that we could consider zones of high, medium, low, and no application. This would allow us to explore correlations between application level and measured chloride values in soil pore water, surface waters, plant tissues, and soils as described in following chapters of this report. We used the nonparametric Kruskal-Wallis test to ensure that cumulative application by mile among our inferred road sections (high, medium, low, and no application zones) was appropriate.

To assess the influence of weather on dust palliative application, we used the non-parametric Kendall rank correlation test to evaluate trends between yearly palliative use (i.e., total miles applied and average concentration) and average summer temperature, total summer precipitation, and the proportion of summer days that were hot and dry. This index counted days between May and August where no precipitation was recorded and where the daily average temperature was greater than the daily average temperature calculated across the period of record (i.e., for Denali Headquarters and Wonder Lake 2003-2016, for Toklat 2006-2016). We used the Denali Headquarters weather station to approximate weather conditions for miles 15-39, the Toklat weather station for miles 39-66, and the Wonder Lake station for road miles beyond milepost 66.

1.3 Results

Annual cumulative $CaCl_2$ application mileage varied between 0 to 75.78 miles and was distributed among 0 to 48 application events (Table 1.1) over this period. Application mileages were greatest during the middle years of our study period (2007-2010; Figure 1.1). The rate of $CaCl_2$ application varied between 0.08 to 0.97 lbs/yd^2, with the highest concentrations being used in the early years of application. Considering the cumulative applied load of $CaCl_2$ along the Denali Park Road over the entire study period (2003-2016), it is clear that the dust suppressant is used most heavily between miles 15 and 39 (Savage River to Sable Pass), moderately between miles 39 and 66 (Sable Pass to Eielson Visitor Center), and minimally beyond mile 66 (Eielson to Kantishna; Figure 1.2). The average cumulative applied load of $CaCl_2$ by mile between these three road segments significantly differed (Kruskal-Wallis $\chi^2 = 63.75$, $P < 0.001$; Figure 1.3), with the mean cumulative load of $CaCl_2$ per mile (over the entire study period) east of Sable Pass being 6.95 lbs/yd^2, while the mean load per mile between Sable and Eielson was 2.02 lbs/yd^2, and the mean load per mile west of Eielson was 0.43 lbs/yd^2 (Figure 1.3). Only five one-mile sections reached cumulative applied loads of $CaCl_2$ greater than 9 lbs/yd^2, all of which were between mileposts 16 and 22. Of the 78 miles of graveled Denali Park Road, 13 miles (16%) have never received $CaCl_2$ application. No dust palliative was applied anywhere along the Denali Park Road in 2016, due to a combination of improved road conditions, generally wet weather, and limited staff resources.

Table 1.1. Total number of application events, and spatial distribution of application miles for the entire study period, 2003-2016. Note that application miles do not equate to coverage along road, i.e., multiple applications a year over the same mileposts are cumulatively counted.

			# Road Miles $CaCl_2$ Applied					
Operations Year	**# Appl. Events**	**First & Last Appl. Dates**	**Eielson to Kantishna**	**Sable to Eielson**	**Savage to Sable**	**Total Appl. Miles**	**Total Palliative Applied (lbs)**	**Average Appl. Rate (lbs/yd^2)**
2003	10.0	6/03 - 7/09	0.00	0.00	10.68	10.68	73,890	0.77
2004	26.0	6/17 - 8/11	10.38	0.80	24.47	35.64	219,210	0.61
2005	24.0	6/16 - 8/22	2.64	9.55	18.51	30.69	160,669	0.53
2006	16.0	6/08 - 8/04	0.00	0.00	35.31	35.31	141,957	0.44
2007	35.0	5/18 - 6/29	0.00	0.00	55.17	55.17	177,587	0.34
2008	44.0	6/05 - 9/04	0.00	27.60	47.14	74.74	240,645	0.37
2009	48.0	6/03 - 8/06	5.17	5.11	65.49	75.78	313,548	0.50
2010	27.0	6/03 - 8/31	0.00	24.85	32.97	57.82	274,397	0.55
2011	22.0	6/04 - 9/06	4.34	21.96	20.74	47.05	129,801	0.32
2012	19.0	6/12 - 8/07	0.00	17.47	21.11	38.58	165,774	0.49
2013	13.0	6/19 - 8/15	0.00	9.92	25.98	35.90	169,730	0.51
2014	14.0	6/06 - 6/25	0.00	0.00	21.52	21.52	84,810	0.42
2015	2.0	7/08 - 7/08	0.00	0.00	4.11	4.11	16,589	0.43
2016	0.0	NA	0.00	0.00	0.00	0.00	0	NA
Average	**21.4**	**NA**	**1.61**	**8.37**	**27.37**	**37.36**	**166,816**	**0.48**

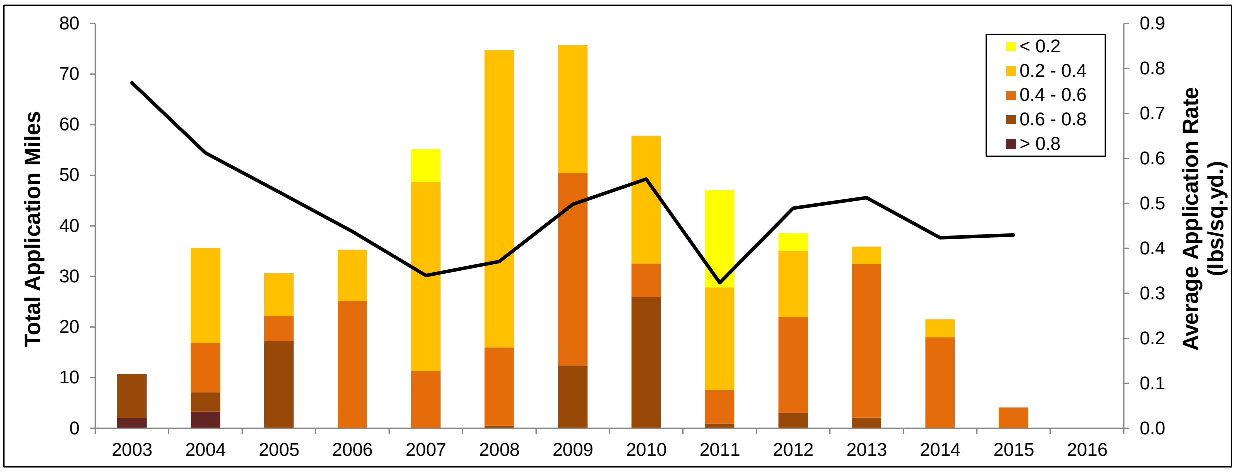

Figure 1.1. Total $CaCl_2$ application miles (histogram presented on left axis) and average application rates (line presented on right axis) along the Denali Park Road over the entire study period, 2003-2016. Colored segments on the histogram indicate the number of total application miles each year applied at a given chloride concentration rate (lbs/yd^2). Note that application miles do not equate to coverage along road, i.e., multiple applications per year on the same road segment are counted cumulatively.

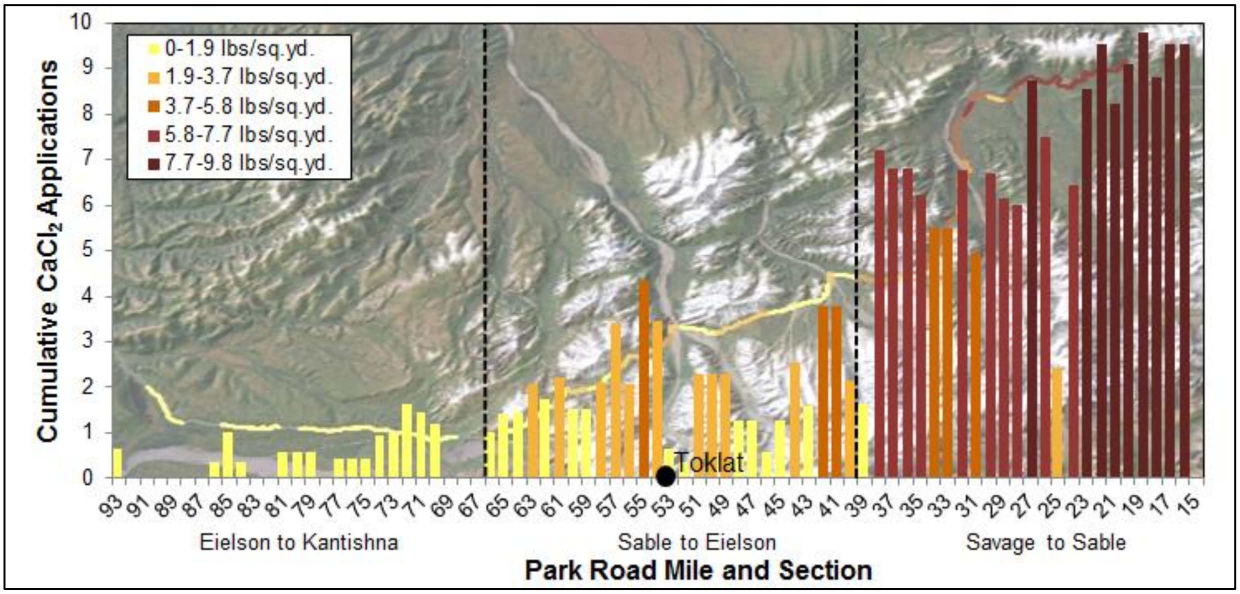

Figure 1.2. Cumulative $CaCl_2$ applications (lbs/yd^2, 2003-2016) for each mile along the Denali Park Road, 2003-2016. Dotted lines demarcate road segments of low, medium, and high (left to right) palliative applications used for analyses in Chapters 2-4 of this report. The location of Toklat is shown on the x-axis to indicate the division between 'west side' (Kantishna to Toklat) and 'east side' (Savage to Toklat) applications as described in Chapter 4. Note that the x-axis is 'reversed', with the highest mileposts listed on the left to reflect their geographic position at the west end of the road.

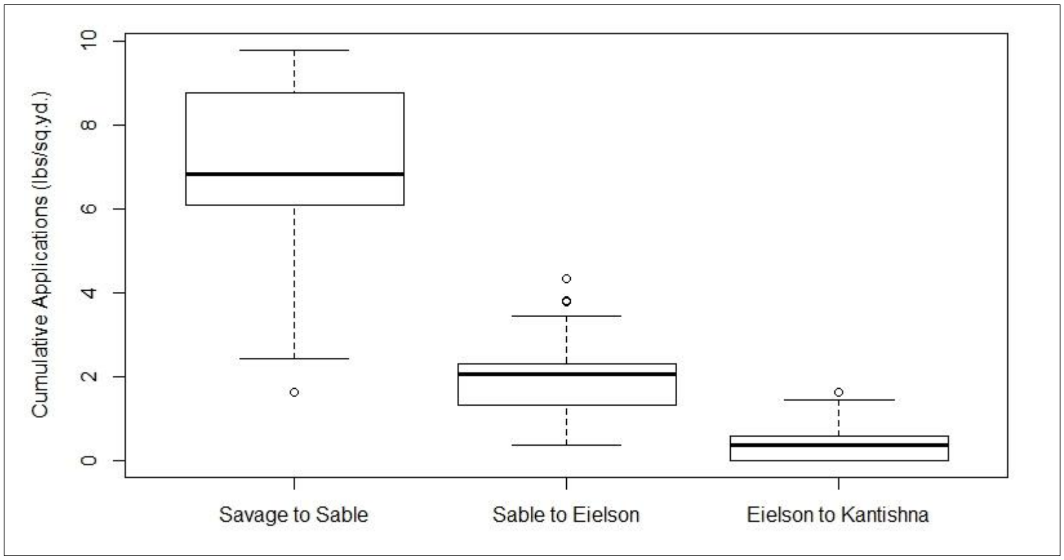

Figure 1.3. Distribution of total $CaCl_2$ applications over the entire study period (2003-2016) for individual miles along three road segments. Number of miles per segment (n) equals, from left to right, 24, 27, and 29.

The total precipitation during the summer months (May-August) averaged across the study period (2003-2016) and across three weather stations (Denali Headquarters, Toklat, and Wonder Lake) was 11.93 inches with a range of 5.6 – 20.8 inches. The average summer temperature was 50.3 °F, with a range of 45.1 – 55.9 °F. See Appendix A for more details on the local climate. Both yearly application miles per road section and average application rate per road section were negatively correlated to the current year's summer precipitation (Kendall's tau = -0.50 and -0.42 respectively, $P < 0.001$; Table 1.2). Total summer precipitation was also weakly correlated with year (Kendall's tau = 0.19, $P < 0.1$). Neither measure of dust palliative use showed correlation with the current year's average monthly temperature or the proportion of hot days that were also dry (Table 1.2).

Table 1.2. Kendall's rank correlation coefficient between measures of dust palliative application, year, and weather from three sections of the Denali Park Road.

Kendall's Tau	Miles applied	Application rate	Year	Total precip.	Average temp.	Prop. of hot/dry days
Miles applied	1	0.52^{A}	-0.21^{D}	-0.50^{A}	-0.038	-0.13
Application rate	-	1	-0.24^{C}	-0.42^{A}	0.037	-0.021
Year	-	-	1	0.19^{D}	-0.091	-0.042
Total precip.	-	-	-	1	-0.027	0.026
Average temp.	-	-	-	-	1	0.20^{D}
Prop. of hot/dry days	-	-	-	-	-	1

^{A} Significance value = $P < 0.001$

^{B} Significance value = $P < 0.01$

^{C} Significance value = $P < 0.05$

^{D} Significance value = $P < 0.1$

1.4 Discussion

In the early years of the dust palliative application program, road managers applied high concentrations of $CaCl_2$ over relatively few miles of road surface. This practice transitioned over several years to applying somewhat lower concentrations spread over more miles, peaking in 2009 with palliative applied to over 75 road miles (including miles counted from repeat applications over the same areas in one season). From 2009, there was a steady decline in miles of palliative applied and a levelling of average application rate. We interpret this change as improved efficacy of the palliative application program and improved road conditions due to the longevity of the program. As road crews have learned the most effective times and concentrations to apply $CaCl_2$, the overall need for dust abatement has decreased. However, this interpretation is complicated by the fact that recent years have been cooler and wetter than the early years of the study period (e.g., the very hot, dry years of 2004 and 2005; see Appendix A), perhaps requiring fewer applications. Regardless, the need for dust abatement is somewhat cyclical, with the benefit of one year's applications often lasting into subsequent years (Riley Tingue, pers. comm.), so the longer dust abatement occurs, greater effectiveness can be expected. And although the temporal pattern of application is likely to change over time (due to shifting precipitation patterns, altered staffing, etc.), we can expect that the maintenance team's growing knowledge of best practices will feed into future decision-making. For example, an ideal application pattern likely involves a low (0.25 lbs/yd^2) concentration of $CaCl_2$ applied over many miles (55-75 miles, including repeat applications), with the ability to treat problem areas more than once (Riley Tingue, pers. comm.).

Over 13 years of dust palliative use, a clear spatial pattern of application has also emerged. Applications are heavier on the more frequently trafficked eastern end of the road, declining greatly beyond the Eielson Visitor Center at milepost 66 (Figure 1.2). Specifically, our data reveal a pattern of applications (e.g., high east of mile 39, medium from mile 40-66, and low applications west of mile 66; Figure 1.2) that likely reflects the particular topographic, geomorphic, and climatic conditions present in those areas along with the amount and timing of traffic there. For example, from mile 15 to about mile 30 the Denali Park Road is characterized by wide-open viewscapes, with many sections built up and exposed to the wind. This section of the road also receives some of the highest traffic and thus the most disruption to the gravel surface, in addition to the lowest precipitation (see Appendix A), resulting in often very dusty conditions. In contrast, the far western end of the road, although having the highest overall precipitation, is also warmer, and had a higher proportion of days that were both hot and dry as compared to the east end. However, a combination of low traffic volumes and distance from the primary road maintenance facility may preclude the need and ability for application to occur there.

In later chapters of this report, we will use this general application framework (i.e., high, medium and low application zones) to investigate possible effects of these patterns of application on the roadside environment, acknowledging that dust abatement activity is not the only factor varying among these sections of road (i.e., road traffic, geomorphology, and climate also vary). In Chapters 2, 3, and 4, we will investigate the effect of the cumulative $CaCl_2$ application load on roadside water, vegetation, and soils. Overall, application loads measured in Denali are well below those measured along graveled roads subject to dust abatement in other parts of the country. For example, along the Denali Park Road, mile 19 has the highest *cumulative* application load (across all years, 2003-2016), receiving 9.7 lbs/yd^2 of $CaCl_2$. In two counties in Colorado, the average *annual* load of $MgCl_2$ applied for dust abatement was 7.3 lbs/yd^2 (Goodrich et al. 2008). Both short- and long-term detrimental effects of this level of use have been noted however (Goodrich et al. 2009a, 2009b, Jacobi et al. 2014), and the specific management goals in that area are certainly different from those in Denali. Thus it remains important to examine the local ecosystems, as each has its own critical load before detrimental impacts occur.

