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Environmental Effects of Magnesium Chloride-Based Dust Suppression Products on Roadside Soils, Vegetation and Stream Water Chemistry

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Executive Summary

Environmental effects of magnesium chloride-based dust suppression products on roadside soils, vegetation and stream water chemistry

Introduction

Roadside vegetation can be exposed to a number of abiotic and biotic stressors, including economically and ecologically important road maintenance procedures such as the application of dust suppressants. Magnesium chloride ($MgCl_2$)-based dust suppression products are applied to non-paved roads during spring and summer months to stabilize road materials, control fugitive dust, and reduce maintenance costs. Dust from non-paved roads can contribute to atmospheric particulate matter, which can have numerous environmental and human health effects. The use of chemical dust suppressants is increasing in the United States due to population growth, traffic demands, and to control particulates in the interest of air quality, especially in arid regions. There is concern that the use of dust suppressants may create environmental liabilities to roadside environments. Research quantifying the environmental impacts of $MgCl_2$ application on roadside soils, vegetation health or stream water chemistry is limited.

Study Objectives

1. Determine the health of dominant roadside vegetation along high and low elevation non-paved roads treated and non-treated with $MgCl_2$-based dust suppression products.

2. Determine if components of $MgCl_2$-based dust suppression products move from treated roads into roadside soils and quantify the vertical and horizontal extent of this movement

3. Determine if roadside vegetation damage is related to $MgCl_2$ movement into roadside ecosystems

4. Determine how precipitation, drainage patterns, slope, and road application procedures influence the extent of $MgCl_2$ movement

5. Determine if $MgCl_2$ is entering streams adjacent to roads treated with $MgCl_2$-based dust suppressants

6. Determine the effects of different concentrations of $MgCl_2$ on common roadside tree species in controlled greenhouse and shadehouse studies (ongoing)

7. Determine if $MgCl_2$ or lignin solutions cause leaching of carbon based compounds from intact and recycled asphalt pavement

Objective Abstracts

Objective 1: Roadside vegetation health condition and $MgCl_2$ dust suppressant use: A roadside survey of major non-paved roads in Grand and Larimer Counties, Colorado.

An initial roadside survey of major non-paved roads in Grand and Larimer County, Colorado examined species composition and general heath condition of dominant woody roadside vegetation. Three hundred and seventy kilometers of forested, shrubland, meadow, rangeland, riparian and wetland roadside habitats were surveyed along major non-paved roads in the two Colorado counties. Dominant species composition and visible damages of woody roadside vegetation were quantified. The majority (72.3 to 79.3%) of roadside vegetation surveyed was considered healthy (<5% damage to crown or stem), depending on whether it was upslope or downslope from the road. Severely damaged (>50% damage) vegetation ranged from 6.4 to 11.4% of roadside cover, with the most severely damaged vegetation occurring downslope from the road. Percent of plants with severe or moderate damage increased with increasing $MgCl_2$ application rates for roadside aspen, Engelmann spruce, and lodgepole and ponderosa pines. Further research is needed to determine the distribution of $MgCl_2$ ions, nutrients, and interactions between $MgCl_2$ and incidence of potential biotic damage agents in roadside soils and plants.

Objectives 2, 3 and 4: Conditions of soils and vegetation along roads treated with $MgCl_2$ for dust suppression.

Investigations of vegetation stress along non-paved roads treated with a range of $MgCl_2$ application rates utilized 60 roadside and 79 drainage plots on 15 and 18 roads, respectively.

Evaluations were completed of foliar damage, plant health, biotic and abiotic damage incidence and severity, soil and foliar chemistry and other common site and stand characteristics of lodgepole pine, aspen, Engelmann spruce, subalpine fir, and lower elevation plots dominated by shrubs and grasses. High concentrations of soil magnesium and chloride (400 to 500 ppm), high foliar chloride (2,000 to 16,000 ppm depending on species) and high incidence of foliar damage were measured in roadside plots along straight road segments in the first 3 to 6.1 m adjacent to treated roads. In drainage plots, where water is channeled off roads, high concentrations of both magnesium and chloride ions and associated foliar damage were measured between 3 and 98 m from the road. High incidence of foliar damage and elevated ion concentrations were not apparent in control plots along non-treated roads. Lodgepole pine appeared to be the most sensitive species, while aspen accumulated the most chloride but exhibited the least amount of damage. Foliar chloride concentrations strongly correlated with percent foliar damage for all species ($r = 0.64$ to 0.74, $p < 0.0001$) while the incidence of biotic damages did not correlate well with foliar damage in any species ($r < 0.20$).

As $MgCl_2$ application rates increased along non-paved roads, either through applying a higher rate per application (increased $kg \cdot km^{-1} \cdot yr^{-1}$) or by applying a constant rate of a product more than once a spring or summer, soil chloride concentrations increased, most significantly in downslope soils within the first 3.0 meters from the road. Soil chloride fluctuated in roadside soils with year sampled, precipitation, slope and topography; and therefore accurately predicting the soil chloride concentrations with only information on application rates is not reliable. The accumulation of chloride ions in conifer needles over time allows foliar chloride to be a better predictor of $MgCl_2$ movement into roadside environments. Positive relationships between foliar chloride and $MgCl_2$ application rates were strong and can be used to predict foliar concentrations and subsequent damage to roadside trees.

Objective 5: Determine if chloride salt is entering aquatic systems adjacent to roads treated with $MgCl_2$-based dust suppression products.

Magnesium chloride-based dust suppression products are commonly used throughout western United States on non-paved roads for dust suppression and road stabilization by federal, state and county transportation agencies. The environmental implications of annually applying these products throughout spring and summer months on adjacent stream chemistry are not known. Sixteen streams were monitored bi-weekly for one to two years in two Colorado counties for a suite of water quality variables up and downstream of non-paved roads treated with $MgCl_2$-based dust suppression products. Nine of sixteen streams had significantly higher downstream than upstream concentrations of chloride or magnesium over the entire monitoring period ($p \leq 0.10$). Mean downstream chloride concentrations ranged from 0.17 to 36.2 mg/L and magnesium concentrations ranged from 1.06 to 12.8 mg/L. Several other ions and compounds, including those commonly found in dust suppression products such as sodium, calcium and sulfate, were also significantly higher downstream at some sites. Downstream electrical conductivity, chloride and magnesium concentrations were positively correlated with road surface area draining water towards the stream and yearly amount of $MgCl_2$ applied (R^2 = 0.75, 0.51 and 0.49, respectively), indicating that road managers can limit the amount of product entering roadside streams by assessing drainage characteristics and application rates in best management practices. Although $MgCl_2$-based dust suppressants did move into some roadside streams, the concentrations detected were below those reported to adversely affect fresh water aquatic organisms, but the ultimate fate of these ions in Colorado waterbodies are not known.

Objective 6. Determine the effects of various $MgCl_2$ concentrations on common roadside vegetation in controlled greenhouse and shadehouse studies (ongoing).

A study investigating the effects of four concentrations of $MgCl_2$ on the foliar health of potted and greenhouse grown lodgepole pine, limber pine, and aspen was conducted in 2005. At the end of 12 weeks, foliar magnesium and chloride concentrations and foliar damage symptoms were significantly greater on trees treated with $MgCl_2$ compared to those that received just water although symptoms were not extensive. These preliminary results indicated that a longer term study, including observations over winter months, was necessary to elucidate the effects of $MgCl_2$ on tree health. Sensitivity to soil applied $MgCl_2$ is currently being tested (year 3 of a 4 year study) on five common roadside tree species with 5 to 7 year old potted trees in an outdoor shadehouse. Lodgepole pine, ponderosa pine, limber pine, Douglas fir, and aspen trees have been consistently treated with four concentrations of $MgCl_2$ solution to keep soil concentrations at 0, 400, 800 or 1600 ppm chloride over three growing seasons. For all species, evaluations of growth rates, crown retention, foliar damage, foliar ion content, and leaf water potentials (in aspen only) were completed each summer. Conifers exhibited little damage during the first 3 to 4 months of treatments but showed severe foliar damage symptoms after 7 to 8 months. Soil applied $MgCl_2$ ($\geq$800 ppm chloride) was associated with needle loss, severe damage and mortality of all conifers except limber pine after two summers of treatment. Aspen also displayed severe leaf damage but was able to flush new, green leaves throughout the summer, although percent of stem with live crown was significantly reduced as soil chloride concentrations increased. Trees were kept outside in ambient conditions during fall and winter months and

$MgCl_2$ treatments will resume in spring of 2009. Measurements of crown retention, foliar damage, foliar ion concentrations and growth rates will be measured in 2009.

Objective 7: Determine if $MgCl_2$ or lignin solutions cause leaching of carbon based compounds from recycled asphalt.

A study was conducted in 2006 to determine the leaching capabilities of lignin and $MgCl_2$ solutions versus distilled water on solid and crushed asphalt-recycled asphalt pavement (RAP). No solution extracted more carbon from the solid asphalt than was already present in the solutions during the 14-day leaching tests. Distilled water extracted more carbon out of two RAP sources than was already present in the control solutions, while $MgCl_2$ and lignin solutions did not. There were no significant differences in the leachate concentrations of the majority of other ions tested between the water, $MgCl_2$ and lignin solutions. Distilled water extracted calcium out of all the solid asphalt sources while $MgCl_2$ and lignin solutions did not. Several ions were extracted from the RAP by all three solutions. Lignin solutions extracted iron and manganese and $MgCl_2$ extracted manganese from all RAP sources tested, while distilled water extracted manganese from one RAP source. Copper and zinc were extracted from one RAP source by the lignin solution. Strontium was leached out of every RAP source by all three solutions and more was extracted by $MgCl_2$ than distilled water in every source tested.