Chapter 2: Effects of $CaCl_2$ Applications on Roadside Water Resources

2.1 Chapter Objectives

We assessed the potential effects of 13 years of dust palliative use on the roadside environment along a 73-mile unpaved road in Denali National Park and Preserve, Alaska. Over the 2005-2016 summer seasons, we examined the temporal and spatial distribution of chloride in soil pore and surface water utilizing a network of permanent soil lysimeters and surface water monitoring sites. Specifically, our objectives were to (1) determine the magnitude and extent of chloride movement from the treated road surface into the roadside environment, (2) assess whether point-in-time measurements of chloride in soil pore- or surface waters are related to $CaCl_2$ applications, and (3) determine whether chloride levels in roadside water resources are approaching or exceeding biologically relevant toxicity thresholds.

2.2 Methods

Field Procedures

We conducted annual monitoring of soil pore water via permanently located suction lysimeters to assess possible migration of dust palliative-derived chloride into the roadside environment (ABR, Inc. 2005). Thirty soil lysimeters were installed in 2005 at 15 locations along the Denali Park Road (Table 2.1). Two lysimeters were buried at each location, at 1-m and 10-m from the edge of the road (Figure 2.1). We chose sites in a variety of vegetation types, and along sections of the road with various structural characteristics (i.e. ditch steepness, near sharp curves in the road that may concentrate runoff). Soil pore water is monitored annually in late August to capture the effects of the entire application season. Monitoring is conducted during or just after a period of significant rain (and before any subsurface freezing has occurred) to ensure adequate soil moisture for obtaining soil pore water samples. On day one, while driving west along the Denali Park Road, we attach vacuum collection bottles to both lysimeters at each sampling site (Figure 2.1) and apply a vacuum of 12-20 psi to draw soil pore water into the bottles. On day two, we return east along the road, collect any pore water sample successfully obtained from the vacuum collection bottles and transfer the samples into clean containers.

In addition to quantifying trends in soil pore water chloride concentration from year to year, we also sought to quantify the maximum point-in-time accumulation of chloride in surface water. Thus we established an annual routine of collecting standing water from 23 locations that appeared to contain water during most years (ABR, Inc. 2005). An additional 10-15 collection sites were collected from opportunistically at water sources connected to more permanent water bodies (i.e. roadside puddles and ditch water). We obtained surface water collections by scooping the sample bottle into the water source. If the water was not deep enough to allow dipping of the sample bottle, we used a syringe rinsed with distilled water to pull sample from just below the surface of the water source without touching the bottom ground surface.

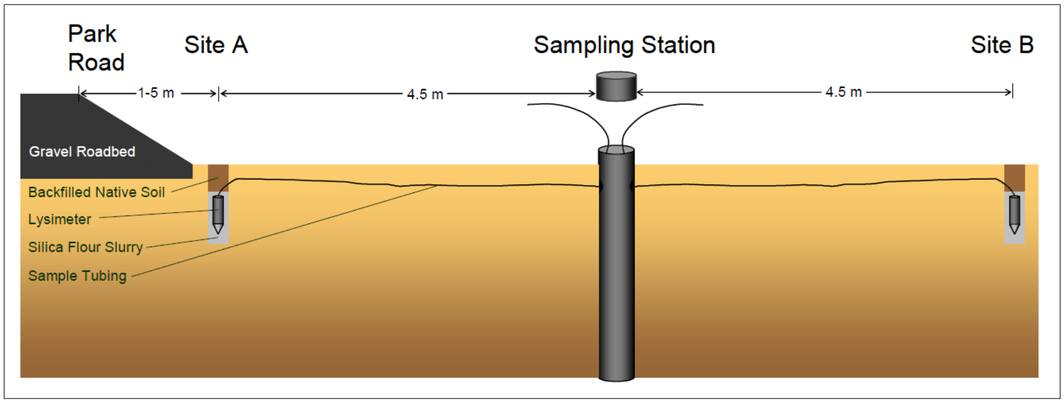

Figure 2.1. Schematic of a typical lysimeter and sampling station as installed in 2005 along the Denali Park Road, Alaska. Diagram courtesy of ABR, Inc.

Laboratory Procedures

Water samples were kept cool (stored in a cooler with ice packs and/or in a refrigerator) until sent for analysis to Analytica International Inc., Fairbanks, AK (2005-2015) or CCAL Lab, Oregon State University, Corvallis, OR (2016) within one week of collection. In 2016 we sent duplicates of a subset (20) of samples to both labs to compare values. Measured chloride levels were comparable, with no significant difference between labs (Mann-Whitney U = 127.8, P = 0.72). Before testing, samples were filtered through a 0.45-micron syringe filter. Chloride concentration was measured via ion chromatography (APHA 4110B method). Results reported reflect a detection limit of 0.25 (2006-2015) and 0.01 ppm (2016).

Data Analyses

Data returned from the lab included non-detects; that is concentrations of chloride that were below the measurable detection limit, with no certainty of how far below. Thus, we chose the NADA package (Lee 2013) in the statistical program R (R Core Team 2016, Version 3.3.2) to plot and summarize our data containing non-detects because it specializes in handling such left-censored data. We used the nonparametric Kaplan-Meier estimation technique to produce mean, median, and standard deviation estimates that are robust to non-detects (Helsel 2012). We used the Peto-Prentice test to compare medians between groups of observations that contained non-detects. When testing for differences among multiple groups in subsets of data free of non-detects, we employed the Kruskal-Wallis nonparametric test to compare medians, and the pairwise Mann-Whitney U-test (Benjamini-Hochberg adjustment) to distinguish between groups (McDonald 2014).

In order to assess the relations of $CaCl_2$ applications and chloride measured in soil pore water, we created a matrix of applications for each lysimeter station relative to the year the measurement occurred. For example, in our matrix, a chloride value recorded at a particular lysimeter in 2011 could be related to 2011 applications (current year applications at that site; t), 2010 applications (previous years applications at that site; t-1), etc., or cumulative applications at that site prior to 2011 (cumm.at.t). We then created simple regression models for each application variable in the matrix to predict when and where elevated chloride in soil pore water was likely to occur. We used a maximum likelihood estimation procedure, assuming a lognormal distribution, to fit a model to the data using the NADA package for R in order to account for non-detects in the data. We compared the fit of the resulting models using the likelihood r correlation coefficient (Loglik-r) measuring the linear association between x and y based on the difference in log likelihood between the fitted and null model.

2.3 Results

Chloride in Soil Pore Water

Between 2005 and 2016, we obtained 274 individual measurements of chloride in soil pore water from 15 lysimeter sites along the Denali Park Road. Of these, 131 measurements were from lysimeters buried 1-m from the road and 143 were from lysimeters buried 10-m from the road bed. See Appendix B for more details on sampling efficacy.

Chloride concentrations in soil water from lysimeters adjacent to the roadbed varied considerably over the study period, both spatially and temporally. However, there is a subset of stations that consistently exhibit the highest chloride concentrations. For example, the 15 highest chloride concentrations observed between 2005-2016 occurred in only four lysimeter stations (S03, S07, S09, S04, at mileposts 18.6, 30.2, 41.4, and 22.2 respectively), and among these only two lysimeters (the 1-m stations at S03 and S07) recorded the maximum readings of ≥ 200 ppm Cl^-. Not surprisingly, we routinely recorded the highest readings at the lysimeter stations located 1-m from the roadbed (14 out of the 15 highest concentrations). Averaging across the entire study period, the highest mean chloride concentrations were found at the proximal stations of S07, S03, S23, and S04 (Table 2.1; Figure 2.2). The single highest reading was 490 ppm Cl- recorded in 2011 at station S07A, milepost 30.2.

Table 2.1. Summary statistics 2005-2016 sampling of 30 lysimeters buried 1- and 10-m from the road edge at 15 sites along the Denali Park Road.

Lysimeter	Milepost	Station	n	Δ Elev. (m) Between Stations	% Below Detection	Mean (ppm Cl^-)	Median (ppm Cl^-)	Std. Dev. (ppm Cl^-)	Max (ppm Cl^-)	Max Year
S01	15.2	1-m	10	5	0%	8.78	7.73	6.14	18	2010
	15.2	10-m	9	-	0%	26.04	28.00	16.74	52.3	2012
S03	18.6	1-m	8	3	0%	187.43	177.00	130.81	378	2011
	18.6	10-m	9	-	0%	69.33	79.10	38.85	140	2010
S04	22.2	1-m	10	2	0%	76.31	54.20	61.24	192	2013
	22.2	10-m	9	-	0%	51.07	39.40	57.98	198	2007
S23	23.4	1-m	4	1	0%	135.55	115.00	50.92	181	2006
	23.4	10-m	9	-	11%	6.63	5.69	2.86	11.3	2005
S05	26.8	1-m	9	4	0%	54.86	51.00	32.51	99	2010
	26.8	10-m	8	-	0%	18.18	17.80	13.47	39.9	2011
S06	28.8	1-m	11	3	0%	22.73	8.27	32.31	99.3	2007
	28.8	10-m	9	-	11%	37.91	19.10	45.40	114	2012
S07	30.2	1-m	9	1	0%	302.31	327.00	144.39	490	2011
	30.2	10-m	9	-	0%	50.44	49.00	16.02	77.5	2007
S09	41.4	1-m	9	4	67%	31.10	NA	74.95	202	2014
	41.4	10-m	9	-	11%	33.96	5.90	62.30	186	2014
S19	49.1	1-m	4	1	25%	1.01	0.68	0.53	1.73	2005
	49.1	10-m	10	-	50%	2.45	NA	2.58	7.63	2012

Table 2.1 (continued). Summary statistics 2005-2016 sampling of 30 lysimeters buried 1- and 10-m from the road edge at 15 sites along the Denali Park Road.

Lysimeter	Milepost	Station	n	Δ Elev. (m) Between Stations	% Below Detection	Mean (ppm Cl^-)	Median (ppm Cl^-)	Std. Dev. (ppm Cl^-)	Max (ppm Cl^-)	Max Year
S11	58.3	1-m	11	2	18%	31.65	6.50	57.59	158	2012
	58.3	10-m	11	-	73%	0.56	0.23	1.05	3.21	2011
S12	60.3	1-m	11	1	9%	7.04	3.09	8.65	27.9	2011
	60.3	10-m	9	-	11%	1.63	1.23	1.21	3.94	2013
S13	64.4	1-m	5	2	60%	1.23	NA	1.68	3.6	2010
	64.4	10-m	11	-	82%	0.91	NA	0.17	1.28	2016
S14	71.2	1-m	10	1	40%	2.73	0.71	3.75	12	2010
	71.2	10-m	11	-	64%	0.67	NA	0.12	0.898	2011
S15	79.7	1-m	10	2	30%	1.86	1.07	1.95	6.36	2007
	79.7	10-m	10	-	50%	0.89	NA	0.86	3.06	2005
S17	88.2	1-m	10	1	60%	0.85	0.16	1.89	5.7	2015
	88.2	10-m	10	-	60%	0.70	NA	0.43	1.81	2014

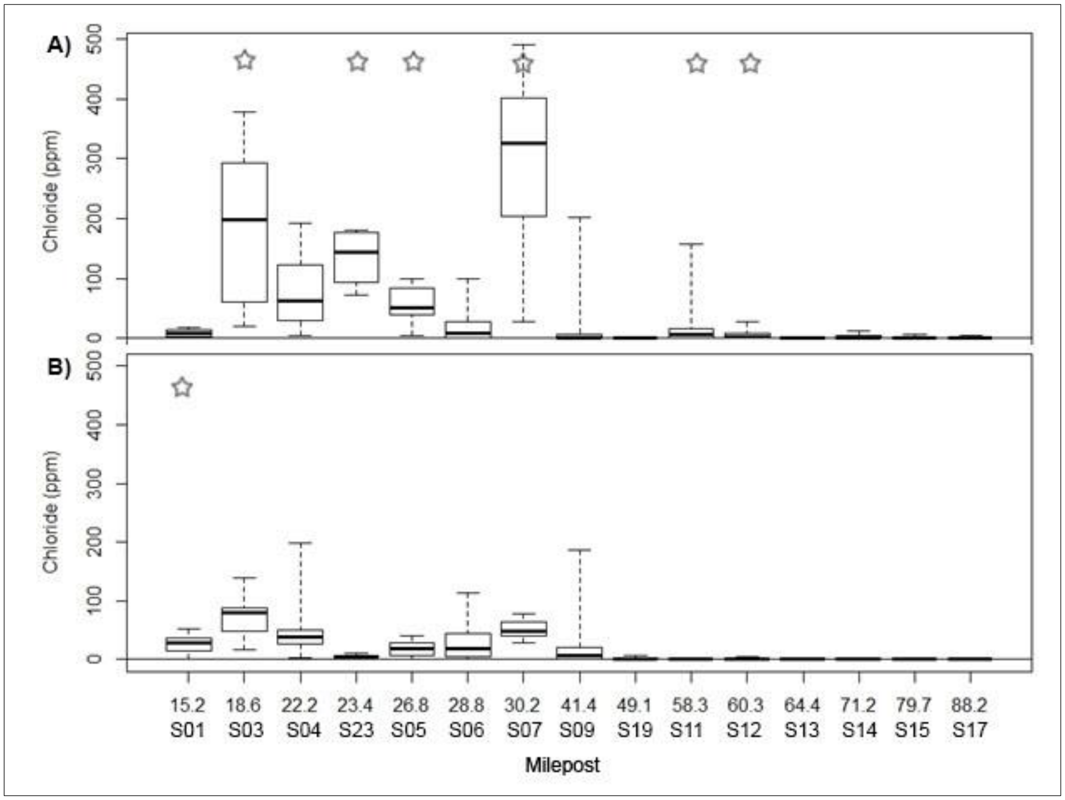

Figure 2.2. Comparison of 2005-2016 chloride in soil pore water measured (A) 1-m from the road edge and (B) 10-m from the road edge at mileposts along the Denali Park Road, Denali National Park, Alaska. Stars indicate where a significant different exists between the 1- and 10-m station, placed on the panel (A or B) with the higher average concentration.

The lowest chloride concentrations were generally recorded at lysimeters located ~10-m from the roadbed (i.e., 63% of 10-m concentrations were below the method reporting limit). The 10m stations at lysimeters S11 and S13 (mileposts 58.3 and 64.4) produce the lowest concentrations most frequently, measuring below the method reporting limit 73% and 82% of the years monitored respectively (Table 2.1). When considering the entire study period, the lowest average chloride concentrations were found at the farthest west stations, i.e., S13, S14, S15, and S17 (Table 2.1; Figure 2.2).

We found a significant difference between median chloride concentrations of the 1-m and 10-m stations at seven of the 15 lysimeter sites over the study period (Figure 2.2), providing strong evidence of relatively restricted patterns of chloride migration into the roadside environment at a distance of 10-m. The soil pore water measured at six 1-m lysimeter stations had significantly higher median chloride concentrations than at the corresponding 10-m stations, indicating that soils 1-m from the road were consistently affected by dust palliative application (tests include data collected over the entire study period). It is important to note, however, that one station (S01, milepost 15.2) displayed the opposite pattern, with the 10-m lysimeter having a significantly higher median chloride concentration than the corresponding 1-m station indicating in certain areas experience substantial migration of chloride does occur.

Relationship of Chloride in Soil Pore Water to $CaCl_2$ Applications

We evaluated the average application rate per mile and measured chloride in soil pore water along road sections with high, medium, and low $CaCl_2$ applications (see Figure 1.2). Chloride in soil pore water at both 1-m and 10-m stations generally reflected the coarse categories of high, medium, and low application rates (Figure 2.3), with very little chloride detected in soil pore water during years where average annual applications for that road section were below 0.2 lbs/yd^2 (Figure 2.3).