Recommended management practices

- **Utilize non chloride-based products for dust suppression and road stabilization**
- **Utilize non chloride-based products at higher risk areas**
  - Roads with trees within 6.1 m (20 ft)
  - Where roadside ditches drain water into forested areas
  - Road corners where road surfaces slope toward roadside environment
  - Areas with steep off-road slopes
- **Application rate reductions**
  - Approximately 4,700 liters $MgCl_2$ solution/kilometer/year (2000 $gal \cdot mi^{-1} \cdot yr^{-1}$) causes mild to moderate damage to roadside conifers
  - Approximately 9,400 to 11,800 liters $MgCl_2$ solution/kilometer/year (4,000 to 5,000 $gal \cdot mi^{-1} \cdot yr^{-1}$) causes severe damage to roadside conifers
  - Chloride from low application rates can be concentrated in roadside ditches and drainage areas and cause damage to trees
- **Application timing protocols**
  - Do not apply products 48 hours after/before precipitation
  - Only apply $MgCl_2$ once at the beginning of the season and use alternative products throughout spring and summer
- **Dust/traffic measurement standards**
  - Only apply to roads that continuously sustain minimum vehicle/day usage
  - Dust monitoring devices along roadsides can quantify fugitive dust
- **Energy dissipaters in culvert and drainage areas can reduce sediment movement into roadsides**

Continuing research objectives between Colorado State University and Larimer County Road and Bridge Department (through 2010):

- Quantify the movement (up to 3.1 m) of $MgCl_2$ ions down into roadside soils.
- Determine how roadside foliar chemistry changes along roads treated with lower $MgCl_2$ application rates and with alternative, non-chloride based products.
- Determine the effects of various concentrations of soil applied $MgCl_2$ on tree health, toxicity thresholds, and mortality rates of common roadside species over four years (Ongoing Project: Objective 6).
- Determine the effects of various concentrations of alternative dust suppression products on tree health, growth and foliar damage of five common roadside species over two years.

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Magnesium chloride-based dust suppression products

Magnesium chloride ($MgCl_2$) is applied to non-paved roads during spring and summer months for dust suppression and road stabilization. Non-paved roads are a major man-made source of fugitive dust and can contribute fine suspended dust into atmospheric particulate matter (Sanders et al. 1997, Singh et al. 2003). Fine particulate matter less than 10 μm (PM-10) needs to be suppressed due to air quality standards set by the U.S. Environmental Protection Agency (EPA) (Singh et. al 2003). Municipal, county and state transportation departments can apply chemical dust suppressants to non-paved roads during spring and summer months to suppress particulates in compliance with these standards, and salts and brines are the most common types used (Singh et al. 2003, Piechota et al. 2004). Hygroscopic salts, such as $MgCl_2$, stabilize road material and control fugitive dust by drawing moisture from the air and keeping the road damp by resisting evaporation (Addo et al. 2004). Dust suppressants are also used to control maintenance costs and erosion from non-paved roads and are associated with economic and safety benefits (Addo et al. 2004). The use of chemical dust suppressants is increasing in the United States due to increases in population growth and traffic demands, and because of the need to control particulates in the interest of air quality, especially in arid regions (Piechota et al. 2004). However, there is concern that the use of chloride based dust suppressants may create environmental damage to roadside vegetation, soils, and adjacent water bodies. A limited amount of published research exists documenting the environmental effects of dust suppressant application (Strong 1944, Hagle 2002, Singh et al. 2003, Piechota et al. 2004).

Chloride salts and plant health

Plant injury as a result of sodium chloride (NaCl) deicing products was reported in Minnesota as early as the 1950s, where trees along city boulevards began showing what are now known as salt-related symptoms (French 1959). Later studies focused on symptoms and toxicity thresholds of various roadside species throughout the United States, Canada, and Europe, and the negative impacts NaCl deicing salts can have on roadside soils and vegetation are well documented (Westing 1969, Shortle and Rich 1970, Hofstra and Hall 1971, Hall et al. 1972, Hall et al. 1973, Piatt and Krause 1974, Dirr 1976, Viskari and Karenlampi 2000, Norrstrom and Bergstedt 2001, Kayama et al. 2003, Czerniawska-Kusza et al. 2004). A limited number of studies have also focused on environmental impacts of $MgCl_2$ deicing products (Trahan and Peterson 2007) and calcium chloride ($CaCl_2$) dust suppressants (Strong 1944, Hagle 2002) to roadside vegetation and soils.

Potential impacts of chloride-based dust suppressants on roadside soils and vegetation may differ slightly from those related to deicing salt exposure. The major differences between deicing and dust suppression practices include the timing of applications (dust suppressants are applied to roads when roadside trees are actively growing and transpiring); reduced aerial drift and spray from dust suppression products compared to deicers (Strong 1944, Hofstra and Hall 1971, Trahan and Peterson 2007); and the absence of snowmelt to dilute soil salts when dust suppressants are applied (Trahan and Peterson 2007). However, the detrimental effects that high concentrations of soil salts have on vegetation may be similar between both road treatment practices. Roadside trees along non-paved roads treated with $MgCl_2$ and $CaCl_2$ dust suppression products have exhibited comparable symptoms to those recorded as NaCl damage, such as leaf scorching, marginal necrosis, and needle tip burn (Strong 1944, Hagle 2002, Piechota et al. 2004). In all cases, Colorado roadside vegetation may be exposed to stress agents similar to those which off-road vegetation is exposed, including fungal pathogens, parasitic plants, insects, or drought (Cranshaw et al. 2000). Thus, thorough assessments of all biotic and abiotic damage agents must be quantified in order to determine the major damaging agent.

High concentrations of ions in the soil matrix affect plant growth and survival both indirectly and directly, via osmotic effects or through direct ion toxicity. At lower salt concentrations, a reduction in plant growth may be due to osmotic effects in the soil-root continuum and a disruption of normal water and nutrient uptake (Munns 2002, Raveh and Levy 2005). Chloride and magnesium are both essential plant nutrients, although very small amounts of chloride are needed for proper plant functioning and growth (White and Broadley 2001, Marschner 2002). Magnesium, a macronutrient, is essential for the activation of many enzymes, including those required for carbon fixation and photosynthesis (Marschner 2002). Chloride is utilized in turgor maintenance and is involved in the water splitting step of photosynthesis (White and Broadley 2001, Marschner 2002). Excess chloride accumulates at the margins or tips of transpiring leaves or needles and can cause foliar necrosis and leaf abscission through dehydration or specific metabolic disruptions, which can lead to branch and tree dieback as a result of losing photosynthetic tissue (Ziska et al. 1991, Romero-Aranda et al. 1998, Kayama et al. 2002, Munns 2002, Trahan and Peterson 2007). Typical injury symptoms appear as a browning of the leaves beginning at the tip or margin and progression towards the base; the higher the salt content the greater the length of the leaves injured (Strong 1944, Hofstra and Hall 1971, Hall et al. 1972, Dobson 1991, Romero-Aranda et al. 1998, Raveh and Levy 2005, Trahan and Peterson 2007). At the cellular level, NaCl can reduce leaf chlorophyll concentrations and lower net photosynthetic performance even in green foliage not exhibiting symptoms (Bedunah and Trlica 1979, Syvertsen et al. 1988, Al-Habsi and Percival 2006). In previous research, injury has been reported to occur when leaf chloride reaches 10,000 ppm (1.0% dry weight [d.w.]) in deciduous tree species and 5,000 ppm (0.5% d.w.) in conifers although variations exist in the literature based on species, experiment, and application method (Holmes and Baker 1966, Westing 1969, Hofstra and Hall 1971, Hall et al. 1972, Bernstein 1975, Dobson 1991, Czerniawska-Kusza et al. 2004, Trahan and Peterson 2007). In contrast to NaCl deicing research, there are no conclusive studies on the environmental impacts of $MgCl_2$-based dust suppression products on roadside environments (Piechota et al. 2004, Trahan and Peterson 2007).

Chloride salts and stream chemistry

When mixed with water, chloride salts may dissociate into the chloride anion (Cl^-) and the corresponding cation (sodium (Na^+), calcium (Ca^{+2}), potassium (K^+), or magnesium (Mg^{+2})). Most species require these elements for optimal health; however, excessive amounts can severely disrupt normal metabolic processes (Evans and Frick 2001, Environment Canada 2001, Fishel 2001, Lewis 2001). Previous research has shown that repeated applications of NaCl for deicing control on paved roads can lead to elevated levels of chloride and sodium in the surface waters adjacent to roads (Howard and Beck 1993, Evans and Frick 2001, Environment Canada 2001, Fishel 2001, Capesius et al. 2005, Kaushal et al. 2005). Dissolved salt may alter the physical properties of surface water by increasing the density, resulting in salt accumulation in deeper waters. This prevents water in lakes and ponds from mixing, which may result in mortality of bottom-dwelling fishes and invertebrates (Environment Canada 2001, Fishel 2001, Lewis 1999). Determining if $MgCl_2$-based dust suppression products move into streams that pass under or parallel treated non-paved roads in the western United States has not been well studied.