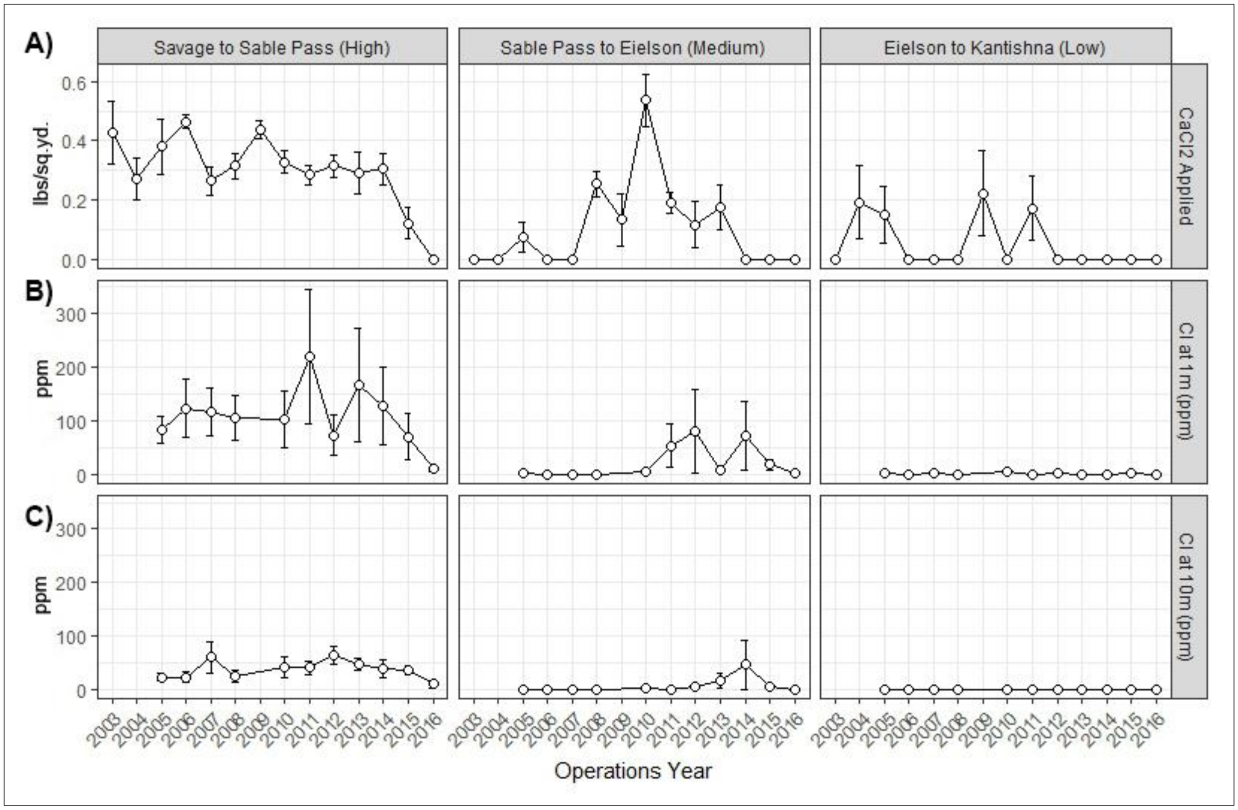

Figure 2.3. Comparison of (A) cumulative $CaCl_2$ applications (lbs/yd^2) and mean pore water chloride concentration (ppm) at soil lysimeter stations (B) 1-m and (C) 10-m from the road edge. Stations are divided along road sections of relative high, medium, and low total cumulative $CaCl_2$ applications (2003-2016, see Figure 1.2). For Savage to Sable, n = 7 lysimeter stations, Sable to Eielson, n = 5 lysimeter stations, Eielson to Kantishna, n = 3 lysimeter stations. Note the scale and units of the Y-axes vary.

Data indicate that we can conservatively estimate 2 ppm to be the maximum background level of chloride in soil pore water collected from areas along the Denali Park Road unaffected by dust palliative use. We retrieved 45 measurements of soil pore water (23 from 1-m and 22 from 10-m stations) from five sites where cumulative $CaCl_2$ applications prior to the time of sampling equaled zero. With the exception of one observation (a 2015 reading of 5.7 ppm Cl^- at the 1-m station at milepost 88.2) all measurements were below 2 ppm, with a range of 0.16-1.8. The mean concentration of chloride at these sites was 0.64 ± 0.90 ppm, with no significant difference between 1-m and 10-m stations.

The regression model that best predicted observed values of chloride in soil pore water included the current year, plus the previous three years' applications (Table 2.2; Figure 2.4). This was true for both 1-m and 10-m measurements, although the quantity of $CaCl_2$ required to reach a particular concentration differed (Figure 2.4). For example, it may take 1.0 lbs/yd^2 of $CaCl_2$ applied in the past 4 years to result in a chloride concentration of 50 ppm 1-m from the road, while at 10-m from the road, the same concentration may result from a cumulative application of 1.5 lbs/yd^2 of $CaCl_2$.

Table 2.2. Loglik-r values of regression models between specific application time period and measured surface water and soil pore water chloride concentration at 1-m and 10-m stations of 15 lysimeters sampled 2005-2016.

Applications Considered	**Soil Pore Water at 1-m**	**Soil Pore Water at 10-m**	**Surface Water**
Current Year (t)	0.389	0.436	0.283
Previous Year (t-1)	0.517	0.480	0.280
Two Years Ago (t-2)	0.487	0.432	0.177
Three Years Ago (t-3)	0.384	0.342	0.220
Current and Previous Years Apps	0.547	0.550	0.343
Current and Previous Two Years Apps	0.627	0.610	0.338
Current and Previous Three Years Apps	0.648	0.630	0.361
Previous Two Years Apps	0.522	0.577	0.287
Cumulative Apps at Time of Measurement	0.502	0.611	0.360

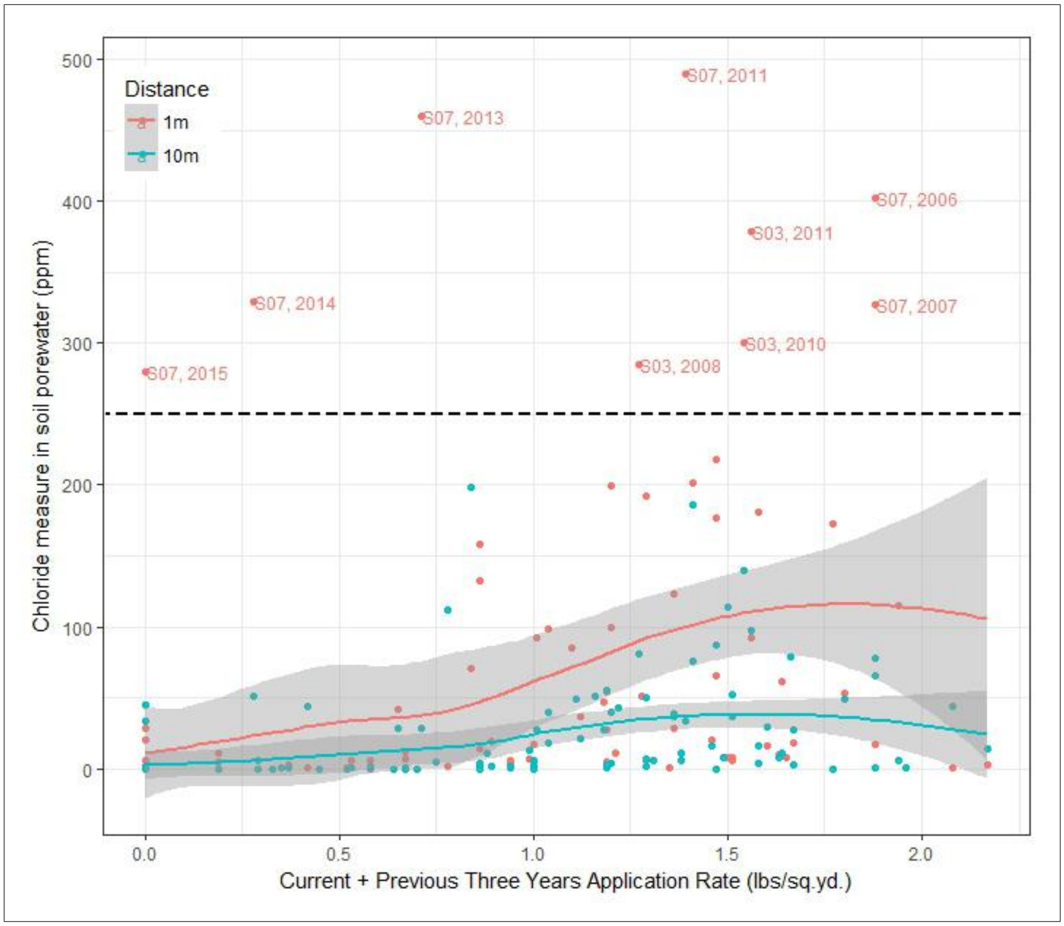

Figure 2.4. Observed chloride in soil pore water 1-m and 10-m from the road edge as a function of the current plus the previous three years application rate. The dashed line indicates the level of chloride considered detrimental to plant life (> 250 ppm, Environment Canada and Health Canada 2001), above which measured concentrations are labeled by site name and year detected. Curves represent a locally weighted regression fit (loess smoothing) through observed values. Shaded area represents a 95 % confidence interval around the smooth.

Chloride in Surface Waters

We collected 400 surface water samples from 131 separate sites along the Denali Park Road over the course of the study period (2005-2016). Sixty-five of the sites were sampled in more than one year, with 21 of the sites visited between 7-12 separate years. Thirty-nine percent of these samples contained concentrations of chloride below the method detection limit, and only 2% exceeded 250 ppm, the Environmental Protection Agency's secondary maximum contamination level for chloride in drinking water (250 ppm; Table 2.3; US EPA 1992). Of the ten surface water samples that exceeded the limit for drinking water, six were recorded in 2011 (Table 2.3), two in 2010, and one each in in 2009 and 2013. Sample values, excluding non-detects, ranged from 0.3 to 1850 ppm, with a median of 0.68 ppm. The sample with the highest chloride concentration came from a puddle at the road edge two weeks after an application of 0.35 lbs/yd^2 $CaCl_2$. In general, chloride concentrations in roadside water bodies were low compared to those in soil pore water (likely due to dilution).

Table 2.3. All recorded occurrences of chloride in standing water that exceeded 250 ppm (the EPA contamination level of drinking water). n = 400 samples taken across 13 years.

Year	Station	Milepost	Max Cl- (ppm)	Sample Date	Site Description
2013	W72	48.8	1850	8/29/2013	puddle in pullout, on road surface
2011	W23	18.1	1050	8/10/2011	puddle in pullout, on road surface
2011	W39	31.5	700	8/10/2011	ditch
2011	W29	31.3	669	8/10/2011	ditch
2011	W38	33.6	556	8/10/2011	ditch
2011	W25	62.0	516	8/10/2011	ditch
2010	W26	60.6	470	9/1/2010	ditch
2011	W36	39.9	311	8/10/2011	ditch
2009	W23	18.1	277	9/22/2009	puddle in pullout, on road surface
2010	W29	31.3	260	9/1/2010	ditch

Relationship of Chloride in Surface Water to $CaCl_2$ Applications

We evaluated cumulative applications and measured chloride in surface water along three road sections with low, medium and high application rates (as described above, see Figure 1.2). Chloride concentrations in surface water generally reflected the coarse categories of high, medium, and low cumulative total applications, with median values of 1.65, 1.51, and 0.24 ppm, respectively. Surface water samples collected beyond milepost 66 (the low application zone; Figure 1.2) had significantly lower chloride concentrations than those in the medium and high application zones ($\chi^2(2) = 53$, $P < 0.001$).

Based on our sampling, we can conservatively estimate 5 ppm to be the maximum level of background chloride concentration in surface waters along the Denali Park Road unaffected by dust palliative use. We retrieved 138 measurements of surface water from 60 sites where cumulative $CaCl_2$ applications prior to the time of sampling equaled zero. Chloride concentrations were below 5 ppm in 135 (98%) of these samples, with the remaining three samples returning values of 6.0, 11.8, and 110 ppm. The mean concentration of chloride for all 138 samples was 1.65 ± 9.38 ppm.

As with chloride in soil pore water, the regression model that best predicted observed values of chloride in surface water included the cumulative amount of $CaCl_2$ applied in the current year, plus the previous three years (Table 2.2). The model for surface waters yielded a weaker fit than the models for soil pore water.

2.4 Discussion

Our monitoring of chloride in soil pore water and surface waters along the Denali Park Road suggests that the effects of chloride on the roadside water resources are generally minimal. Exceptions occurred along a few road segments where dust palliative use has been high, and where palliative is concentrated due to road geometry and drainage patterns. At these locations, we detected elevated levels of chloride up to 10-m from the road edge with concentrations occasionally reaching levels of potential biological concern.

Movement of Chloride away from the Road Surface

Our data indicate that palliative-derived chloride migrates at least 10 m from the road surface and likely farther where the slope from the road edge is steep. At the one site with an extreme (50%) slope (milepost 15.2), the concentration of chloride was regularly higher at the 10-m station, indicating that chloride was rapidly transported away from the road edge (Figure 2.2). In contrast, where the transition from the road edge to roadside environment is low-angle (e.g., mileposts 23.4 and 30.2), soil solution chemistry was less affected further from the road edge (Figure 2.2). Few studies have used soil pore water as a measure of chloride contamination (although see Pedersen et al. 2000), but several have shown similar patterns of chloride migration beyond the road edge in other ecosystem components (e.g., soils and surface waters). For example, Goodrich et al. (2009b) documented elevated soil chloride up to 6-m from the road along straight road segments, and up to 98-m from the road along segments of road where water is channeled. We also detected possible effects of channeling of runoff on the transport of chloride in solution. The highest mean chloride concentration detected 10-m from the road was at milepost 18.6, a banked road curve. Although the slope is moderate, a large surface area is drained, which can act to concentrate chloride in solution (Goodrich et al. 2009b).

Several factors likely contribute to the migration of chloride from the road surface and into the roadside environment, particularly in soil solution, and we did not attempt to quantify them in this study. The chloride ion tends to move freely through the environment, as it is unlikely to form complexes with other ions or remain bound in the soil (White and Broadley 2001; although see Oberg and Bastviken 2012). In our area, we primarily expect palliative-derived chloride to flow from the road surface in runoff during precipitation events, spilling off the road edges into native soils (Goodrich et al. 2009b). However, we observed several additional processes that may also influence the spread of chloride into native ecosystems. For example, road base material occasionally moves of into the roadside environment through road grading activities, or due to erosion of the road edge. Very wet road material sometimes splashes off of the roadway as traffic passes, thereby introducing additional palliative-derived chloride into the roadside environment (Hofstra and Hall 1970). Alternately, when $CaCl_2$ is sufficiently dried, no longer acts as an efficient palliative, and can be transported as fugitive dust via the wind. Upon wetting, the chloride-laced dust can then travel again in solution into the soil matrix. These phenomena likely contribute to our findings of elevated chloride beyond the road edge, and in some cases could be mitigated (i.e., erosion repair and ditch development).

Spatial Variation of Chloride in Relation to Dust Palliative Use

We found the highest soil pore water chloride concentrations where dust palliative use was frequent and application rates were high. Several studies of both dust palliative and de-icing salt use have identified similar correlations between amounts of chloride compound applied and chloride levels detected in soils, vegetation, and surface waters (Goodrich et al. 2009a,b, Goodrich et al. 2008, Munck et al. 2010), confirming the direct impact of this road management practice on the roadside environment.

Chloride levels were consistently highest at the lysimeter stations at mileposts 18.6 (S03) and 30.2 (S07). The cumulative application loads in these areas were > 8 lbs/yd^2, near the highest in our system. However, other stations with similar high application loads had lower chloride concentrations; thus it is worth examining how the particular location of these stations may contribute to their high readings. Milepost 18.6 is at a broad curve in the road that drains a large area, concentrating runoff towards the lysimeter station. Milepost 30.2 is located in a flat, forested area near the Teklanika Rest Stop, an area of heavy traffic with slow-moving, accelerating, and braking vehicles. It is possible that the dust palliative application process in these areas influences chloride concentrations. For example, on road curves, or when likely to encounter other vehicles, palliative application equipment may need to move more slowly, resulting in higher application rates than intended. On road segments that slope, such as banked curves, the spray may run off the road surface and concentrate more rapidly than on unbanked road portions. In the absence of instrumentation or continuous monitoring, it is important for land managers to consider variation in road shape, roadside geometry and traffic flow when aiming to identify possible areas of high chloride inputs.

The pattern of frequent palliative application being spatially correlated to high chloride concentration was also apparent when considering surface water concentrations, but anomalies were frequent (e.g., 1850 ppm Cl- at milepost 48.8 where cumulative applications were < 3 lbs/yd^2). In general, chloride concentrations in roadside water bodies were low compared to soil pore water concentrations, likely due to dilution (Goodrich et al. 2009b). As with soil pore water, we postulate that the highest concentrations of chloride in surface water are influenced not only by application frequency and rates, but also by other aspects of the application activity. For example, three of the highest concentrations occurred in the same area (milepost 31) in 2011 (Table 2.3). Consultation with road maintenance staff revealed that the truck must pause at this milepost to ensure the road is free of traffic, and that there was a small leak in the application truck that year (Riley Tingue, pers. comm.). The combination of these factors likely resulted in temporarily elevated levels of $CaCl_2$ on the roadway and in nearby surface waters. While most studies on the effects of dust palliative use (including this one) focus on longer-term cumulative effects, it is also critical to recognize the possibility for short-term impacts caused by catastrophic events such as equipment failures or spills.

Temporal Variation of Chloride in Relation to Dust Palliative Use

The rate of chloride migration into the roadside environment is complex in relation to $CaCl_2$ applications and we detected evidence of a lag effect between application and detection year. For example, dust palliative was applied at an above average rate (> 0.5 lbs/yd^2) along several road segments in 2009 and 2010, but high values of chloride in soil pore water along those road segments were not recorded until 2011 and 2012 (Figure 2.3). Shaw et al. (2012) also detected a lag in road salt-derived chloride, finding that chloride in streams continued to rise even when road salt applications declined. Our models of chloride in soil pore water and surface water further indicated that incorporating the current and previous three years of palliative application best predicted concentration.

We attribute this apparent lag in the migration of palliative-derived chloride from the road surface to the time required for transport of road materials into the roadside environment. Precipitation events can be relatively few and far between (see Appendix A), so although runoff will occur soon after precipitation, this may occur some time after palliative was applied. By definition, when a dust palliative is applied effectively, both transport of fugitive dust potentially laced with chloride, and road runoff should decrease (Sanders et al. 1997), thus it may be that areas subject to high palliative loads are physically constrained from releasing those loads into their environment until the palliative effect has diminished. Regardless of the mechanism, it is clear that the effect of palliative applications persists for at least several years.

Relevance of Chloride Levels Detected to Roadside Water Resources

We determined that the background level of chloride in soil solution along segments of the Denali Park Road not treated with dust palliative is approximately 2 ppm . However, soil solutions along the Denali Park Road occasionally contain chloride in concentrations > 250 ppm, which are potentially detrimental to plant life (Environment Canada and Health Canada 2001, ABR, Inc. 2005). Road segments where potentially detrimental levels are reached consistently (i.e., mileposts 18.6, 30.2, and areas with similar palliative application histories and roadside geometries) are thus experiencing an altered soil chemistry and may be at risk of vegetation damage. Indeed, at such sites, concentrations remained high for several years after application, and therefore may be affected by new applications in different ways than other sites (e.g., note lysimeter S07 in Figure 2.4).

Very few samples from surface waters along the Denali Park Road contained chloride concentrations likely to pose a threat to aquatic life, but our sampling regime was inadequate to conclude that a risk to aquatic life does not exist. This is in part due to the low frequency and spatial coverage we were able to sample for this long term monitoring program. For example, we cannot know whether there may be intermittent and temporary “flushes” of dangerously high concentrations that affect road-adjacent surface waters. Overall, the chloride concentrations we detected in surface waters are similar to those detected in other areas where chloride-based dust palliatives were used. For example, streams draining unpaved roads in Colorado treated with $MgCl_2$ as a dust palliative had mean Cl^- levels ranging from 0.17-36.2 ppm (Goodrich et al. 2009b). In that study, the mean concentrations (of bi-weekly samples over two summers) were considered well below levels considered detrimental to aquatic life, although the authors recognized that limited research on chronic effects of low-levels, or acute effects of high-levels exists. Approximately 10% of freshwater aquatic species are likely to be affected by 240 ppm chloride (i.e., a biological response to the toxic substance is detectable), but the toxicity threshold ranges up to 30,300 ppm depending on exposure time (Environment Canada and Health Canada 2001). We detected chloride concentrations up to 1850 ppm while sampling sites once a year, but cannot estimate how long detected levels persisted. And although no particular sites or sampling years yielded consistently high concentrations, limited sampling limits our ability to draw conclusions. One consolation is that most of the puddles and roadside ditches we sampled are connected to larger water bodies, so chloride is likely to be diluted in the greater water volumes, thus reducing possible risk to aquatic life in roadside water bodies.

Chapter 3: Effects of $CaCl_2$ Applications on Roadside Vegetation

3.1 Chapter Objectives

We investigated the condition of roadside vegetation after 13 years of dust palliative use along a 73-mile unpaved road in Denali National Park and Preserve, Alaska. Utilizing prior study of dust palliative application patterns (Chapter 1) and chloride in roadside soil solution (Chapter 2) to structure our efforts, we sought to (1) understand the extent to which chloride in soil solution interacts with other site factors to influence chloride accumulation in plant tissues, and (2) identify both background and toxicity thresholds of chloride in spruce needle tissue.

3.2 Methods

Field Procedures

We estimated roadside vegetation health via visual surveys and collection of plant tissues from both declining and healthy plant populations. For herbaceous plants, woody shrubs, and deciduous trees we targeted our survey to 12.7-km (7.9 miles) of the road that have been subjected to the highest cumulative application rates (10.7-km within the Savage to Sable historically 'high' application zone and 2-km in the Sable to Toklat 'medium' application zone; see Figure 1.2). For all miles of the road included in our on-foot survey, we searched the roadside environment up to 10-m from both sides of the road edge for plant populations showing foliar decline or damage. For such populations of herbaceous plants (n = 17), woody shrubs (n = 8), or deciduous trees (n = 4), we collected tissue both from the affected populations, and any nearby non-affected populations for comparison when possible. We picked enough of the youngest mature leaves to obtain a sample with a dry weight of five grams.

In addition, we aimed to survey and sample tissue of white spruce (*Picea glauca* (Moench) Voss) from all areas along the road where this species is found. We concentrated our efforts in areas of densest forest (i.e., milepost 20-35, the Teklanika Flats and Igloo Forest), but attempted to sample from all white spruce stands. Thus, spatial gaps in the sampling along the road are areas where white spruce was absent. For spruce tissue collection, we targeted the current season's fully hardened lateral branches, collecting from at least 3 sides of the tree (so as not to collect only from the side of the tree facing the road and potentially receiving higher dust inputs), 1.5-m above ground level, and combining material from each tree into one sample. Where tree stands extended well away from the road edge, we collected additional samples to assess the spatial extent of possible roadside effects We collected samples from 2-3 trees approximately 10 meters apart in transects perpendicular to the road, recording their estimated distance from the road into classes (1-m, 10-m, or 20-m).

At each sampled white spruce tree we visually assessed overall health and assigned a health class: (healthy – < 5% crown showing symptoms of damage, slightly affected/declining – 5-50% crown showing symptoms of damage, or severely affected/dying – > 50% crown showing symptoms of damage; Goodrich et al. 2008). Chloride-damaged coniferous species in the Rocky Mountains showed needle tip burn and full necrosis of needles (Goodrich et al. 2009a), so we also estimated the percentage of yellow needles on the entire tree. We also estimated slope steepness (0-5%, 5-25%, >

25%) and drainage position (upslope, downslope, or even with road surface). We took a GPS location at each tree and later rendered distance to road center and determined the milepost in a GIS for coordination of tissue samples with dust palliative application data.

Laboratory Procedures

Immediately upon retrieval, we stored sample tissues in paper bags and placed them in a cool, dry place. Within 24 hours, we dried plant tissue samples in a ventilated oven set at 65°C for 48 hours to obtain a constant dry weight. We gently brushed samples particularly caked with dust to remove excess, but for most samples this was not necessary. We sent dried tissue samples to the Soiltest Farm Consultants lab in Moses Lake, Washington. They tested tissue for chloride concentration via the water extraction method (Liu 1998).

Data Analyses

To assess relationships between proxies of tree health (i.e., percent yellow needles, chloride concentration) and tree location characteristics (i.e., milepost, distance from road) we used the non-parametric Kendall rank correlation coefficient. When testing for differences between continuous variables and categorical groups (e.g., chloride concentration and perceived health class), we employed the Kruskal-Wallis nonparametric test to compare medians, and an exact or asymptotic permutation test to compare means, followed by a pairwise Mann-Whitney *U*-test (Benjamini-Hochberg adjustment) to distinguish between groups (McDonald 2014). To test for differences in categorical response variables in relation to other categorical variables (e.g., perceived health and drainage position) we used the Pearson's chi-squared test for count data (contingency table analysis).

Because soil pore water is one of the pathways in which chloride can enter plant tissues, we also leveraged the soil pore water dataset described in Chapter 2 (e.g., Table 2.1, Figure 2.2) to consider differences between the mean foliar chloride concentration of trees within 500-m of each lysimeter station.

3.3 Results

Overall, roadside vegetation health of herbaceous plants, woody shrubs, and deciduous trees appeared relatively unaffected by chloride toxicity, as we did not observe any consistent evidence of decline among species or growth forms. We recorded 45 observations of plant populations showing stress, but these were not consistently associated with elevated chloride levels. We observed tissue damage in 15 different species spanning multiple functional groups (deciduous trees, shrubs, forbs, graminoids, fern allies, and mosses). See Appendix C for a photo catalog of observed tissue damage. The health of roadside spruce trees, however, was more compromised, and displayed some correlation with chloride applications. Over half of the 262 spruce trees sampled had some crown damage or decline (43% showed slight decline, and 8% were in a state of severe decline).

Chloride in Plant Tissues

We measured chloride in tissues of 11 different species in 6 growth forms. The background level of chloride appears to vary widely among different species and growth forms, but a limited sample size for all species except *Picea glauca* restricts more detailed analyses. See Appendix C for full results of the roadside plant tissue damage survey, including chloride detected in herbaceous plants and shrubs.

Our data indicate we can conservatively estimate 2000 ppm to be the maximum level of chloride detected in white spruce needle tissues along the Denali Park Road presumably unaffected by dust palliative use. All spruce needle tissues collected from road segments with no history of $CaCl_2$ applications (n = 16 from healthy trees, n = 2 from slightly affected trees) were below the 2000 ppm threshold. Further, less than 10% of samples (n = 26) had chloride concentrations > 2000 ppm. Of the 49 trees with elevated foliar chloride, 88% were located < 10-m from the road edge (Figure 3.1) and all were located within the Savage to Sable historically 'high' application zone (see Figure 1.2). Foliar chloride levels detected in trees of the severely declining health class were significantly different from those in the less compromised health classes (asymptotic $\chi^2 = 48.89$, $P < 0.01$). Mean foliar chloride for trees classified as healthy was 1415.5 ± 974.9 and those classified as slightly declining was 1498.7 ± 789.9. For the most severely declining trees, mean foliar chloride was well above the 2000 ppm background level (3302 ± 2200.6).

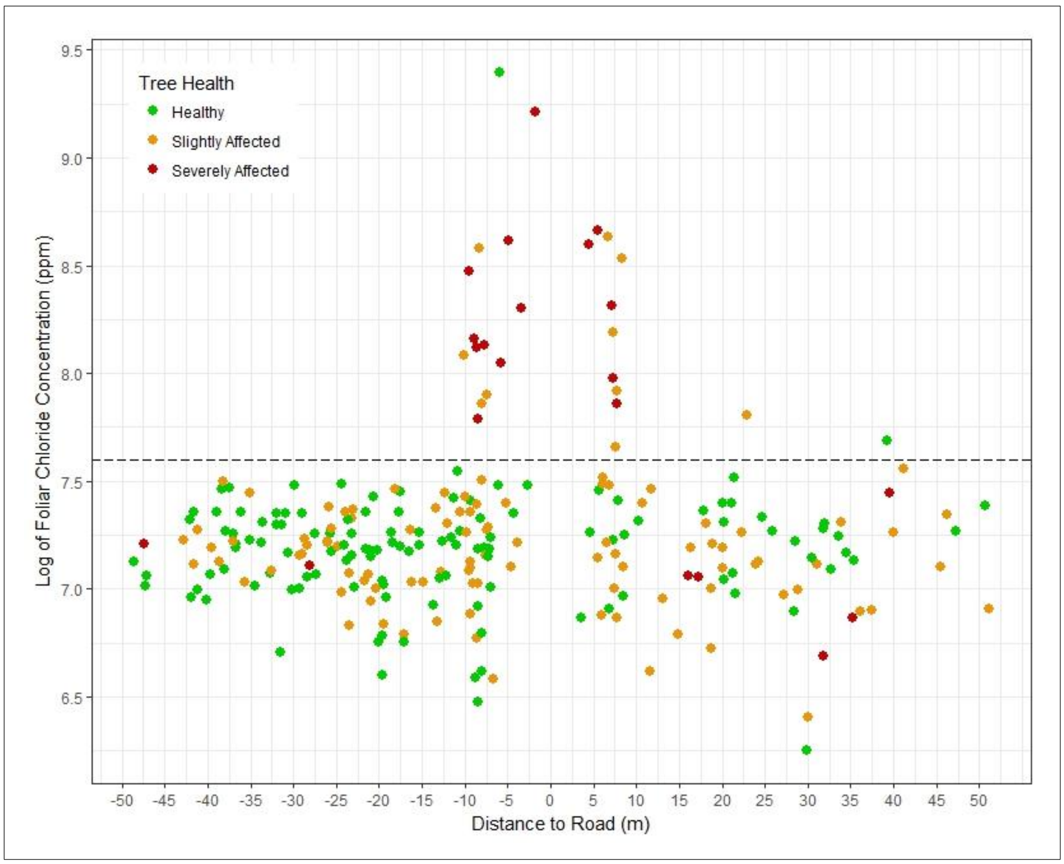

Figure 3.1. The concentration of chloride in foliar tissues of white spruce within 50-m of the Denali Park Road (n = 254), Denali National Park and Preserve, Alaska. Chloride concentration is plotted on a logarithmic scale. Sample trees located upslope or on slopes even with the road are plotted with positive distance to the road, while trees located downslope from the road are plotted with negative distances. The dashed line demarcates 2000 ppm foliar chloride, our estimated background level of chloride in white spruce.

Despite variation in the chloride concentrations of soil pore water measured at the lysimeter stations (see Chapter 2), our data did not confirm differences in the mean foliar chloride concentration of trees within 500-m of each station (asymptotic $\chi^2 = 10.771$, $P = 0.215$), though sample sizes for some stations were small due to a lack of trees (e.g., n = 2 trees near S01 and S03).

Effect of Site Factors on Tree Health

The location of trees along the road (milepost) and their distance from the road influenced tree health. For example, the proportion of trees in each health class differed by road section (Pearson's $\chi^2 = 28.95$, $P < 0.01$), with trees located between miles 25 and 35 having a higher probability of being in a state of decline than elsewhere (Figure 3.2a). Sampled trees were between 1- and 126-m from the road, with 50% of samples collected within 20-m of the road and 75% within 32-m. The probability of encountering a tree in each health class varied with distance from the road (asymptotic $\chi^2 = 9.2$, $P < 0.01$; Figure 3.2b). The proportion of trees in each health class was also significantly influenced by position relative to the road surface; trees with bases level with or upslope of the road showed worse health than those positioned downslope (Pearson's $\chi^2 = 7.27$, $P < 0.05$; Figure 3.3). The steepness of the slope between the tree's base and the road edge just missed having a significant effect on this measure of tree health ($P = 0.06$). We did not detect any confounding relationships between slope position or steepness and general distance to the road (1-, 10-, or 20-m categories; Pearson's $\chi^2 = 0.57$, $P = 0.96$ and $\chi^2 = 1.64$, $P = 0.81$ respectively).

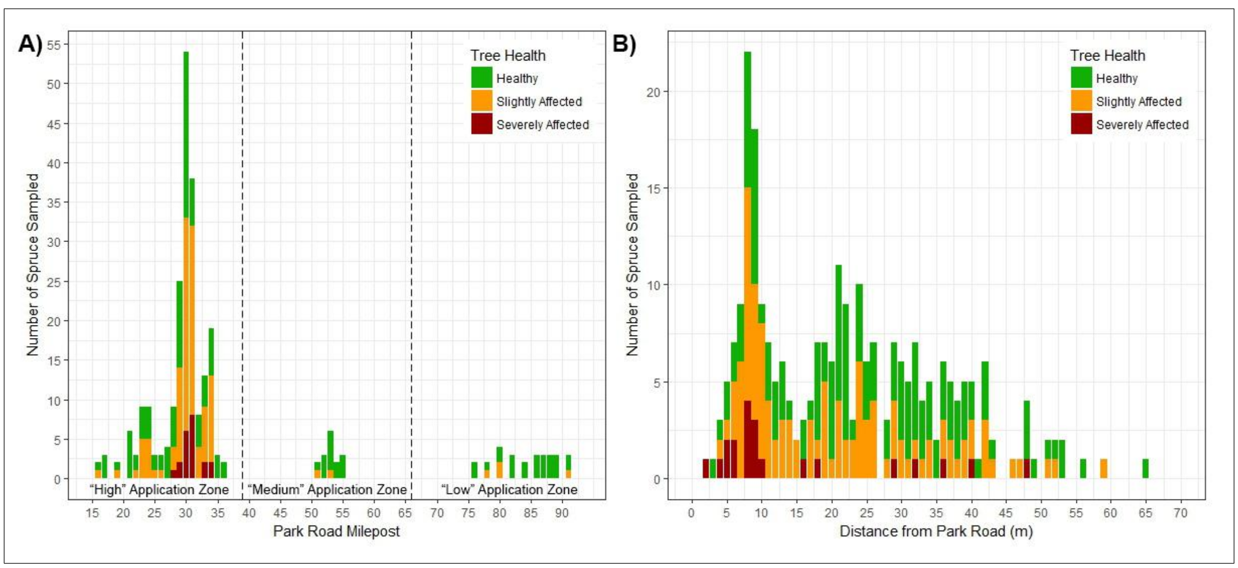

Figure 3.2. The number of spruce in each health class sampled for chloride as encountered at different (A) milepost along and (B) distances from the Denali Park Road, Denali National Park and Preserve, Alaska. Total number of trees sampled was 262; for healthy trees, n = 130, slightly affected trees, n = 111, severely affected trees, n = 21. The vertical dashed lines (A) align with the cumulative application classes of high (milepost 15-39), medium (milepost 39-66), and low (milepost 66-93) identified in Chapter 1 (see Figure 1.2).