Natural chloride inputs to Colorado streams are normally through precipitation and result in negligible concentrations ranging from 0.05 to 0.11 mg/L (NADP/NTN 1999, Stevens 2001, Bossong et al. 2003). In general, background concentrations of stream chloride in Colorado are less than 5.0 mg/L depending on the geology of the area; but where human inputs have altered stream chemistry, concentrations have been measured up to 400 mg/L (Muselmann, et al. 1996, Fishel 2001, Stevens 2001, Bossong et al. 2003, Jassby and Goldman 2003, Capesius et al. 2005, Coal Creek Watershed Coalition 2007). Evidence in Colorado and other parts of North America suggests that deicing salt runoff can increase ion concentrations in streams in urban areas and those adjacent to treated roads. Bossong et al. (2003) measured increases in chloride concentrations from 1970 (9.3 mg/L) to 1999 (78.9 mg/L) in 22 streams of Turkey Creek watershed, southwest of Denver, CO. Kaushal et al. (2005) reported that chloride concentrations have significantly increased over the past decade in many bodies of fresh water in several states in northeastern U.S.A. In Baltimore, MD., chloride concentrations from stream water receiving runoff from suburban and urban communities ranged from 24.0 to 4,630 mg/L. Chloride concentrations were the highest during the winter months (181 to 4,630 mg/L), and lower during the summer months (30.0 to 469 mg/L) (Kaushal et al. 2005). In contrast, streams passing through nearby agricultural lands contained only 3.0 to 8.0 mg/L chloride (Kaushal et al. 2005). In Canada, natural background concentrations of stream chloride are generally no more than a few mg/L, with some local or regional instances of higher natural chloride concentrations; the median concentrations of chloride in 400 lakes without road salt inputs in Eastern Canada were 0.3 to 4.5 mg/L (Environment Canada 2001). However, summer waters impacted by road salts were measured with 189 to 330 mg/L chloride (Environment Canada 2001). High chloride concentrations of 4,000 to 4,300 mg/L were reported in water collected from ponds and watercourses that received runoff from nearby roadways treated with deicing salts (Environment Canada 2001).

The USEPA has set the Secondary Maximum Contamination Level (SMCL) for chloride in drinking water at 250 mg/L for human potability. In addition, higher chloride concentrations in aquatic ecosystems may reduce the normal populations of organisms (USEPA 1992). There are not always consistent toxicity ranges among the reports of the effects of chloride on aquatic systems, but lethality data summarized by Environment Canada (2001), modeled for chronic exposure, indicated that 5% of freshwater aquatic species would be affected at chloride concentrations of about 210 mg/L, and 10% would be affected at approximately 240 mg/L chloride. A literature review by Evans and Fricke (2001) found the raw acute toxicity of chloride ranged from 184.5 mg/L for water flea (*Ceriodaphnia dubia)* to 1724 mg/L for the black eel stage of the American eel *(Anguilla rostrata)*. The USEPA reported mean acute values from tests based on NaCl, where they found invertebrates were more sensitive to the ions than vertebrates in general. Acute LD_{50} of fresh water organisms ranged from 86.0 to 1,000 mg/L while chronic LD_{50} ranged from 372 to 922 mg/L (USEPA 1988).

Overall project research objectives

The effects of summer applied chloride-based dust suppression and road stabilization products on surface water concentrations are not currently known (Environment Canada 2001), and no conclusive studies have been published on the environmental effects of $MgCl_2$-based dust suppressants in roadside soils and plants (Piechota et al. 2004). Most published research has been conducted by industry and has focused on the effectiveness and performance of dust suppressants (Muleeki 1987, Sanders et al. 1997, Addo et al. 2004, Travnik 2001, Piechota et al. 2004). A series of studies investigating the environmental impacts of $MgCl_2$-based dust suppression products on roadside environments was initiated in spring 2004 along major non-paved roads in Grand and Larimer Counties, Colorado to quantify the amount of visible damage to roadside woody vegetation, determine site factors influencing vegetation damage, measure roadside soil and tree foliar chemistry and determine if $MgCl_2$-based dust suppression products altered surface water chemistry in adjacent streams.

Objectives: Roadside surveys

A roadside survey was conducted along non-paved roads both treated and non-treated with $MgCl_2$-based dust suppression products in Larimer and Grand Counties, Colorado. The specific objectives of this roadside survey were to: 1) define major habitat types and dominant roadside species composition along major, non-paved county roads both treated and non-treated with $MgCl_2$ based dust suppressants throughout both counties, 2) determine the visible health conditions of dominant roadside vegetation and 3) determine site factors' influence on vegetation health along these roads and view the relationships between site factors and patterns of damage.

Objectives: Roadside and drainage vegetation health plots

Investigations of vegetation stress along non-paved roads treated with a range of $MgCl_2$ application rates utilized 60 roadside and 79 drainage plots on 15 and 18 roads, respectively, in Grand and Larimer Counties. The objectives of this research were to determine: 1) if components of $MgCl_2$ dust suppression products move from treated roads and quantify the vertical and horizontal extent of this movement in roadside soils, 2) if foliar damage was related to $MgCl_2$ movement from the road in four native tree species and various herbaceous and woody ground cover species and 3) how site factors such as precipitation, drainage patterns, slope, and road application procedures influenced the movement and spatial distribution of $MgCl_2$ ions in roadside soils and plants.

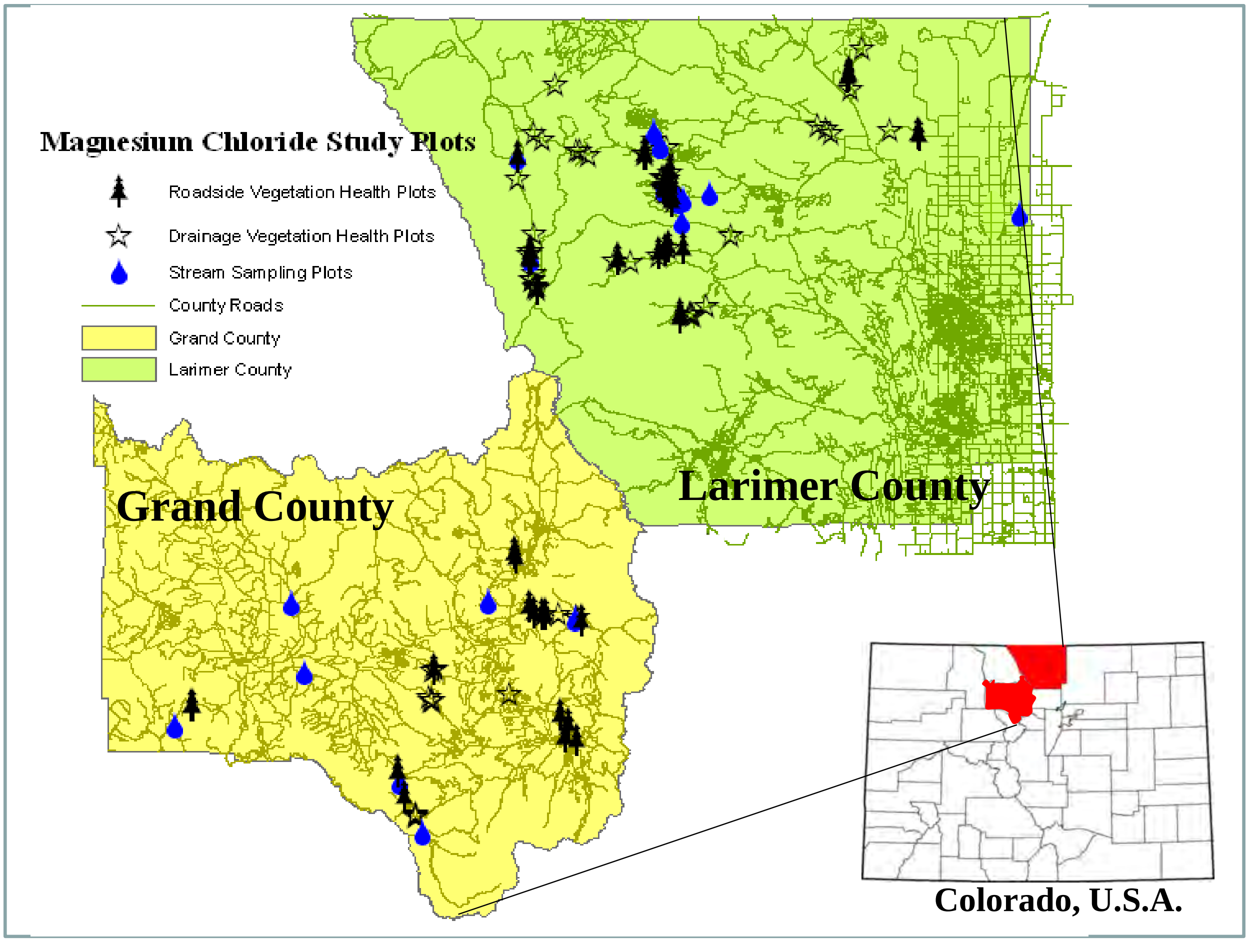
Objectives: Stream water sampling

Sixteen streams were monitored upstream and downstream of treated non-paved roads bi-weekly for one to two years in Grand and Larimer Counties. This study was initiated to determine how

$MgCl_2$-based dust suppressant products affect the chemistry of surface waters adjacent to treated non-paved roads and to determine if site factors explained the variation in stream chemistry.

Objectives: Leaching potential of intact and recycled asphalt pavement

The objectives of these studies were to determine: 1) if $MgCl_2$ solution leaches more carbon or other ions from solid intact asphalt pavement or recycled asphalt pavement (RAP) when compared to the leaching potential of distilled water, 2) if $MgCl_2$ solution leaches carbon or other ions from solid intact recycled pavement or RAP compared to initial $MgCl_2$ solution concentration, and 3) if lignin solution leaches more carbon or other ions from RAP compared to initial lignin solution concentrations.



Study Site Map. County borders and road networks, roadside and drainage vegetation health plot locations and stream sampling site locations established 2004 to 2006 in Grand and Larimer Counties, Colorado along county non-paved roads both treated and non-treated with $MgCl_2$-based dust suppression products.

Section 1: Roadside vegetation health condition and magnesium chloride-based dust suppressant use: A roadside survey of major non-paved roads in Grand and Larimer Counties, Colorado

Abstract

Many abiotic and biotic factors affect the health of roadside vegetation, including the application of $MgCl_2$ dust suppression products. Three hundred and seventy kilometers of forested, shrubland, meadow, rangeland, riparian and wetland roadside habitats were surveyed along major non-paved roads in two Colorado counties. Dominant species composition and visible damages of woody roadside vegetation were quantified. The majority (72.3 to 79.3%) of roadside vegetation surveyed was considered healthy (<5% damage to crown or stem), depending on slope position from the road. Severely damaged (>50% damage) vegetation ranged from 6.4 to 11.4% of roadside cover with the most severely damaged vegetation occurring downslope from the road. Percent of plants with severe or moderate damage increased with increasing $MgCl_2$ application rates for roadside aspen, Engelmann spruce, and lodgepole and ponderosa pines. Further research is needed to quantify the distribution of $MgCl_2$ ions and nutrients and to determine the interactions between $MgCl_2$ and potential biotic damage agents in roadside soils and plants.

1.1 Study objectives

A roadside survey was conducted along non-paved roads both treated and non-treated with $MgCl_2$-based dust suppression products in Larimer and Grand Counties in northern Colorado. The specific objectives of this roadside survey were to 1) define major habitat types and dominant roadside species composition along major, non-paved county roads both treated and non-treated with $MgCl_2$ based dust suppressants throughout both counties, 2) determine the visible health conditions of dominant roadside vegetation and 3) determine site factors' influence on vegetation health along these roads and view the relationships between site factors and patterns of damage.

1.2. Methods and materials

Larimer County is located in north central Colorado. Elevation along study roads ranged from 1,753 to 3,210 m and the dominant habitat types ranged from lowland shrub and grass cover to high elevation mixed spruce and fir forests. Grand County is located in northwestern Colorado and study roads ranged in elevation from 2,484 to 2,780 m. In 2004, Larimer County had 938 km of non-paved roads and 60% of these roads were treated with $MgCl_2$-based dust suppression products (563 km) (Colorado Department of Transportation 2004, personal communication Larimer County Road and Bridge Department 2006). Grand County had 1,143 km of non-paved roads in 2004 (Colorado Department of Transportation 2004) and approximately 25% of these roads were treated with $MgCl_2$-based dust suppression products (292 km) (personal communication Grand County Department of Road and Bridge 2006).

Two hundred and sixty-seven km of non-paved roads were surveyed in Larimer County (n = 33 roads, 29% of total county mileage). Ninety-seven km were surveyed along non-paved roads in Grand County (n = 22 roads, 8% of total county mileage) in spring and summer of 2004. County maintained or owned non-paved roads were selected using county maps and information regarding $MgCl_2$ treatment, land ownership, and occurrence of continuous roadside vegetation (personal communication, D.L. Miller, Larimer County Road and Bridge Department and A. Green, Grand County Department of Road and Bridge 2006). Major county roads of interest to the researchers were those that ran through forested habitats and public, federal or state land, so permanent vegetation health plots could be established in the future. Therefore, the vegetation composition along surveyed roads does not accurately estimate actual percentages of different habitats along total non-paved road mileage in each county. Road sections were eliminated from the survey if they occurred in housing developments or other locations with extensive disturbance, removal of native vegetation, irrigation, or lack of continuous roadside habitat. Single or two-track roads were not surveyed and are not comparable to maintained roads because of the major differences between road width, vehicular usage, and potential habitat disturbance, although these types of roads are included in non-paved road mileage in both counties.

On each road, two plots, 30.5 m wide by 6.0 m deep, were visually estimated on both sides of the road every 0.32 km. Global Position System waypoints were recorded along with site factors such as elevation, habitat and slope position from road edge at each plot. The percent cover of the top five dominant species (adding up to 100% cover at each stop) and any disturbances were recorded at each plot (n = 2055 plots adjacent to $MgCl_2$-based dust suppressant treated roads, n = 528 plots adjacent to non-treated roads). Visible damage and health condition were recorded for each species based on visible damage to crown, stem or branches, percent crown defoliation or discoloration, amount of dead branches, or biotic disease symptoms obvious from the road (foliar brooms or visible fungal cankers). Severely damaged vegetation had damage to crowns or to stem circumference greater than 50%, moderately damaged vegetation had damage ranging from

26 to 50%, mildly damaged vegetation ranged from 5 to 25% damage, and non-damaged (healthy) vegetation had less than 5% damage.

County roads varied in maintenance procedures, years of treatment, cumulative and average amount of $MgCl_2$ applied, and chemical specificity of dust suppressants. Total and average $kg{\cdot}km^{-1}$ of $MgCl_2$ applied (calculated from $gal{\cdot}mi^{-1}$ of $MgCl_2$ solution applied, removing gallons of any other products applied, such as lignosulfonates) were calculated for study roads following the survey (personal communication, Larimer County Road and Bridge Department and Grand County Department of Road and Bridge, 2006). Spatially gridded (800 m), averaged monthly and annual precipitation data for the climatological period 1971-2000 (PRISM Group 2006) were gathered at a mid-point on each study road following the survey (n = 55).

Statistical analysis

Frequencies of habitat types and species composition were produced with The Frequency Procedure (SAS 9.1, Copyright 2002-2003 by SAS Institute Inc., Cary, N.C., USA). Vegetation cover and health condition were analyzed by fitting random and fixed effects in the Mixed Procedure. Fixed effects included $MgCl_2$ application information (total and average $kg{\cdot}km^{-1}$ $MgCl_2$ applied), slope position (upslope, downslope or no slope from the road edge), county, and precipitation (summer: May - September, winter: October - April, and yearly averages). Roads were treated as random effects, nested within counties. Least square means of class effects were compared and Type 3 Tests of Fixed Effects and Fisher's LSD was used to determine statistical significance ($p \leq 0.05$) between each site factor and roadside species' health condition (healthy, mild, moderate or severely damaged). Multiple regression was used to compare relationships between effects, and the Solution Function was used to determine slopes for continuous fixed variables (application rate, slope position and tree health status interactions), holding precipitation at a 30-year average summer constant throughout the analysis. Levels of significance are indicated as $p < 0.01$, $p < 0.05$, or $p < 0.10$ in all tables and figures.

1.3 Results

Habitat types and species composition

Habitat types were based on the dominant vegetation type in the area and six major habitats were prevalent throughout surveyed roads in both counties (Table 1.1). The major types along surveyed roads in both counties were forested or wooded roadside areas, followed by shrubland and riparian zones (Table 1.1). Lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) and trembling aspen (*Populus tremuloides* Michx.) were principle components of roadside forested areas along roads surveyed in both counties (Table 1.2). Ponderosa pine *(Pinus ponderosa* C. Lawson var. *scopulorum* Engelm.) was the dominant roadside species in Larimer County, but did not occur along roadsides in Grand County. Subalpine fir (*Abies lasiocarpa* [Hook] Nutt.) and Engelmann spruce (*Picea engelmannii* [Parry] Engelm.) occurred along roadsides in both counties, although Larimer County had more mileage of both than Grand County (Table 1.2).

Riparian and shrubland communities were also frequent along roadsides surveyed in both counties (Table 1.1). Dominant shrub species throughout both counties in riparian habitats were willow (*Salix* L. spp.) and alder (*Alnus* Mill. spp.) species. Aspen was prevalent in riparian zones along with narrow-leaf cottonwood (*Populus angustifolia* James) (Table 1.2). Big sagebrush

(*Artemisia tridentata* Nutt) was the dominant shrub along roadsides in Grand County along with rabbitbrush species (*Chrysothamnus* Nutt. spp.) (Table 1.2). In the foothills and eastern plains (Larimer County) some shrubland areas were dominated by shadescale or saltbush (*Atriplex confertifolia* [Torr. & Frém.] S. Watson) and rabbitbrush (Table 1.2). No prevalent herbaceous dominant ground cover species were identified in meadow or rangeland habitats along roads throughout the counties (Table 1.2). More meadow, rangeland and shrubland km were surveyed in Larimer County, accounting for the more diverse ground cover species richness in that county (Tables 1.1 and 1.2). Species occurring as more than 1.0% of total cover observed are listed in Table 1.2. Dominant roadside vegetation identified were generally trees or woody shrub species, along with a few herbaceous species that were easily identified from the vehicle, thus counts do not encompass the entire range of species that occur along non-paved roads in these counties (i.e. not all grasses and forbs were identified in this survey).