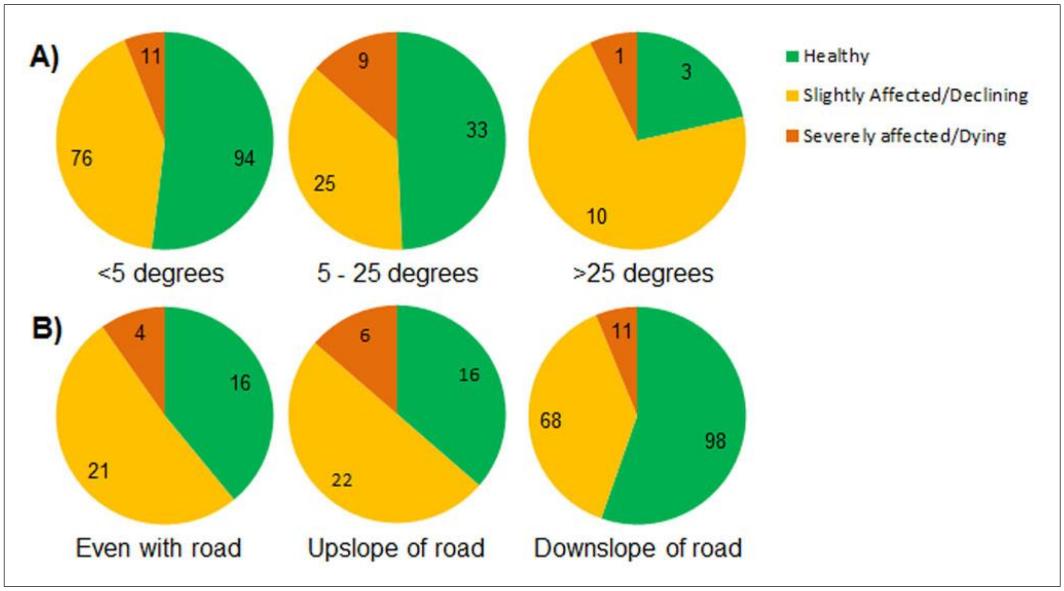

Figure 3.3. Relationship of spruce health to roadside (A) slope steepness and (B) drainage position. Numbers show the number of trees in each class.

Another proxy of tree health, the percentage of yellow needles at time of sampling, was less influenced by the location of the tree. Percent yellow needles only weakly correlated with road section (asymptotic $\chi^2 = 6.0$, $P = 0.05$) and did not differ based on position of tree base relative to the road surface ($P = 0.07$). However, trees nearer to the road, and on the steepest slopes had higher percentages of yellow foliage than those far from the road and on flatter slopes (Kendall's tau = -0.22, $P < 0.01$ and Kruskal-Wallis $\chi^2 = 10.43$, $P < 0.01$ respectively). There was a significant correlation between percent yellow foliage and chloride concentration of needle tissue (Kendall's tau = 0.10, $P < 0.05$; Figure 3.4).

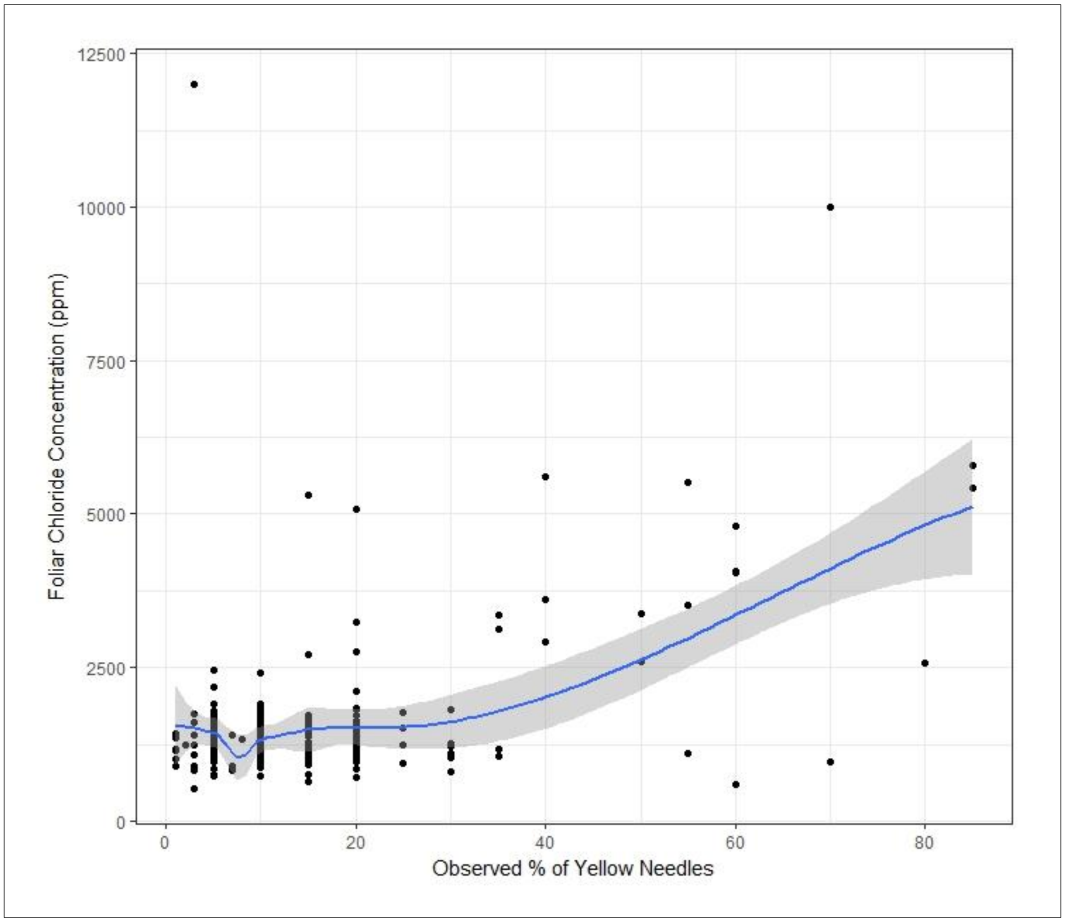

Figure 3.4. Correlation of the approximate percentage of yellow needles and measured foliar chloride concentration (ppm) in 262 white spruce along the Denali Park Road, Denali National Park and Preserve, Alaska. A locally weighted regression line (loess smoothing) is shown through observed values, with a 95% confidence interval (shaded area).

3.4 Discussion

Health of vegetation along the Denali Park Road is generally good, with the exception of the dense forests between mileposts 25 and 35. Our initial survey of herbaceous plants and woody shrubs detected sporadic, partial tissue damage that cannot be conclusively linked to application activities, foliar chloride, or other site variables measured. However, a low sample size for those growth form groups limits our interpretation. White spruce health on the other hand, was more variable, with nearly half of the trees sampled showing at least slight crown damage. This sensitivity of tree species to dust abatement effects agrees with Goodrich et al. (2009a) who also found impacts to the herbaceous and woody plant layer were more limited than those on tree species.

Spatial Variation of Tree Health in Relation to Dust Palliative Use

Our data indicate a complex relationship between cumulative $CaCl_2$ applications, foliar chloride, and perceived spruce health. For example, cumulative applications influenced whether a tree was healthy or not, but not the extent of decline (slight or severe), even though chloride in spruce needle tissues was higher in unhealthy vs. healthy trees. Similarly, the amount of road salt applied correlated with the incidence of tree damage, but not the severity of damage in Lake Tahoe (Munck et al 2010). In addition to uptake of chloride into needle tissue via roots, chloride may also accumulate via airborne particulate deposition during application activities (White and Broadley 2001), thus complicating the effect of chloride on overall tree health.

The most concerning impacts to tree health were observed in the Teklanika and Igloo forest areas (milepost 25-35), where dense vegetation and complex road angles appear to concentrate the effects of both fugitive road dust and palliative application activities. In these areas, the forest is very close to the road edge and forms a distinct "wall" significantly slowing and concentrating any wind-born particles. Our finding of worse spruce health in trees with their bases level with or upslope of the road highlight the implications of this "wall" effect.

Additional severe impacts were observed on the numerous road curves in these areas, where we observed "vortex" –like effects of fugitive dust being deposited onto to particular roadside trees at each bus pass. According to road maintenance personnel, in areas where the forest vegetation creates a catchment, fines from the road are recirculated in the air and trapped in the road corridor rather than getting blown away (Riley Tingue, pers. comm). The initial studies on dust and palliative impacts along the Denali Park Road occurred only on straight sections of road (Karle 1999, Marshall 1997) selected to reduce complexity in their studies, thus the possible effects of road curves may have been overlooked. Appendix D provides a catalog of special considerations for measuring and mapping impacts of dust palliative use on vegetation.

Traffic around the Teklanika Rest Stop is heavy, with almost all vehicles actively accelerating or decelerating through this zone. Direct observations indicate that many trees are subject to mechanical damage caused by passing traffic and maintenance equipment. The abrupt road-forest interface also seems to create a 'wind tunnel' effect by which fugitive dust suspended by passing traffic is transported and concentrated along the roadway, rather than away from it. It seems likely that road maintenance activities also may add stress to the vegetation in this area. The heavy traffic in this area may cause the application truck to move more slowly, which could inadvertently increase the application rate. In at least one previous year there was a leak in the tank, which may have unintentionally increased the amount of palliative deposited, particularly in areas where the application truck idled to clear traffic (Riley Tingue, pers. comm.).

The intensity and spatial distribution (e.g., slope position) of the crown damage observed in the Teklanika Forest area, in combination with the high levels of vehicular activity there, suggests that the chloride damage may primarily be occurring through salt spray and/or stomatal interference (i.e., dust caked on the needles) in addition to uptake of elevated chloride in soil solutions.

Relevance of Chloride Levels Detected in Roadside Vegetation

We detected elevated chloride levels (> 2000 ppm) in white spruce needle tissues up to 40-m away from the road edge, but the majority of high values were from trees < 10-m from the road. Factors that may contribute to elevated chloride concentrations include chloride runoff from the road surface and uptake via plant roots, direct spray of palliative onto vegetation, and/or chloride contained in fugitive dust (e.g., Pedersen et al. 2000). With our current dataset, it is not possible to distinguish whether spruce are accumulating foliar chloride via root uptake from soil solution or from unintentional salt spray (foliar absorption). Additionally, our observations indicated very little variation in damage characteristics.

The foliar chloride levels we observed in severely affected trees suggest a threshold of approximately 3000 ppm after which significant decline is likely. Similarly, Munck et al. (2010) found a mean foliar chloride content of 1903 ppm for asymptomatic (healthy) trees, and 4019 ppm for symptomatic (declining) trees along roads in Nevada treated with road salts in winter. They suggested that 3700 ppm foliar chloride was the tipping point at which salt damage symptoms were likely to manifest. Goodrich et al. (2009a) detected higher thresholds along Colorado roads treated with $MgCl_2$, where spruce tissues with 6000-7000 ppm chloride exhibited 50% crown damage, and full crown necrosis occurred at 9000 ppm chloride. The disparity in these values may reflect the different processes by which salts applied in summer (i.e., the Colorado study) vs. winter (i.e., the Nevada study) accumulate in the roadside environment (Piechota et al. 2004), or point to the varying ways that salts can lead to toxicity in plants (White and Broadley 2001). Regardless, our data indicate that if aggressive $CaCl_2$ application continues along sensitive areas of the road where numerous trees are already stressed or declining (i.e. the Teklanika Forest), it may contribute to a high incidence of whole-tree death in the coming years. Conifers have demonstrated the ability to recover from salt damage (Munck et al 2010), so a change in management practice in this area may slow or stop the processes that have caused the current problems we detected.

Chapter 4: Effects of $CaCl_2$ Applications on Roadside Soils

4.1 Chapter Objectives

We investigated the condition of roadside soil chemical properties before and after 13 years of regular dust palliative use along a 73-mile unpaved road in Denali National Park and Preserve, Alaska. We used identified patterns of dust palliative application (Chapter 1) and mean chloride in soil solution (Chapter 2) to evaluate the influence of cumulative dust palliative applications and related site factors on 2016 soil chemistry, including testing for the presence of heavy metals. We compared 2016 soil chemistry to 2003 soil chemistry tested with a similar study design (Roland 2003).

4.2 Methods

Field Procedures

We modelled our 2016 study after a 2003 study of dust palliative use effects on roadside soil chemistry. In 2003, after 9 years of preliminary testing and applications of various dust palliatives, Roland (2003) selected seven sites along the Denali Park Road (mileposts 15.5, 22.3, 26, 26.8, 27.7, 87.3, and 87.8) to investigate soil chemical properties. To assess the road's influence on the spatial pattern of soil chemical properties at each site he collected soil samples from the road shoulder, road edge (0-m), 1, 3, 5, 7, 9, 11, 13, and 15-m (Figure 4.1) out from the road edge on transects set perpendicular to the road. Because soil properties vary at small spatial scales, he installed three 15-m replicate transects at each site, placing them 5- to 10-m apart from one another. In 2016, we aimed to replicate Roland's (2003) study while also co-locating additional sites with soil lysimeters that had been installed in 2005 to assess the effects of dust palliative use on soil solutions (see Chapter 2; ABR, Inc. 2005). Because Roland's (2003) transects were not permanently marked, we used the mileposts indicated to estimate their location, adjusting locations slightly when a lysimeter had been installed within 0.5 miles. We investigated soil properties at 12 sites (mileposts 15.2, 18.6, 22.2, 23.4, 26.8, 28.8, 30.2, 49.1, 60.3, 71.2, and 88.2), collecting soil samples along three replicate transects each, at 1-, 3-, 7-, 11-, and 15-m from the road edge (an abbreviated form of Roland's (2003) methods; Figure 4.1). During both sample iterations (2003 and 2016), soil samples were retrieved from the upper 10-cm of the mineral horizon and frozen within 6 hours of collection. In 2016, we also collected several site variables potentially relevant to soil chemical properties (data not shown) including slope of the 1-m area around each sampling site, soil temperature, living mat type and depth, litter layer (Oi horizon) type and depth, organic mat (Oa horizon) type and depth, and depth to restrictive layer, which may be relevant to future monitoring efforts.

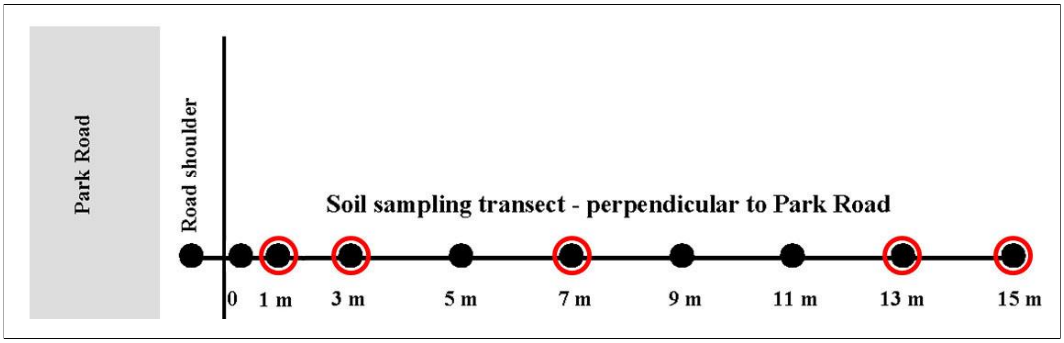

Figure 4.1. Schematic of a soil sampling transect employed by Roland (2003). Three replicate transects were installed at each site. 2016 sampling followed the same procedure but collected soils from the 1-, 3-, 7-, 13-, and 15-m pits only.

Laboratory Procedures

In 2016, we shipped frozen samples to the University of Idaho Analytical Sciences Lab in Moscow, Idaho for analyses of chloride, calcium, pH, and electrical conductivity (EC). They measured pH and EC using the 1:1 paste method and concentration of both chloride and calcium using a saturation paste extract method. The 2003 samples were analyzed by the University of Alaska Fairbanks Agricultural and Forestry Experiment Station Soil and Plant Analysis Laboratory, which was closed in 2015. Both laboratories used the same analytical methods.

Calcium chloride pellets used to create the slurry applied to the road surface during palliative application are comprised of 90-92% calcium chloride, with small amounts of potassium, sodium, and strontium chlorides mixed-in (Marshall 1997). However, as with any purchased compound, contamination is possible. To ascertain if additional compounds might be present in the applied palliative, particularly those known to cause detriment to plants in even small amounts, we also tested for the presence of heavy metals (Pb^{4+}, Cd^{2+}, and Hg^{2+}) in a subset of soils (n = 20). Laboratory personnel analyzed for lead and cadmium via an acid digest ICP-MS method (EPA 3050B/6020B), and mercury via a cold vapor technique (EPA 7471B modified method).

Data Analyses

To evaluate change in soils 2003 to 2016 while comparing changes between areas of heavy and minimal palliative application, we aggregated sites by their broad application class, considering ‘east end’ sites as treated road segments (n = 5 in 2003 and n = 8 in 2016), and ‘west end’ sites as control segments (n = 2 in 2003 and n = 3 in 2016; Roland 2003). The east and west end framework was part of original study design (Roland 2003) that did not include any areas of moderate palliative use, thus ‘medium’ application areas used in Chapters 1-3 (see Figure 1.2) and sampled in 2016 (n = 2) were excluded from this comparison. Because soil properties vary at small spatial scales, we utilized the three replicate transects for each sampling iteration and site to produce a mean with variance for each soil attribute at all measured distances from the road, at each site.

To evaluate the influence of cumulative dust palliative applications on soil chemistry, we aggregated 2016 site locations by the cumulative application classes identified in Chapter 1 (high, medium, and low applications; see Figure 1.2) to compare the relative influence of $CaCl_2$ application on soil chemical properties. Considering prior study of mean chloride in soil solution (Chapter 2), in which we identified particularly high chloride in soil solution along segments of the road with (1) banked curves draining large areas (i.e., milepost 18.6), (2) high-traffic congestions areas (i.e., milepost 30.2), and (3) steep slopes (i.e., milepost 15.2; see Chapter 2 discussion), we also investigated soil chemical properties at these three sample sites singly, aggregating only by replication transect.

To test for differences in soil chemical property means (pooled across replicate transects and distances) between sample years, treatment types (i.e., treated or control), and application classes, we used an exact permutation test estimated by 5000 Monte Carlo replications in the 'perm' package (Fay and Shaw 2010) in R (R Core Team 2016), determining a difference in means existed when the p-value was below 0.05. We followed with a pairwise Mann-Whitney *U*-test (Benjamini-Hochberg adjustment) to distinguish between groups (McDonald 2014). We also followed those procedures to investigate the influence of road-edge slope on the distribution of soil chloride away from the road, allowing distance to vary and pooling data into categories of "flat" or "sloping" or "steep". We used the non-parametric Kendall rank correlation coefficient to evaluate trends between soil properties and cumulative application rate.

4.3 Results

Comparison of Soil Properties 2003 – 2016

Analyses of soil chemical properties before and after 13 years of dust palliative use (see Chapter 1) revealed that an alteration of soil properties related to the amount of $CaCl_2$ applied may be occurring, but that the process was spatially and temporally complex. In general, soils along 'control' segments of the road (west end) that were subject to very little palliative application over the study period had significantly lower mean chloride, pH and EC than east end 'treated' road segments regardless of sampling year (Figure 4.2).

Across the study period (2003-2016), soils along the Denali Park Road, regardless of road end, exhibited a significant decrease in chloride concentration and EC. For some soil properties, changes across the study period differed between the east ("treated") and west ("control") road ends; for example, pH of west end soils significantly increased, while pH of east end soils significantly decreased. Other soil properties showed similar changes across the study period for west and east ends of the road; for example EC declined over time in both east end and west end soils. Chloride concentration decreased significantly in east end soils, mostly due to decreasing levels within 7-m of the road (Figure 4.2), but chloride levels in west end soils did not change significantly. Calcium concentrations in 2016 were ten times lower than in 2003 in both east and west end soils.

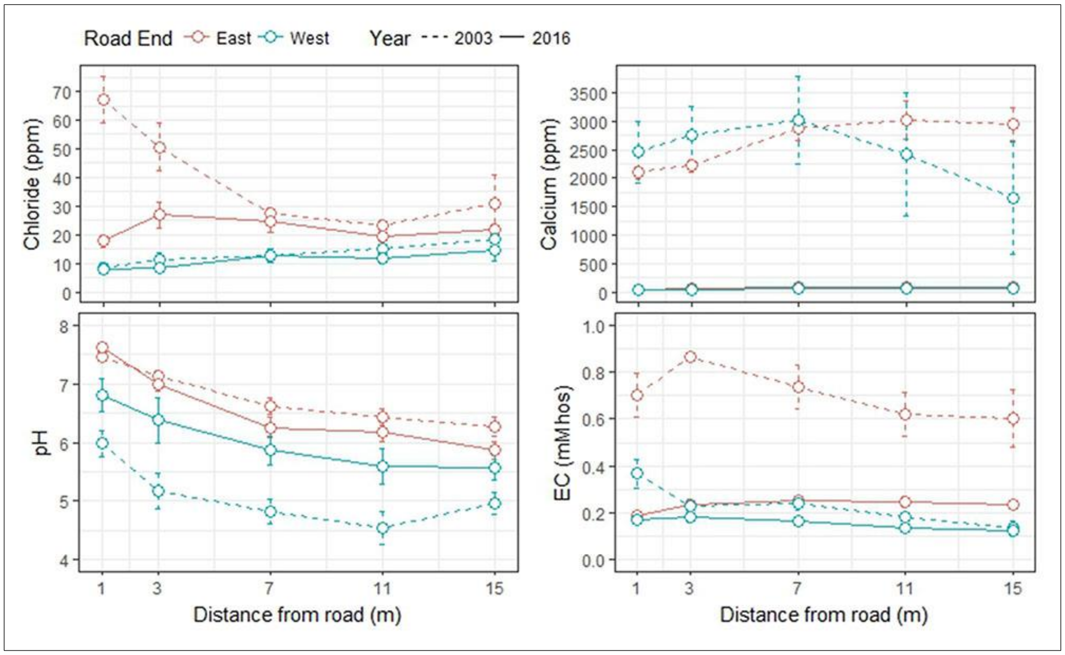

Figure 4.2. Chemical properties of roadside soils along road segments in the east ('treated' with 13+ years dust palliative applications), and west ('control' with very few dust palliative applications) ends of the Denali Park Road, Denali National Park and Preserve, Alaska. Sampling year is indicated by line type, with 2003 samples occurring after 4 years of preliminary palliative testing and use, and 2016 samples occurring after 13 years of regular $CaCl_2$ applications.

2016 Soil Properties in Relation to Cumulative $CaCl_2$ Applications and Site Factors

Cumulative $CaCl_2$ application was significantly correlated with 2016 soil chloride, EC, and pH (Kendall's tau = 0.20, 0.13, 0.19 respectively, $P < 0.05$). Analyses of soil chemical properties along road segments with high, medium, or low cumulative $CaCl_2$ applications (2003-2016) revealed evidence that cumulative application rate likely has an effect on soil chloride concentration and EC, especially in the first 7-m from the road edge (Figure 4.3). High application zones exhibited significantly higher chloride than other zones and low application zones had significantly lower EC and pH than both high and medium zones (Figure 4.3). Based on soil chloride detected along segments of the Denali Park Road not treated with dust palliative, we estimate the background level of chloride in native roadside soils to be < 40 ppm. Calcium across distances from road did not vary between application zones ($P = 0.11$).

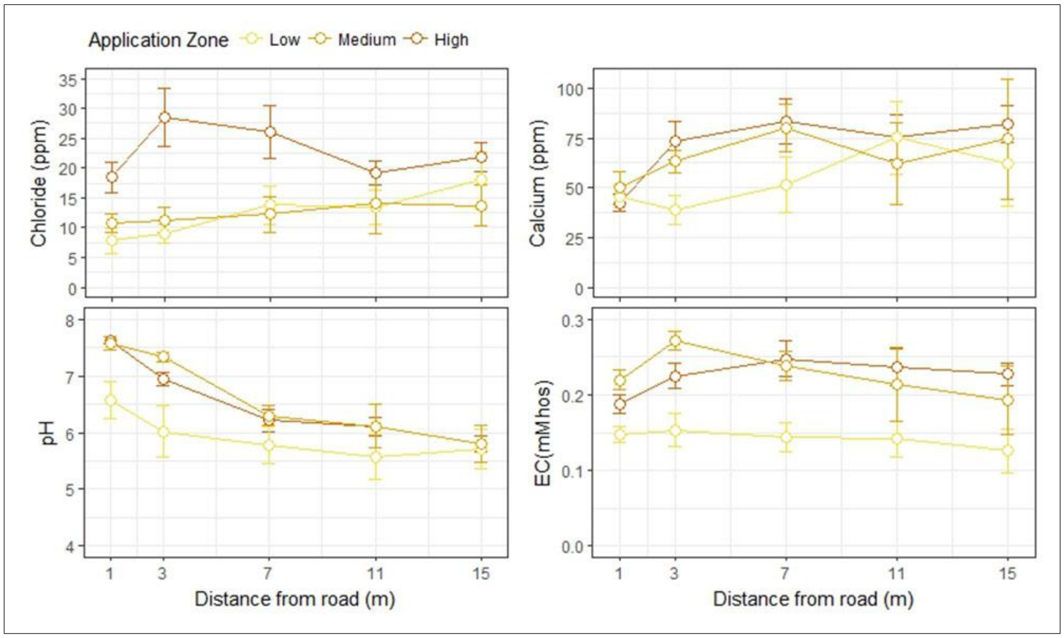

Figure 4.3. Chemical properties of 2016 roadside soils along road segments of varying levels of cumulative dust palliative applications (see Figure 1.2) on the Denali Park Road, Denali National Park and Preserve, Alaska.

The sampling transects with the highest mean soil chloride were at mileposts 28.8 (S06) and 30.2 (S07; also site of the highest soil pore water chloride, see Figure 2.2). These sites also had the highest maximum values recorded in our 2016 dataset, with 93.6 and 82.9 ppm chloride respectively (Table 4.1). To investigate the influence of site factors on the distribution of soil chloride away from the road edge we plotted 2016 soil chloride against distance from the road edge relationship at sites of interest (Figure 4.4). For example at milepost 28.8, a steep slope, chloride was highest at 7-m from the road edge, while at milepost 30.2 where the slope away from the road edge is flat, maximum chloride was closer to the road (3-m) and less variable based on distance overall (Table 4.1; Figure 4.4a and b). Across all soil sampling transects, those that traversed notable slopes down away from the road edge exhibited higher mean soil chloride (asymptotic $\chi^2 = 16.88$, $P < 0.001$), but this trend was not significant at individual distances from the road.

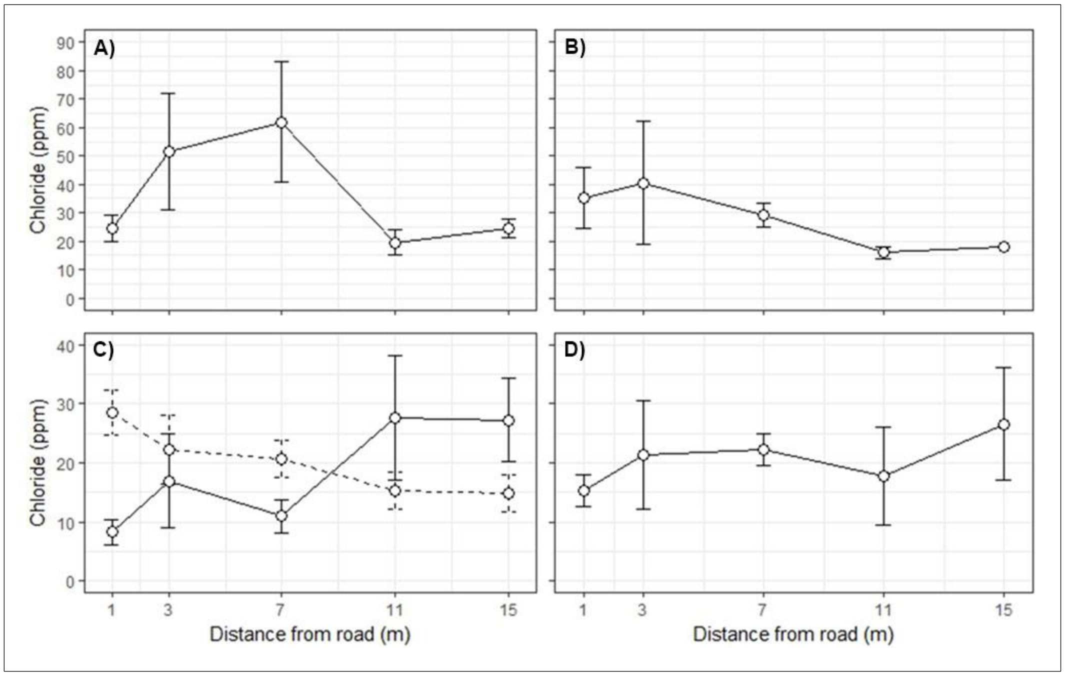

Figure 4.4. Chloride concentration of roadside soils at lysimeter stations along the Denali Park Road, Denali National Park and Preserve, Alaska. The sites of highest soil chloride were found at along a steep slope at milepost 28.8 (A) and a flat area at milepost 30.2 (B). Soil chloride on an extremely steep slope (milepost 15.2; C) and a banked road curve (milepost 18.6; D) are also shown, but note change in the scale of the y-axes. The dashed line in C represents soil chloride recorded at that site in 2003. The other sites did not have corresponding data from 2003.

Table 4.1. Summary of measured chloride concentrations in 2016 roadside soils along the Denali Park Road, Denali National Park and Preserve, Alaska. n = number of soil samples in three replicate transects.

Milepost	Associated Lysimeter	Site Description	n	Mean	Median	Std. Dev.	Max Cl- (ppm)	Distance from Road (m) where Max Cl- Detected
15.2	S01	steep slope, willow shrub	15	18.2	11.17	13.05	40.65	15
18.6	S03	banked curve, willow shrub	15	20.7	18.72	11.26	45.45	15
22.2	S04	flat, willow shrub	15	12.9	13.12	4.39	23.14	11
23.4	S23	flat, forested	15	22.3	19.5	8.81	39.78	15
26.8	S05	steep slope, willow shrub	15	20.6	23.54	9.24	34.39	3
28.8	S06	steep slope, forested	15	36.5	23.82	26.56	93.60	7
30.2	S07	flat, forested, congested	13	29.3	20.56	19.95	82.96	3
49.1	S19	flat, willow shrub	15	16.9	14.28	7.81	38.29	11
60.3	S12	flat, willow shrub	15	7.88	7.02	3.39	13.40	7
71.2	S14	flat, willow shrub	15	8.17	7.45	5.05	23.99	15
88.2	S17	flat, forested	12	8.71	7.07	5.47	19.14	11

Heavy Metals in Soils

Heavy metal contamination in the calcium chloride pellets sourced for dust palliative applications along the Denali Park Road was not major a concern based on our tests. Of 20 soil samples tested in 2016, we detected only one case of slightly elevated mercury (0.84 ppm; accepted range 0.01-0.5 ppm (Obrist et al. 2016)) at milepost 49.1. Another sample from the same milepost returned an 'accepted' mercury reading of 0.37 ppm. No elevated levels of lead or cadmium were detected in our samples.

4.4 Discussion

Change in Soil Properties after 13 Years of Dust Palliative Use

Soil chemical properties likely to be influenced by the addition of $CaCl_2$ to the roadside environment have declined or stayed the same over the study period. Both chloride and EC decreased between 2003 and 2016, particularly in the east ("treated") end, where Roland (2003) detected elevated chloride concentrations in soils up to 5-m from the road edge. He suggested experimental dust palliative treatments applied in the early stages of the dust abatement program (1994-1999) as the cause of these elevated levels, and proposed further monitoring to assess whether soils would reach equilibrium or continue to rise. After 13 years, chloride levels in soil have decreased, even near the road in the zones of highest $CaCl_2$ application. Thus, in concurrence with Roland (2003), we attribute the decline in soil chloride and EC recorded over the study period as "recovery" of the system after very high application rates used during the testing period (1994-1999; Karle 1999). It is likely that the more conservative application rates adopted since the testing period have resulted in no, or only temporary, additional accumulations of soil chloride,. The accumulation of chloride in soils is limited by the fact that chloride is highly soluble (White and Broadley 2001), although retention can occur, particularly in highly organic soils (i.e., Oberg and Bastviken 2012). Goodrich et al. (2009a) showed no change in soil chloride over two years of sampling $MgCl_2$-effected roads. Similarly, a study along heavily salted roads in Nevada could not confirm that salts were accumulating in soils, as EC had not changed significantly even after 17 years of application (Munck et al. 2010).

We consider the change detected in the other two soil chemical properties to be influenced more by site factors or natural variation than trends related to dust palliative use. Our data show that west end pH has risen considerably between 2003 and 2016, but we attribute this to the lack of precision in site selection when repeating the 2003 study. Many west end road segments are proximal to wetlands, and wetland-influenced soils, that could have a major impact on soil chemical properties recorded. Calcium concentrations were an order of magnitude lower in 2016 than in 2003, for both east and west road ends. We consulted with both laboratories used for the different samples to confirm methodologies and rule out unit conversion error. It is possible calcium could be leached from the soil if replaced by other cations as has occurred with the use of $MgCl_2$ dust palliatives (Goodrich et al 2009a), but if so, pH would also decrease (Melissa Dick, former Palmer Lab Supervisor, pers. comm.). However, there has not been a known introduction of cations likely to push calcium into leachable solution, and we did not detect the associated pH decrease predicted if this hypothesis were true. In lieu of identifying or hypothesizing a physical or biological mechanism for this apparent loss of calcium from the roadside environment, we tentatively conclude these data are not comparable.