Health conditions of dominant roadside vegetation

The majority of roadside vegetation surveyed along non-paved roads was considered healthy, depending on slope position from the road (72.3 to 79.3% of all vegetation cover). Proportions of severely damaged vegetation ranged in cover from 6.4 to 11.4%, with the most severely damaged vegetation occurring downslope from the road (Figure 1.1). Although some proportion of severely damaged vegetation was observed at all slope positions from the road center, a larger percentage occurred downslope compared to upslope positions ($p < 0.0001$, Figure 1.1).

Overall, plant species along roads treated with $MgCl_2$ dust suppression products had a larger proportion of severely damaged vegetation than species along non-treated roads (Table 1.3).

These percentages varied by species, and the health condition of some were not significantly different between road treatments (Table 1.3). For several species, the average amount of $MgCl_2$ applied ($kg{\cdot}km^{-1}{\cdot}yr^{-1}$) was positively related to the percentage of severely damaged individuals, or negatively related to the percent of healthy individuals.

Lodgepole pine (*Pinus contorta*). Lodgepole pine was ubiquitous along surveyed roads throughout both counties where it was a component of 22% of the 2583 plots (Table 1.2). Lodgepole pine occurred along roads with no $MgCl_2$ treatment and along roads treated with up to 7,500 kg $MgCl_2$ per km per year (26,600 $lbs{\cdot}mi^{-1}{\cdot}yr^{-1}$). A higher percentage of severely damaged lodgepole pine was observed along treated roads compared to non-treated roads (Table 1.3). Higher mean percentages of severely damaged lodgepole pine occurred downslope from the road (15.7%) compared to areas upslope from the road (7.3%), although no difference occurred between downslope trees and trees at no slope (14.9%). Overall, the percent of lodgepole pine with severe damage increased along non-paved roads as the average amount of $MgCl_2$ applied increased (Figure 1.2a). The percentage of severely damaged trees downslope from the road increased with average application rate while upslope trees did not (Figure 1.2a). The "no slope" position was not prevalent enough throughout the range of application rates to be included in this analysis of interaction and was dropped from all further interactions between slope and application rates.

Ponderosa pine (*Pinus ponderosa*). Ponderosa pine was also common along roadsides and was a species component in 10.3% of the 2583 plots, but only occurred along Larimer County roads. Ponderosa pine grew along a range of treated and non-treated roads, from 0 to 16,600 $kg{\cdot}km^{-1}{\cdot}yr^{-1}$ (59,000 $lbs{\cdot}mi^{-1}{\cdot}yr^{-1}$). A higher percentage of severely damaged ponderosa pine was observed along treated roads compared to non-treated roads (Table 1.3). The percent of severely damaged trees increased at both slope positions with an increase in average application rate (Figure 1.2b). The average percent of ponderosa pine with severe damage was higher downslope from the road (5.3%) compared to upslope from the road (2.2%), although the rate of increase with application rates was equal between slope positions (Figure 1.2b).

Aspen *(Populus tremuloides*). Aspen was prevalent along roadsides throughout both counties and was a species component in 17.9% of plots. Aspen occurred along non-treated roads through roads treated with approximately 16,600 kg$\cdot$ km$^{-1}\cdot$yr^{-1} (59,000 lbs$\cdot$mi$^{-1}\cdot$yr^{-1}). A higher percentage of severely damaged aspen was observed along treated roads compared to non-treated roads (Table 1.3). Downslope habitats had a higher proportion of severely damaged aspen trees (10.9%) than upslope (6.7%), and the percentage of severely damaged aspen increased with the average amount of $MgCl_2$ applied at similar rates both upslope and downslope from the road (Figure 1.2c).

Engelmann spruce (*Picea engelmannii)*. Engelmann spruce occurred as a component of 99 plots along roads ranging from no $MgCl_2$ application to approximately 5,900 kg$\cdot$ km$^{-1}\cdot$yr^{-1} (21,000 lbs$\cdot$mi$^{-1}\cdot$yr^{-1}). No significant differences occurred between the percent of severely damaged Engelmann spruce on treated versus non-treated roads, although a lower percentage of non-damaged (healthy) Engelmann spruce was observed along treated roads (Table 1.3). More moderately damaged (26 to 50% damage) spruce occurred along treated roads (15.9%) compared to non-treated roads (0.3%) and more also occurred downslope (7.2%) compared to upslope from the road (1.8%) (Figure 1.2d). A positive relationship occurred between moderately damaged Engelmann spruce and average application rates ($p = 0.002$), and the percent cover of spruce with 26 to 50% damage increased with average application rate of $MgCl_2$ in downslope trees (Figure 1.2d).

Alder (*Alnus* spp.) and willow (*Salix* spp.). Proportions of alder species considered healthy or severely damaged did not significantly differ between treated and non-treated roads (Table 1.3). A larger proportion of healthy appearing willow species occurred along non-treated roads compared to treated roads, although no significant differences existed when comparing severely damaged willow (Table 1.3). A negative relationship existed between healthy willow and average $MgCl_2$ application rate, where the percentage of healthy appearing willow decreased with increasing average application rate. On average, less healthy willow occurred downslope from the road (75.8%) compared to upslope from the road (84.9%).

Big sagebrush (*Artemisia tridentata*) and rabbitbrush (*Chrysothamnus* spp.). No significant differences between healthy or severely damaged cover existed for big sagebrush with respect to $MgCl_2$ application (Table 1.3). Significantly more healthy-appearing rabbitbrush occurred along non-treated roads (89.1%) than treated roads (68.6%), although no significant differences occurred when comparing severely damaged rabbitbrush plants (Table 1.3).

Influence of precipitation rates. Average yearly precipitation along surveyed roads was similar between counties in this study (43.7 cm/yr in Grand County and 42.6 cm/yr in Larimer County), although Grand County appeared to receive a larger proportion of its precipitation during non-summer months than Larimer County in the form of snowfall (23.9 cm/winter in Grand County compared to 18.9 cm/winter in Larimer County). Summer precipitation (May through September) was negatively related to the percentage of vegetation showing severe damage symptoms, and an increase in precipitation was related to a decrease in the amount of severely damaged vegetation when control and treated roads were combined ($p = 0.05$). When only treated roads were included in the analysis, an increase in summer precipitation was not related to a decrease in severely damaged cover ($p = 0.27$) or an increase in healthy cover ($p = 0.55$). Summer, winter, and total precipitation were always higher on non-treated roads compared to treated roads (all analyses $p < 0.0001$), as was elevation on non-treated roads ($p < 0.0001$), indicating some relationship between elevation, precipitation, and the probability that a road will or will not be treated with dust suppressants.

1.4. Discussion

Habitat and species composition. We observed some variation in roadside habitat types and species composition between counties, although many commonalities occurred. Woody species within forested and wooded habitats provided the best means to measure health conditions of dominant vegetation along non-paved roads because of the prevalence along both treated and non-treated roads surveyed. Also, large woody vegetation proved to be easier to identify and estimate crown conditions compared to smaller, seasonal dependent graminoids, forbs, and shrubs in non-forested habitats. While most tree species' percent cover accurately represents coverage in county roadside forested areas, it may not accurately reflect percent coverage along all non-paved county road mileage.

Vegetation health conditions. A major objective of this survey was to determine the health conditions of roadside vegetation throughout both counties and quantify the percentage of each species with no damage, mild, moderate, or severe visible damage to the crown or stem. Using multiple regressions, we determined the major site factors that related to the health conditions of dominant roadside vegetation. Treatment of non-paved roads with $MgCl_2$-based dust suppression products correlated with the increase in foliar damage, hence the decline in health condition, of several roadside species (Table 1.3). Several species had significantly higher proportions of severely damaged individuals along treated roads, including major components of Colorado forests such as lodgepole pine, ponderosa pine, and aspen. In addition, Engelmann spruce, willow species, common rabbitbrush, and Rocky Mountain juniper (*Juniperus scopulorum)* all had significantly lower percentages of healthy cover along treated roads (Table 1.3). Generally, damage to roadside vegetation was observed as dieback of crown or the entire plant in deciduous species and discoloration as necrotic or marginally burned needles in conifers. Crown defoliation, dieback and foliage discoloration are important biological diagnostic tests of vegetation health (Stravinskiene 2001). The higher severity of damage observed in many dominant roadside species along roads treated with $MgCl_2$ dust suppression products is indicative of the declining health condition of these individuals.

Influence of application rates and slope position. The two major site factors that frequently related to the health conditions of roadside vegetation in multiple regression analyses were the average $MgCl_2$ application rate and slope position from the road edge. Although the rate of increase varied between species, the application rate of $MgCl_2$ was directly correlated with increases in the proportion of damaged individuals observed on several roadside species. Runoff of chloride salts are known to move through the soil matrix downslope with water movement via mass displacement (Westing 1969, White and Broadley 2001). Many previous research efforts have focused on differences in soil and foliage properties based on slope direction from the road.