Spatial Variation of 2016 Soil Properties in Relation to Dust Palliative Use

Despite differences in the underlying native soils along the Denali Park Road, patterns of 2016 soil chemical properties suggest that at least some of the observed variation is due to cumulative $CaCl_2$ applications. For example, segments of road subject to high cumulative applications displayed higher soil chloride and EC, especially within the first 7-m from the road edge. Similar patterns of elevated soil chloride 5- to 10-m from the road edge have been detected after short-term palliative use in our study area (Marshall 1997, Roland 2003), and long-term use of dust palliatives elsewhere (Hofstra and Smith 1984, Goodrich et al. 2009a). The finding of elevated soil chloride and EC correlated with $CaCl_2$ applications is somewhat in contrast to our data gathered across the two sampling iterations (2003 and 2016) described above, likely reflecting the apparent temporary influence of recent applications (< 4 years). Indeed, chloride is highly soluble and not thought to accumulate much in soils over time (White and Broadley 2001), thus we suspect that differences detected in 2016 as compared to 2003 more accurately reveal the soil condition at two independent (and unassociated) points in time. For example, the chloride in soil pore water at time of sampling likely influences chloride in soils. Soil processes are both spatially and temporally complex and it remains unclear on what time-scale the accumulation of chloride occurs (e.g., Svensson et al. 2012).

Our data show that the inputs of chloride in soil solution (the presumed source of soil chloride) varied greatly based on site factors (see Chapter 2); thus we were also interested in how specific road properties (i.e., banked curves and steep off-road slopes) influence the accumulation of soil chloride. Soils alongside sloping edges of the road had higher chloride concentration overall, but not when considering specific distances. That is, there was not a consistent pattern in the distribution of chloride away from the road related to slope (i.e., steep slopes effectively “pushing” the maximum soil chloride detected on a given transect further from the road edge). Similarly, percent slope did not have an influence on the pattern of soil chloride levels with respect to distance from the road edge in Colorado, but presence of road curves and drainages channeling water into the roadside environment did (Goodrich et al. 2009a). Although we did not test explicitly for the influence of road curves due to limited sample size (n = 1), it is reasonable to expect that the patterns of concentration at individual sites are controlled by such road edge and drainage morphologies. Indeed, similar to chloride in soil solution, our data indicate that it is likely site factors contribute to how the $CaCl_2$ applied at a given site enters the soils of the roadside environment.

Relevance of Chloride Levels Detected in Roadside Soils

The highest soil chloride value we recorded along the Denali Park Road was < 100 ppm; well below the levels of chloride contamination detected in other studies of dust palliative effects (e.g., 400 ppm, Goodrich et al. 2009b). We estimate the background level to be no more than 40 ppm, as conservatively estimated along segments of the Denali Park Road not treated with dust palliative. This is comparable to background soil chloride measured in Colorado (20-30 ppm) where soil chloride along roads treated with dust palliative was 10-20 times higher (Goodrich et al. 2009b). Soil chloride along treated segments of the Denali Park Road was 2-3 times higher than background levels.

Our tests for heavy metal accumulation in soils returned one unexpected high value (for mercury), which we do not consider a cause for concern, because a replicate at the same site did not exceed threshold. Heavy metals could originate from palliative contamination or could be transported into the park via vehicle exhaust or tires. These metals are known to mobilize in soils, especially the acidic soils common in our subarctic environment (Mikkelsen et al. 1994). It is recommended to test for heavy metal contamination in soils occasionally, and to test the dust palliative itself when a new batch is obtained, or if a new supplier sourced.

Synthesis and Conclusions

We undertook a detailed set of analyses of the effects of thirteen years of dust palliative use on the roadside environment along the Denali Park Road in subarctic Alaska. In this report, we have described the effects quantified during annual monitoring of surface and soil pore waters, targeted studies on soils over the entire study period, and vegetation health after years of $CaCl_2$ applications. We submit our findings to assist managers in planning the next decade of dust palliative use in Denali.

Concurrence of Elevated Chloride in Roadside Soil Pore Water, Plant Tissue, and Soils

Our analyses provide evidence that the level of chloride in soil pore water contributes to chloride levels detected in roadside plant tissues and soils. Although the uptake of chloride in solution via plant roots is a complex phenomenon (White and Broadley 2001), and the accumulation and residence of chloride in soils is variable (Öberg and Bastviken 2012), trends in our data indicate that effects to one ecosystem component are often compounded by effects to another. Segments of the road with similar vegetation, topography, and application histories are likely to display similar patterns in chloride accumulation. Further, chloride measured in several components of the roadside ecosystem (i.e., surface waters, soil water in solution, plant tissues, and soils) tend to vary together. However, additional research into the various chemical pathways and transformations of $CaCl_2$ in the soil profile, and the interactions between these reactions, would be necessary to make more definitive judgements regarding causal factors and precise thresholds. Such an undertaking would be very costly to be definitive at the scale of the Denali Park Road corridor.

Concurrence of $CaCl_2$ Applications and Chloride in the Roadside Environment

Our analyses provide ample evidence that the level of chloride detected in the roadside environment (i.e., soils, water, and plants) is related the level of $CaCl_2$ applied. Segments of the road with the highest cumulative $CaCl_2$ applications routinely contained the highest concentrations of chloride in soil pore water, surface water, vegetation, and soils, both near and far (~10 m) from the road edge. Similarly, segments of the road with the very little or no $CaCl_2$ applications routinely contained very low concentrations of chloride. However, spatial and temporal factors complicate this relationship, such that sites bearing the very highest application loads were not necessarily the sites with the highest accumulated chloride levels or the most severe vegetation damage. For example, we found that the influence of palliative-derived chloride in soil pore water extends > 10 m on either side of the road, but up to 25 m or more where steep slopes adjoin the road. Additionally, palliative-derived chloride has the ability to influence soil solutions for several years after application, but this varies based on the precipitation patterns during the season of application and the local runoff geometry among other factors (Jacobi et al. 2014).

Are We Approaching or Exceeding Environmental Thresholds?

Our data indicate that background levels of 2 ppm chloride in soil pore water, 5 ppm in surface water, 40 ppm in soils, and 2000 ppm in spruce needle tissue can be expected in areas of little to no influence of dust palliative use (i.e., > 20-m from the road and/or along control segments of road not treated with $CaCl_2$). Identifying the background levels of chloride in our area was a critical step for monitoring ecosystem function and helpful in predicting how dust palliative inputs may affect ecosystem components (i.e., vegetation, water, and soils). For example, our surveys of vegetation health along the Denali Park Road indicate that white spruce health declines when accumulation of chloride in needle tissues exceeds 3000 ppm. Chloride in needle tissue accumulates primarily via uptake of chloride in soil solution by plant roots (White and Broadley 2001), thus chloride-laden runoff is most likely contributing to localized spruce decline.

Management Recommendations

There is no question of the need for dust palliative application along the Denali Park Road, even when considering *only* the health of the roadside environment, as several studies in subarctic Alaska have shown the negative effects of fugitive road dust on native vegetation and soils (i.e., Myers-Smith et al. 2006). Additional concerns of Denali's road management team to preserve an acceptable visitor experience and road surface sustainability only add to the need for effective dust abatement. Our data indicate that although dust abatement activities certainly influence the spatial and temporal pattern of chloride in roadside water, vegetation, and soil resources, after 13 years of dust palliative use, concentrations remain unlikely to cause environmental harm – with a few critically important exceptions. Moving into the next decade of dust palliative application along the Denali Park Road, road managers will face several pertinent questions. For example, how can dust palliative application activities be modified to reduce harm to those segments of the road most susceptible to chloride accumulation (i.e., along road curves and steep road embankments, or in the Teklanika Forest area)?

Noting trends in the pattern of dust applications since the establishment of the dust abatement program, it is apparent that both total application miles and the average application rate have declined because of improved program efficacy. Through the early phases of the dust abatement program, road maintenance staff developed a better understanding of palliative effectiveness along the Denali Park Road. This improved understanding, along with enhancements to application equipment, has resulted in a more focused approach, with lower application rates targeted at only the highest-priority road segments. We regard this adaptability on part of the maintenance staff as indication that further modifications to application procedures may be successful. The specific suggestions below should allow road managers to reduce the environmental impacts of dust palliative use along the Denali Park Road, while still meeting dust abatement objectives:

- Limit cumulative palliative applications such that any particular road segment does not receive accumulations more than 1.5 lbs/yd^2 during any 4-year period. Monitoring indicates that accumulations above that amount may contribute to chloride in soil solution above biologically detrimental levels (> 250 ppm).
- Decrease palliative applications along 'high-risk' road segments such as (1) tight curves where large surface areas drain to smaller points, concentrating chloride (i.e., milepost 18.6) and (2) locations where road embankments are particularly steep (> 25% grade) and runoff is likely to occur quickly (i.e. milepost 15.2, 28.8). If aggressive $CaCl_2$ application continues in these areas, tissue damage or plant death in roadside vegetation may occur. Compile a comprehensive inventory of these areas and select the most vulnerable to restrict palliative use.

- Ensure palliative application practices do not contribute to elevating concentrations along 'high-risk' road segments, by (1) checking application equipment for leaks regularly and (2) avoiding unnecessary stopping or slowing while actively spraying. Communicate these tenets among staff as best management practices to follow.
- Consider use of non-chloride based dust suppression (i.e., water) or alternate road stabilization products in the Teklanika and Igloo Forests areas, where white spruce is showing considerable decline and stress that is related, at least in part, to chloride uptake. However, any stabilization products considered should be sufficiently tested for effectiveness and safety by industry experts.
- Observations of dust palliative effects on the roadside environment warrant a continued program of monitoring.
    - Records of application events supplied by roads staff are critical to effective monitoring.
    - Annual soil solution monitoring is working well as an indicator of initial chloride inputs to the roadside environment.
    - Decadal (or preferably more frequent) monitoring of vegetation, particularly spruce, is necessary, and should include a targeted study of the balance between dust palliative use and fugitive dust impacts to plant health.
    - Decadal monitoring of soil chemical properties, at least in 'high-risk' areas, will add to a critical understanding of the long-term effects of dust palliative use.

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Appendix A. Denali Park Road Weather Summaries, Summer 2003-2016

The east end of the road (Denali Headquarters weather station) is generally the driest and warm, receiving an average of 9.01 inches precipitation during the summer (May - August) with an average summer temperature of 51.6 °F across the study period (2003 – 2016; Table Appendix A.1). The central park area (Toklat weather station) is wetter and very cool, receiving an average of 12.3 inches precipitation, with an average summer temperature of 47.9 °F (2006 – 2016). The west end of the road is the wettest, but as warm as Denali Headquarters, with an average precipitation of 14.5 inches and temperature of 51.3 °F (Wonder Lake weather station; 2003 – 2016). Interestingly, the proportions of hot and dry days only partially coincided with the trends in average temperature and precipitation. For example, the Toklat and Wonder Lake stations had a higher proportion of hot and dry days even though they had more precipitation than the east end, which apparently receives more frequent precipitation events (Table Appendix A.1).

The coldest year of the study period was 2008 at all stations, while the wettest years were 2015 on the east end, and 2016 farther into the park (Figure Appendix A.1). The warmest year of the study period was 2004 at all stations (Toklat missing data), while the driest years were 2013 on the eastern end of the road, 2007 in the central park, and 2009 on the west end.

Table Appendix A.1. Summer weather data (May – August) for three stations along the Denali Park Road, Denali National Park and Preserve, Alaska. Percent days hot and dry includes summer days with above average temperature (as compared across the study period) and without precipitation.

	Denali Headquarters			Toklat			Wonder Lake		
Year	**Total Precip. (in.)**	**Temp (°F)**	**% Days Hot & Dry**	**Total Precip. (in.)**	**Temp (°F)**	**% Days Hot & Dry**	**Total Precip. (in.)**	**Temp (°F)**	**% Days Hot & Dry**
2003	9.25	50.61	23.08	NA	NA	NA	15.81	53.25	41.30
2004	7.49	55.93	46.72	NA	NA	NA	12.44	55.58	54.10
2005	9.19	53.56	17.07	NA	NA	NA	12.81	52.80	39.84
2006	9.69	50.01	24.59	11.29	46.79	28.46	18.99	49.57	23.58
2007	8.35	53.13	27.05	8.76	49.35	45.53	15.6	51.79	30.89
2008	9.92	47.89	11.67	12.34	45.05	17.07	13.37	47.94	22.76
2009	7.11	50.92	33.33	9.05	48.79	45.53	8.45	50.62	34.96
2010	7.69	50.92	23.77	14.07	48.61	31.71	9.28	50.99	23.58
2011	7.02	49.74	20.33	9.92	46.75	28.46	10.93	49.65	24.39
2012	7.92	49.32	22.76	10.93	46.92	24.39	18.88	49.65	19.51
2013	5.60	50.78	38.21	9.14	48.28	39.02	10.22	51.75	40.65
2014	11.01	49.83	21.95	14.94	47.44	28.46	16.38	49.84	30.89
2015	14.22	51.34	28.46	16.28	49.06	34.15	19.57	52.07	38.21
2016	11.64	52.20	17.07	18.84	50.10	41.46	20.8	52.12	26.83
Average	**9.01**	**51.16**	**25.43**	**12.32**	**47.92**	**33.11**	**14.54**	**51.26**	**32.25**

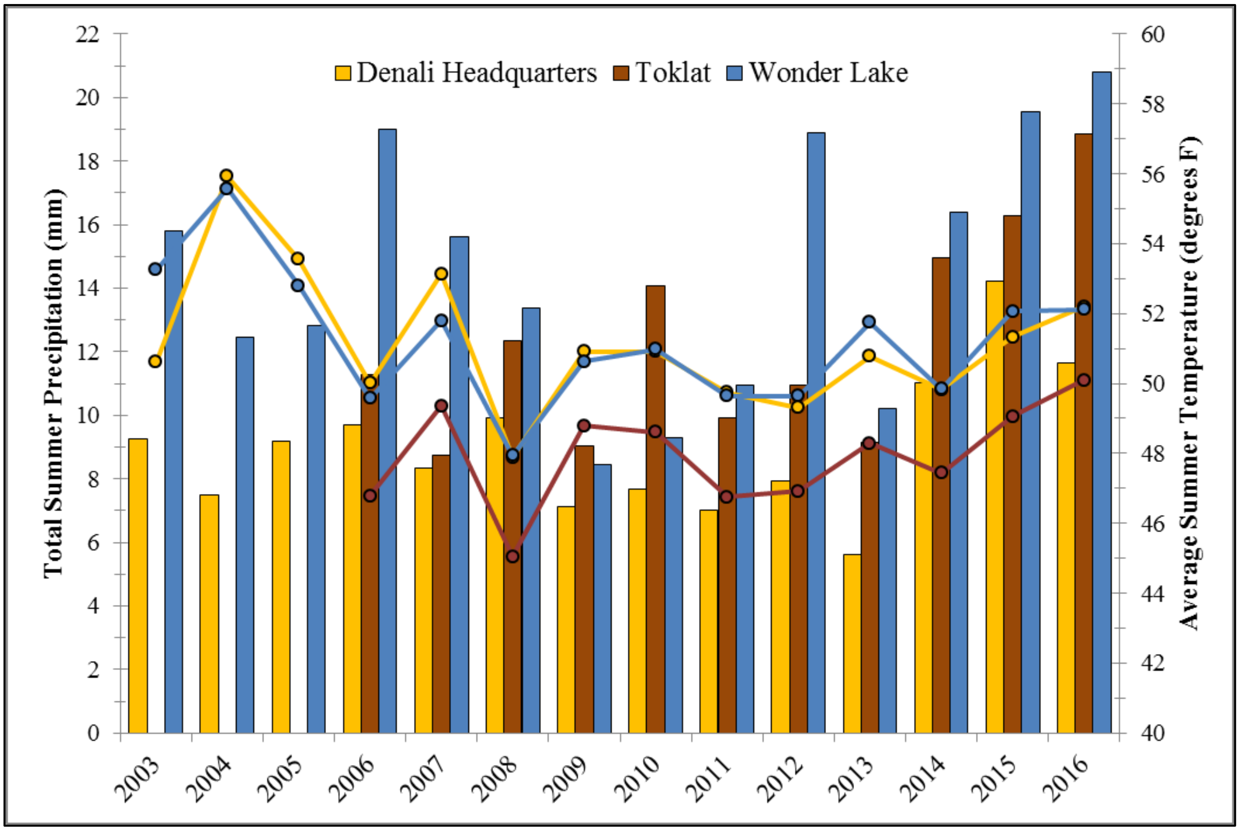

Figure Appendix A.1. Comparison of summer weather data (May – August) for three stations along the Denali Park Road, Denali National Park and Preserve, Alaska.