These studies have shown that environments upslope from the road do not receive as much salt compared to downslope sides and soils and foliage do not display as much damage. However, symptomatic foliage upslope from the road affected by deicing salts has certainly been observed, presumably through spray and aerial drift from the road (Hofstra and Hall 1971, Piatt and Krause 1974, Fleck et al. 1988). We observed severely damaged vegetation in upslope areas, which we speculate may be due to upslope trees with extended roots under the road or roadside drainage ditches. $MgCl_2$ may move with water through the soil matrix into roadside soils and is then taken up by plant roots, mostly in downslope areas. We do not believe that aerial spray of salts or dust caused damage to roadside trees, because no symptoms specific to spray were noted, including necrotic specks, crystallized salt deposits or dust particles on foliage (Strong 1944, Trahan and Peterson 2007).

Precipitation. Precipitation was a significant factor in the analysis but was confounded by several parameters including elevation, road treatment and the vegetation types at different levels of precipitation. In general, vegetation health increased with precipitation, however, species were not stratified over all precipitation levels and thus these results could not be accurately modeled. Precipitation may influence the movement of $MgCl_2$ into roadside environments by moving ions further from the road or diluting ions in roadside soils. More extensive surveys with similar vegetation types, elevations, roads, accurate precipitation and soil chemistry data are required to deduce the effects of precipitation and $MgCl_2$ interactions on roadside vegetation health.

Other potential roadside vegetation stress agents. Surface erosion of road material should move downslope from the road in the same manner as runoff (Kahklen 2001). Forest roads can be major sources of accelerated soil erosion along roadsides due to the removal of surface cover and modifications or compaction to natural soil structure. Erosion of surface particles from non-paved roads is influenced by traffic, precipitation incidence and intensity, and road maintenance procedures such as grading (Kahklen 2001). Sedimentation is a possible explanation for declining tree health downslope from the road. However, sedimentation alone does not explain the increase in severely damaged vegetation upslope from the road (in aspen and ponderosa pine) with an increase in $MgCl_2$ application rates. The $MgCl_2$ road applications and movement of $MgCl_2$ ions into the soil matrix is the best explanation for increases in damaged vegetation does.

The relationships observed between increasing visible damage, increasing $MgCl_2$ application rates, and the increase in damage observed in the downslope positions from the road also help rule out biotic damages (such as common fungal pathogens or insects) as the sole agents responsible for declining roadside vegetation condition. Potentially, stress induced by an increase in $MgCl_2$ exposure to roadside environments may predispose vegetation to such biotic stresses, and a more intensive study to quantify these relationships is currently underway.

1.5. Conclusions. The majority of roadside vegetation surveyed along non-paved roads in both counties was considered healthy or only mildly damaged, and the degree of this damage was dependent upon species and slope position. Although some severely damaged vegetation occurred along most roads regardless of maintenance or $MgCl_2$ treatment procedures, a higher occurrence of severe damage was observed on many roadside species along roads treated with $MgCl_2$. From this survey, we conclude that some species growing alongside non-paved roads in

Larimer and Grand Counties, Colorado were negatively affected by the application of $MgCl_2$-based dust suppression products. Visible health condition declined in relation to increasing $MgCl_2$ application rates for several species. The declines in visible health condition were potentially directly and indirectly related to maintenance procedures and by the position the vegetation stood from the road center. Further research to more extensively study the distribution of $MgCl_2$ ions, nutrients, and incidence of potential biotic damage agents in roadside soils and foliage along these non-paved roads is needed.

1.6. Section 1 Figures and Tables

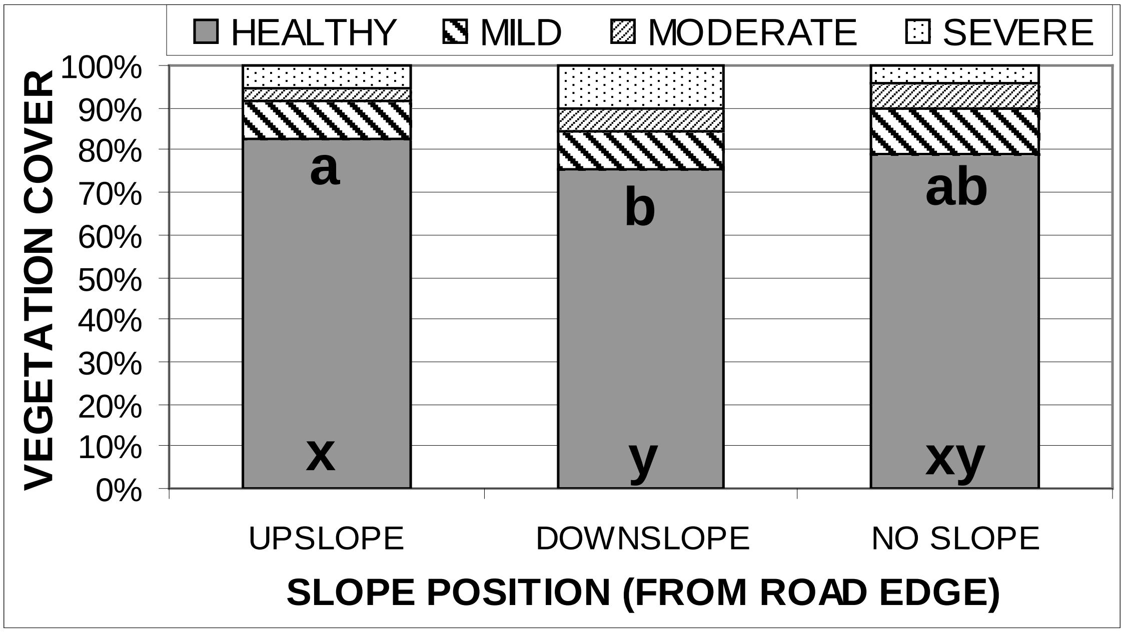


Figure 1.1. Roadside vegetation health condition adjusted means along non-paved roads both treated and non-treated with $MgCl_2$-based dust suppression products in Larimer and Grand Counties by slope position from road edge (healthy = < 5% damage, mild = 5 to 25% damage, moderate = 26 to 50% damage, severe > 50% damage to crown or stem, *n* = 2,583 plots). Letters (a, b, ab) signify significant differences ($p < 0.05$) between percent of severely damaged vegetation between upslope, downslope and no slope positions. Symbols (x, y, xy) signify significant differences ($p < 0.05$) between percent of healthy vegetation between upslope, downslope and no slope positions.

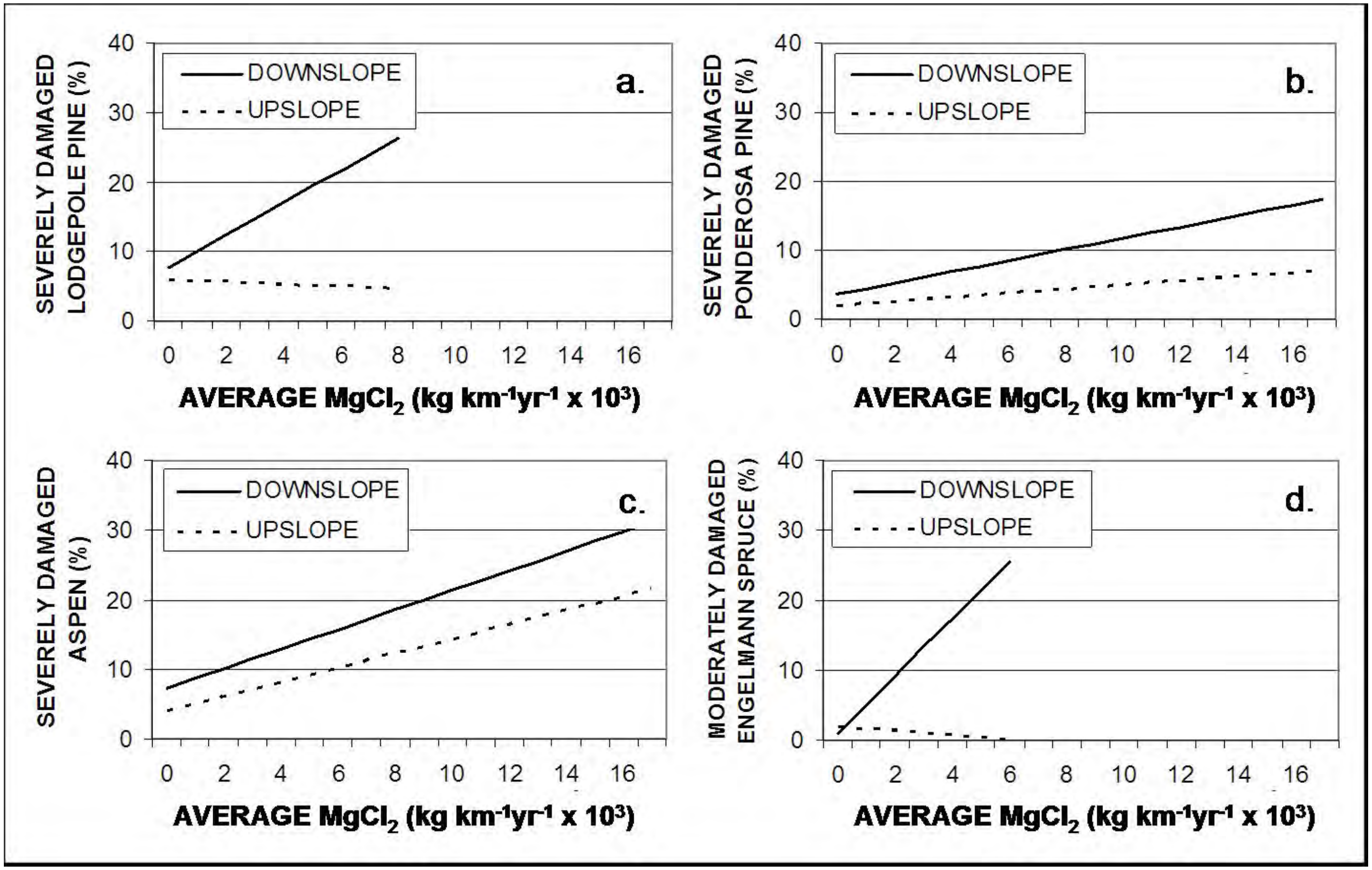


Figure 1.2a-d. Modeled percent severely damaged (a) lodgepole pine , (b) ponderosa pine, (c) trembling aspen and moderately damaged (d) Engelmann spruce adjusted means along non-paved roads both treated and non-treated with $MgCl_2$-based dust suppression products in Larimer and Grand Counties by slope position and increasing amount of $MgCl_2$ applied per year ($kg \cdot km^{-1} \cdot yr^{-1}$). The Solution Function in SAS 9.1 used to generate slopes for each species and slope position and only site factors significant at $p < 0.05$ were illustrated.