Appendix B. Efficacy of Soil Pore Water Sampling

Lysimeter Sampling Success

Because the soil lysimeters installed rely on negative pressure to draw soil pore water out of the ground and into water sample bottles above ground, it is imperative that adequate negative pressure is achieved and maintained in the lysimeter system during sampling. Over the study period (2005-2016), soil pore water was successfully collected from each soil lysimeter at least 4 times. Six soil lysimeters produced a valid soil pore water sample every year of sampling (Table Appendix B.1; excluding 2009 in which sampling failed in almost all lysimeters due to freezing conditions). Over 11 years of sampling (excluding 2009) in which 30 lysimeters were set with negative pressure to draw soil pore water into a sample bottle, 83% of those sampling attempts produced enough soil pore water for chloride concentration analysis. Moving forward with the monitoring program, at least three soil lysimeters should be dug up for repairs (Table Appendix B.1; S19A and S23A which have not produced a sample since 2008, and S13A whose last sample was 2010).

Table Appendix B.1. Sampling success at each soil lysimeter station over the study period (2005-2016).

		Station A (1m from road)		Station B (10m from road)	
Lysimeter	**Milepost**	**Success Rate***	**Last Success**	**Success Rate***	**Last Success**
S01	15.15	91 %	2016	82 %	2016
S03	18.56	73 %	2016	82 %	2016
S04	22.12	91 %	2016	82 %	2016
S23	23.34	36 %	2008	82 %	2015
S05	26.80	82 %	2016	73 %	2016
S06	28.76	100 %	2016	82 %	2016
S07	30.12	82 %	2016	82 %	2015
S09	41.40	82 %	2016	82 %	2016
S19	49.04	36 %	2008	91 %	2016
S11	58.27	100 %	2016	100 %	2016
S12	60.22	100 %	2016	82 %	2016
S13	64.38	45 %	2010	100 %	2016
S14	71.11	91 %	2016	100 %	2016
S15	79.64	91 %	2016	91 %	2016
S17	88.15	91 %	2016	91 %	2016

*Success rate = percentage of years (2005-2016, excluding 2009) where a valid sample of soil pore water was obtained from the lysimeter.

Temporal Variation of Chloride in Soil Pore Water

We generally undertake soil pore and standing water sampling in mid-August; near the end of the season but before the first frost or snowfall, when freezing may affect the stratification of salts in water. In 2015 and 2016, we sampled a subset of 7 lysimeter stations and 20 standing water sites in

July as well for a brief look into how the timing or seasonality of sampling may influence chloride concentrations.

No clear pattern variation of chloride concentrations in soil pore or standing waters was apparent; however, this exercise highlighted the temporal variability of chloride moving through the roadside environment. For example, the range of chloride in soil pore water measured twice (July and August) at one site varied between 0.1 ppm and 170 ppm, with an average of 19 ppm. Similarly, the range of chloride in standing water measured twice (July and August) at one site was between 0.1 ppm and 106 ppm, with an average of 5.7 ppm.

$CaCl_2$ was applied (0.43 lbs/yd^2) between the July and August sampling iterations at two sites in 2015. The standing water site W34, located in a roadside ditch at milepost 17.5, showed a 106 ppm increase in chloride after the $CaCl_2$ application. In contrast, the lysimeter site S03, located on a banked curve at milepost 18.6, showed a 127 ppm decrease in chloride 1-m from the road, and a 0.01 ppm increase 10-m from the road.

Table Appendix B.2. Comparison of chloride in soil pore and standing water in July and August at a subset of monitoring sites in 2015 and 2016.

Site Name	Milepost	Site Type	Location Notes	Sample Year	July Cl- (ppm)	August Cl- (ppm)	Interim Appl. Rate	Δ July - August
S01B	15.15	soil lysimeter	~10m from roadbed	2016	2.18	1.63	-	-0.55
W34	17.53	auxiliary water	ditch	2015	4.20	110.00	0.43	105.80
W34	17.53	auxiliary water	ditch	2016	0.29	0.41	-	0.12
W23	18.07	permanent water	puddle on pullout	2015	20.00	3.40	-	-16.60
W23	18.07	permanent water	puddle on pullout	2016	0.13	0.70	-	0.57
S03A	18.56	soil lysimeter	~1m from roadbed	2015	180.00	53.00	0.43	-127.00
S03B	18.56	soil lysimeter	~10m from roadbed	2015	30.00	49.00	0.43	19.00
S03A	18.56	soil lysimeter	~1m from roadbed	2016	0.34	0.35	-	0.01
S03B	18.56	soil lysimeter	~10m from roadbed	2016	3.87	0.76	-	-3.11
W01	22.11	permanent water	-	2015	0.34	0.25	-	-0.09
S04B	22.12	soil lysimeter	~10m from roadbed	2015	22.00	37.00	-	15.00
S04A	22.12	soil lysimeter	~1m from roadbed	2016	4.82	5.63	-	0.81
S04B	22.12	soil lysimeter	~10m from roadbed	2016	0.27	0.56	-	0.29
S23B	23.34	soil lysimeter	~10m from roadbed	2015	5.50	4.60	-	-0.90
S23B	23.34	soil lysimeter	~10m from roadbed	2016	1.36	1.43	-	0.07
W31	25.31	auxiliary water	ditch	2016	6.47	1.04	-	-5.43
W22	27.61	permanent water	culvert	2015	0.60	0.25	-	-0.35
S06A	28.76	soil lysimeter	~1m from roadbed	2015	1.40	0.92	-	-0.48
S06B	28.76	soil lysimeter	~10m from roadbed	2015	86.00	44.00	-	-42.00

Table Appendix B.2 (continued). Comparison of chloride in soil pore and standing water in July and August at a subset of monitoring sites in 2015 and 2016.

Site Name	Milepost	Site Type	Location Notes	Sample Year	July Cl- (ppm)	August Cl- (ppm)	Interim Appl. Rate	Δ July - August
S06A	28.76	soil lysimeter	~1m from roadbed	2016	4.78	2.02	-	-2.76
S06B	28.76	soil lysimeter	~10m from roadbed	2016	28.61	33.71	-	5.10
W02	28.80	permanent water	pond	2015	0.43	0.39	-	-0.04
W21	29.60	permanent water	backwater of stream	2015	6.60	5.50	-	-1.10
W21	29.60	permanent water	backwater of stream	2016	9.02	16.46	-	7.44
W03	30.07	permanent water	-	2015	2.20	0.96	-	-1.24
W03	30.07	permanent water	-	2016	4.62	5.20	-	0.58
S07A	30.12	soil lysimeter	~1m from roadbed	2015	450.00	280.00	-	-170.00
S07B	30.12	soil lysimeter	~10m from roadbed	2015	52.00	45.00	-	-7.00
S07A	30.12	soil lysimeter	~1m from roadbed	2016	32.87	1.19	-	-31.70
W20	30.91	permanent water	pond	2015	28.00	0.30	-	-27.70
W20	30.91	permanent water	-	2016	23.06	28.83	-	5.77
W29	31.34	auxiliary water	ditch	2016	6.00	61.45	-	55.45

Appendix C. Results of Roadside Survey of Potential Plant Tissue Damage

We restricted our formal analyses of vegetation tissue damage related to $CaCl_2$ application to white spruce due to a limited number of samples from other species. We present a summary of chloride in plant tissues of all species sampled in Table Appendix C.1 and C.2. Table Appendix C.3 presents a comparison of chloride in paired declining and healthy samples, including photographs which may assist future monitoring efforts.

Table Appendix C.1. Mean chloride concentration (ppm) in plant tissue of various species.

	Chloride concentration (ppm)				
Species	**n**	**Mean**	**Std. Dev**	**Min**	**Max**
Arctostaphylos rubra	1	2343	n/a	2343	2343
Artemisia tilesii	2	9277	4855	5844	12710
Carex sp.	3	8568	766	7714	9194
Cornus canadensis	2	15010	6548	10380	19640
Epilobium angustifolium	3	12563	9375	6788	23380
Hylocomium splendens	5	212	19	184	235
Picea glauca	262	1602	1165	520	12002
Populus balsamifera	4	4285	2005	2139	6138
Pyrola grandiflora	1	6969	n/a	6969	6969
Rubus arcticus	5	8508	287	8212	8856
Salix pulchra	8	11950	3691	7817	19220

Table Appendix C.2. Mean chloride concentration (ppm) in plant tissue of various growth forms.

	Chloride concentration (ppm)				
Growth Form	**n**	**Mean**	**Std. Dev**	**Min**	**Max**
Coniferous tree	262	1602	1165	520	12002
Deciduous tree	4	4285	2005	2139	6138
Graminoid	3	8568	766	7714	9194
Herbaceous	14	9865	5493	2343	23380
Moss	5	212	19	184	235
Shrub	8	11950	3691	7817	19220

Table Appendix C.3. Comparison of chloride in paired healthy and declining populations of roadside plants.

Sample species	Location; Cumulative app. rate (lbs/yd2)	Cl- in healthy plant (ppm)	Cl- in declining plant (ppm)
Artemisia tilesii	Milepost 43.18; 2.55	5844*	12710*
Carex sp.	Milepost 19.23; 8.76	9194	7714
Cornus canadensis	Milepost 33.8; 6.24	10380*	19640*
Epilobium angustifolium	Milepost 41.19; 3.79	7521*	23380*
Hylocomium splendens	Milepost 33.46; 6.24	220	216
	Milepost 87.86; 0	207	184
Picea glauca	Milepost 28.87; 5.27	1459*	10000*
	Milepost 32.76; 5.5	1426*	5416*
Rubus arcticus	Milepost 35.92; 6.82	8856	8707
	Milepost 40.55; 2.83	8540	8225
Salix pulchra	Milepost 17.83; 9.75	10723*	12515*
	Milepost 18.22; 9.78	10557*	19220*
	Milepost 26.37; 7.73	10963*	15120*

* Indicates where chloride in declining tissue was greater than in healthy tissue indicating a possible effect of chloride on plant health (table cell also highlighted in pink).

Figure Appendix C.1. Photograph of observed decline in *Artemisia tilesii.*

Figure Appendix C.2. Photograph of observed decline in *Carex sp*.

Figure Appendix C.3. Photograph of observed decline in *Cornus canadensis.*

Figure Appendix C.4. Photograph of observed decline in *Epilobium angustifolium.*

Figure Appendix C.5. Photograph of observed decline (left) and an appearing healthy population (right) of *Hylocomium splendens.*

Figure Appendix C.6. Photograph of observed decline in *Picea glauca.*

Figure Appendix C.7. Photograph of observed decline in *Rubus arcticus.*

Figure Appendix C.8. Photograph of observed decline in *Salix pulchra.*

Appendix D. Notes on the Observed Complexity of Roadside Plant Tissue Damage

This appendix presents a catalog of the primary complexities of observed tissue damage in spruce. For instance, an example of the fine-scale spatial variability of tree decline is shown in Figure Appendix D.1. Figure Appendix D.2 illustrates the potential relevance of tree size and the related variation in nutrient uptake. Figure Appendix D.3 offers two examples of ways in which the shape of the road can influence the distribution of chloride into the roadside environment, road curves and culvert drainages.

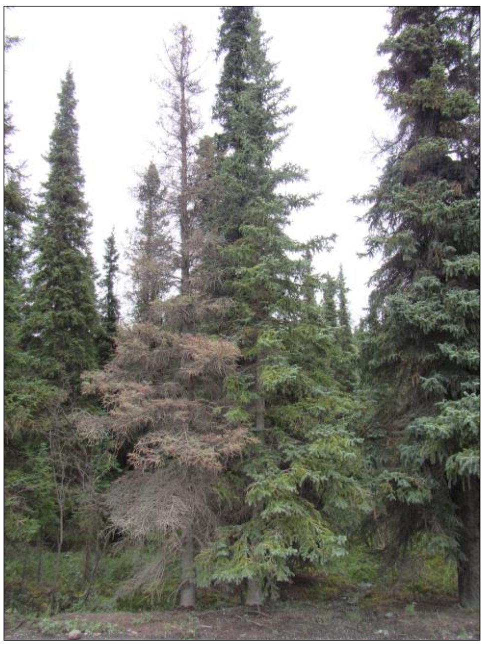

Figure Appendix D.1. These two trees located at milepost 28.87 are experiencing vastly different fates considering their proximity. Needle tissue of the severely declining tree in the left side of the photograph (picgla-166; 70% yellowed) was 10,000 ppm, the second highest level of chloride in the dataset. Needle tissue from the similar-sized and healthier tree at right (picgla-167; 20% yellowed) measured 1459 ppm chloride. Cumulative $CaCl_2$ applications at this milepost are in the medium range (5.29 lbs/yd^2).

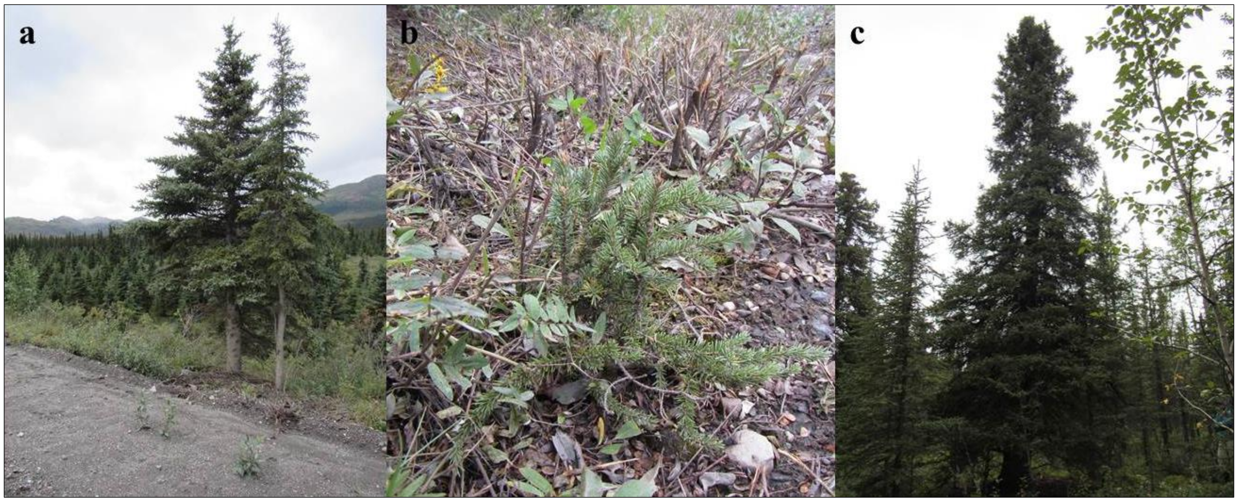

Figure Appendix D.2. Trees of different size classes likely allocate nutrients differently, as illustrated by the photos above. **a)** These trees at milepost 27.97, where cumulative $CaCl_2$ applications were in the medium range (6.15 lbs/yd^2), exhibited different foliar chloride. Tissues from the larger tree at left (picgla-087) had 3132 ppm chloride and was 35% yellowed. The smaller tree at right (picgla-088) had 874 ppm measured chloride and was 10% yellowed. **b)** The seedling pictured (picgla-136; 0.3 cm dbh) and a nearby sapling (picgla-135; 9 cm dbh) had 1771 and 3607 ppm foliar chloride respectively. They are located at milepost 20.34 where cumulative $CaCl_2$ applications were in the low range (4.54 lbs/yd^2). **c)** This very large and particular healthy spruce (picgla-119; 5% yellowed) at milepost 29.55 is located 65 m from the road edge. Sampled needle tissue revealed a chloride level of 1072 ppm, below the natural threshold. Cumulative $CaCl_2$ applications at this milepost are in the low range (4.54 lbs/yd2), but trees located nearer to the road edge did exhibit some signs of decline and chloride levels above threshold (i.e., piclga-124, picgla-120, picgla-117).

Figure Appendix D.3. Visual evidence that road architecture (i.e., road curves and channeled runoff) likely has great influence on the distribution of chloride into the roadside environment. a) A curve in the road at milepost 32.76 seems to cause the tree in the foreground (picgla-053) to catch the brunt of the dust spun up by passing traffic, showing signs of decline, while the tree in the background (picgla-054) remains healthy. Chloride levels measured in their respective tissues indicated that the foreground tree had 5416 ppm foliar chloride and the healthy tree had 1426 ppm. Cumulative $CaCl_2$ applications at this milepost are in the medium range (5.5 lbs/yd^2). Another spruce at milepost 32.78, on the opposite side of the road curve, measured 962 ppm chloride and showed no signs of decline. b) At milepost 33.45, road runoff extended far into the forest, channeled by a culvert. This tree (picgla-042) was located 16 m from the road edge, and showed signs of decline, appearing to be negatively influenced by such culvert flow. However, foliar chloride in this tree was 1134 ppm, while tissue from a similar-sized tree at the road edge did (picgla-041; 4040 ppm). Interestingly, calcium levels in the tissue of this tree were among some of the highest measured. Cumulative $CaCl_2$ applications at this milepost are in the medium range (6.24 lbs/ yd^2).

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