Table 1.1. Major habitat types, plot frequencies and kilometers surveyed along non-paved roads both treated and non-treated with $MgCl_2$-based dust suppression products in Larimer and Grand Counties, Colorado.

	HABITAT TYPE	FREQUENCY OF PLOTS (*n*)	KM (MI) OF ROAD COVERED
GRAND COUNTY	Forested/Wooded	665	56.8 (35.3)
	Meadow	31	2.6 (1.6)
	Riparian	54	4.7 (2.9)
	Shrubland	341	29.3 (18.2)
	Wetland	34	2.9 (1.8)
	Rangeland	0	0.0
	TOTAL	**1125**	**96 (60)**
LARIMER COUNTY	Forested/Wooded	841	157.6 (97.9)
	Meadow	39	7.4 (4.6)
	Riparian	250	46.8 (29.1)
	Shrubland	239	42.2 (26.2)
	Wetland	43	8.2 (5.1)
	Rangeland	38	7.1 (4.4)
	TOTAL	**1450**	**269 (167)**
BOTH COUNTIES	Forested/Wooded	1506	214.4 (133.2)
	Meadow	70	10.0 (6.2)
	Riparian	304	51.5 (32.0)
	Shrubland	580	71.5 (44.4)
	Wetland	77	11.1 (6.9)
	Rangeland	38	7.1 (4.4)
	TOTAL	**2575**	**365 (227)**

Table 1.2. Major dominant species and percent of roadside cover along non-paved roads both treated and non-treated with $MgCl_2$-based dust suppression products surveyed in [1]Grand and [2]Larimer Counties, Colorado in 2004.

SPECIES	**COMMON NAME**	**SPECIES TYPE**	**GC[1] (%)**	**LC[2] (%)**
Pinus ponderosa	ponderosa pine	coniferous tree	-	18.2
Populus tremuloides	trembling aspen	deciduous tree	18.8	17.1
Pinus contorta	lodgepole pine	coniferous tree	29.4	15.3
Salix species	willow	deciduous shrub	11.6	7.8
Artemisia tridentata	big sagebrush	deciduous shrub	14.8	0.3
Chrysothamnus nauseosus	common rabbitbrush	woody shrub	6.1	6.3
Picea engelmannii	Engelmann spruce	coniferous tree	2.3	5.0
Pseudotsuga menziesii	Douglas-fir	coniferous tree	1.2	4.9
Alnus species	alder species	deciduous shrub	3.5	4.5
Juniperus scopulorum	Rocky mountain juniper	coniferous tree	4.0	3.4
Abies lasiocarpa	subalpine fir	coniferous tree	2.7	2.8
Rhus trilobata	squawbush, skunkbush	deciduous shrub	-	1.9
Amelanchier alnifolia	saskatoon serviceberry	deciduous shrub	1.6	-
Populus angustifolia	narrowleaf cottonwood	deciduous tree	1.2	1.8
Pinus flexilis	limber pine	coniferous tree	0.2	1.7
Acer glabrum	Rocky mountain maple	deciduous shrub	0.3	1.4
Atriplex confertifolia	shadscale, saltbush	late deciduous to evergreen shrub	-	1.1

Table 1.3. Percentage of species healthy and severely damaged along non-paved roads treated and non-treated with $MgCl_2$-based dust suppression products in Grand and Larimer Counties, Colorado in 2004. Levels of significance are between road treatments for healthy and severely damaged vegetation.

	HEALTHY VEGETATION COVER (%)			**SEVERELY DAMAGED VEGETATION COVER (%)**		
SPECIES	NON-TREATED ROADS	TREATED ROADS		NON-TREATED ROADS	TREATED ROADS	
All vegetation combined	89.2	78.3	***	4.0	7.6	***
Abies lasiocarpa	99.2	87.8		0.8	4.3	
Acer glabrum	79.2	69.5		19.7	30.3	
Alnus species	73.9	75.3		10.5	19.3	
Artemisia tridentata	98.1	98.7		1.1	1.3	
Chrysothamnus species	68.6	89.1	*	0.0	6.3	
Juniperus scopulorum	95.4	62.3	**	0.6	1.9	
Pinus contorta	65.9	58.7	*	6.5	13.3	**
Pinus flexilus	49.8	58.6		1.1	17.3	
Picea engelmannii	94.8	75.4	***	2.5	3.1	
Pinus ponderosa	98.0	69.2	***	0.0	5.4	***
Populus angustifolia	98.3	68.4		0.1	6.5	
Populus tremuloides	85.0	74.1	***	7.4	12.3	**
Pseudotsuga menzeisii	95.3	93.7		2.0	5.7	
Salix species	80.3	71.9	*	7.6	11.8	

***$p < 0.01$, **$p < 0.05$, *$p < 0.10$ between percent healthy or severely damaged cover between road treatments.

Section 2. Conditions of soils and vegetation along roads treated with magnesium chloride for dust suppression

Abstract

Investigations of vegetation stress along non-paved roads treated with a range of $MgCl_2$ application rates utilized 60 roadside and 79 drainage plots on 15 and 18 roads, respectively. Evaluations were completed of foliar damage, plant health, biotic and abiotic damage incidence and severity, soil and foliar chemistry and other common site and stand characteristics of lodgepole pine (*Pinus contorta)*, trembling aspen (*Populus tremuloides)*, Engelmann spruce (*Picea engelmannii)*, subalpine fir (*Abies lasiocarpa)*, and lower elevation plots dominated by shrubs and grasses. High concentrations of soil magnesium and chloride (400 to 500 ppm), high foliar chloride (2,000 to 16,000 ppm depending on species) and high incidence of foliar damage were measured in roadside plots along straight road segments in the first 3 to 6.1 m adjacent to treated roads. In drainage plots, where water is channeled off roads, high concentrations of both magnesium and chloride ions and associated foliar damage were measured between 3 and 98 m from the road. High incidence of foliar damage and elevated ion concentrations were not apparent in control plots along non-treated roads. Lodgepole pine appeared to be the most sensitive species, while aspen accumulated the most chloride and exhibited the least amount of damage. Foliar chloride concentrations strongly correlated with percent foliar damage for all species ($r = 0.64$ to 0.74, $p < 0.0001$) while the incidence of biotic damages did not correlate well ($r < 0.20$). Relationships between foliar chloride and $MgCl_2$ application rates were strongly positive and can be used to predict foliar concentrations and subsequent damage to roadside trees.

2.1. Study objectives

The objectives of this research were to determine: 1) if components of $MgCl_2$-based dust suppression products moved from treated roads and to quantify the vertical and horizontal movement in roadside soils, 2) if foliar damage on four native tree species and various ground cover species was related to $MgCl_2$ movement from the road, and 3) how site factors such as precipitation, drainage patterns, slope, and $MgCl_2$ application rates influenced the movement and spatial distribution of $MgCl_2$ in roadside soils and plants.

2.2. Methods and materials

Study sites. Research was conducted along $MgCl_2$ treated and non-treated (control) roads in Larimer and Grand Counties of northern Colorado in 2004 through 2006. Plot elevation in Larimer County ranged from 1,750 to 3,210 m, and the vegetation types ranged from low elevation shrub and grass cover to subalpine fir and spruce forest. Grand County plots ranged from 2,490 to 2,740 m in lodgepole pine and trembling aspen dominated stands. Spatially gridded (800 m) averaged monthly and annual precipitation for the climatological period 1971-2000 (PRISM Group 2006) was determined for each plot. County roads varied in maintenance procedures, years of dust suppression treatment, amount of products applied, and chemical components and concentrations of products used (Table 2.1 and 2.2). Though $MgCl_2$ was the major focus of this study, some roads had been treated with a combination of liquid $MgCl_2$ and lignin sulfonate products, generally in a ratio of 50/50 (Tables 2.1 and 2.2). Quantitative calculations of application rates (total and average $kg \cdot km^{-1}$ of $MgCl_2$ applied calculated from $gal \cdot mi^{-1}$ of $MgCl_2$ solution applied, removing gallons of any other products applied) were determined for study roads, and $MgCl_2$ weight was calculated using 368.59 g anhydrous $MgCl_2$

per liter of dust suppression solution applied as the active ingredient weight/solution ratio (Appendix E) (D.L. Miller, Larimer County Road and Bridge Dept. and A. Green, Grand County Dept. of Road and Bridge, personal communication 2006).

Based on the results from a previous roadside survey in both study counties (Section 1), roadside and drainage plots were established and sampled within four common vegetation types: 1) lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.), 2) trembling aspen (*Populus tremuloides* Michx.), 3) stands with a combination of Engelmann spruce (*Picea engelmannii* [Parry] Engelm.) and subalpine fir (*Abies lasiocarpa* [Hook] Nutt.) and 4) lower elevation shrubs and grasses. Fifty roadside vegetation health plots along 12 treated roads and 10 plots along 3 non-treated (control) roads were established in summers of 2004 and 2005 (a total of 60 roadside plots) (Appendix A: Table A1). Fifty-three drainage plots along 11 treated roads and 26 drainage plots along 7 non-treated (control) roads were established in summers 2005 and 2006 in the same four vegetation types (a total of 79 drainage plots) (Appendix A: Table A2).

Roadside vegetation health plots. Plots were paired in upslope and downslope sets of similar vegetation, stand structure and slope on the same road, consisting of three rectangular subplots spaced 15 m apart and perpendicular to the road (Appendix A: Figure A1). The three subplots were replications within a plot for quality assurance purposes and were treated as such in statistical analyses. Plots along treated roads varied in $MgCl_2$ application rates and plots along non-treated roads were considered control plots (Table 2.2). Subplots began directly off the road edge (where no maintenance or fill material occurred) and were each 6.1 m wide and 12.2 m long (Appendix A: Figure A1). Upslope and downslope were defined by the slope (positive or negative) of the land from the road edge to 12.2 m from the road. In each subplot, all trees taller than 30.5 cm were rated for: 1) diameter class (< 5.1 cm, 5.1 to 15.3 cm, >15.3 to 30.6 cm, >30.6 cm) if over breast height (1.37 m) or for total height if below; 2) health status, regardless of cause, (1: healthy, 2: mildly damaged, 3: severely damaged, 4: recently dead, 5: old dead, 6: cut or decayed stump); 3) crown class (dominant, co-dominant, intermediate, understory or open); 4) total percent crown (proportion of tree height with live, damaged or dead crown present); 5) percent damaged crown (necrotic, banded, chlorotic or marginally burned needles or leaves) and 6) distance from the road and the incidence and severity (percent of tree affected) of any damage agents affecting 5% or more of the crown or stem (Appendix A: Tables A13 and A14). Percent cover and health of woody and herbaceous plants were also recorded within each subplot with 11.5 m radius circle shrub plots at 0 and 12.2 m and two 0.75 m^2 groundcover plots at each distance: 0, 3, 6.1 and 12.2 m.

Twenty-five plots were dominated with lodgepole pine along treated roads and 6 along non-treated roads (control plots) (Appendix A: Table A1). Plots ranged in elevation from 2,540 to 2,850 m and average slopes were -23% in downslope plots and 18% in upslope plots. Thirteen plots were established in aspen dominated stands along treated roads and 2 plots along a control road (Appendix A: Table A1). Plots ranged in elevation from 2,490 to 2,740 m; downslope plots had an average slope of -15%, while upslope plots averaged 19%. Engelmann spruce and subalpine fir study trees grew in the same areas and were available to sample in only 1 county, Larimer. Six plots were sampled along 1 treated road, with 2 more plots along 1 control road; the plots ranged in elevation from 2,680 to 3,210 m and had average slopes of -14 and 8% (Appendix A: Table A1). Spruce and fir trees were specifically grouped together to report stand characteristics at a plot level, but foliar ion concentrations differed between spruce and fir tissue, and were therefore separated in all chemical analyses and statistics. Six plots were established along 2 treated roads in non-forested areas, where various shrubs and grasses were the dominant species; these plots ranged in elevation from 1,750 to 2,100 m, and the slopes averaged -7 and 12% (Appendix A: Table A1). Twenty-four of the 50 permanent plots along treated roads were sampled twice (2004 and 2005), while the rest were sampled once in 2004 or 2005. The 10 control plots were established in 2005 and sampled once.

Soil samples were collected from two depths (0 to 30.5 and 30.5 to 61.0 cm) at four distances from the road (0, 3.0, 6.1 and 12.2 m) in each subplot (Appendix A: Figure A1). Depths were averaged within each distance and distances were averaged between the three subplots. One foliar and twig sample was collected from each of two trees in close vicinity of the soil sample at the same four distances within each subplot. In conifers, a combination of needle ages was collected, including the most recent growth. Foliar and twig samples were collected from the mid-height of the tree, if possible, and from a well-lit portion representative of the overall crown condition of the tree.

Drainage vegetation health plots. Drainage plots were established to quantify $MgCl_2$ movement, vegetation health, and sediment occurrence through drainage or culvert channels. A survey of culverts was conducted along major non-paved roads in both counties, and 79 drainages were randomly selected from the population of culverts and drainages for plot establishment on 18 roads. Drainage plots were variable in length and ended 6.1 m past the last visibly damaged trees. The last foliar and soil samples collected in each plot were designated as control samples, because this is where it was believed that the movement of water ended based on crown damage and the end of visible water and sediment paths on the ground. Fifty-three drainage plots along treated roads varied in $MgCl_2$ application rates, and the 26 drainage plots along non-treated roads were considered control plots (Appendix A: Table A2). Based on the length of the plot (related to the maximum distance from the road with crown damage in trees), the plots were separated into four classes: control, low impact, medium impact, and high impact drainage plots. Twenty-four plots along treated roads were 12.2 to 24.4 m long (low impact drainages), 19 plots were 27 to 46 m long (medium impact drainages), and 10 plots along treated roads were greater than 49 m (high impact drainages) (Appendix A: Figure A2). Twenty-five out of 26 control plots along control roads were 12.2 m long (the minimum plot length); with the exception of one control plot that was 24.4 m in length (Appendix A: Figure A2).

The 6.1 m wide plots followed the drainage and water channel 6.1 m past the last trees with crown damage in the drainage. All trees within the variable length transect were assessed for crown characteristics and health in the same manner as trees in roadside vegetation health plots. Twenty-one drainages along 4 treated roads and 9 drainages along 4 control roads were dominated by lodgepole pine (Appendix A: Table A2). Trembling aspen was the dominant species in 15 drainages along 5 treated roads and in 10 control drainages along 6 non-treated roads (Appendix A: Table A2). Mixed Engelmann spruce and subalpine fir were the dominant species in 10 drainages along 2 treated roads and in 7 control drainages along 3 non-treated roads (Appendix A: Table A2). Seven non-forested drainage plots were dominated by various shrub and grass species along 3 treated roads, and no control drainages were established with shrubs as the dominant vegetation along non-treated roads (Table A2).

Soil and foliar samples, from two trees closest to the middle soil sample, were collected at doubling increases in distance from the road (0, 3, 6.1, 12.2, 24.4, 48.8 m, etc.). Three upper horizon (0 to 30.5 cm) soil samples were taken at each distance from the road. The three samples (one at plot center and one from each plot border) were homogenized into one sample. Depth of sediment was measured at each of the three soil samples, and the average and maximum sediment depths were calculated at each distance soil was sampled. The surface area that potentially channeled surface water into the drainage was measured at each plot, based on the surface area of the road, as well as the length and slope of roadside ditches and embankments that potentially drained surface water into the plot (Appendix A: Figure A3). Site factors, such as precipitation, slope, topography, and the total and average $MgCl_2$ application rates were collected at each plot and used to build statistical models relating these factors to ion movement from treated roads (Appendix E). Each drainage plot was established in 2005 or 2006, and sampled for foliage and soils only once.

Soil and foliar chemical analyses. Soil samples were sieved (0.6 cm) in the field to exclude organic matter and rocks, and they were mixed thoroughly, air dried for 72 hours, sieved again (2.0 mm) and sent for chemical analysis (Brown 1998, Byron Vaughan, AgSource Harris Laboratory, personal communication 2007). Soil pH was measured in a 1:1 soil/water slurry paste and electrical conductivity was measured from a saturated paste extraction. The Bray-1-P test was used for extractable (plant available) phosphorus. Extractable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were extracted with ammonium acetate, pH 7.0, and analyzed with Flame Atomic Absorption or inductively coupled plasma (ICP) Spectrometry. Extractable micronutrients (Cu^+,

Fe^{3+}, Mn^{2+}, Zn^{+}) were extracted with the chelator diethylene triamine penta acetic acid (DTPA) and analyzed by ICP. Inorganic sulfur and boron were measured using ICP. Soil organic matter was estimated from combustion/loss-on-ignition methods. Available soil chloride was extracted with calcium nitrate and analyzed with the Mercury (II) Thiocyanate colorimetric method. Twigs and leaves were washed with distilled water and oven dried at 85° C for 72 hours, separated, and ground using a 2.0 mm sieve (Type SM2000, Retsch GMbh and Co.). Extractable nitrate, phosphate and potassium were all measured using 2% acetic acid digestion and ICP. Chloride was analyzed using the Mercury (II) Thiocyanate colorimetric method. Total nitrogen was measured using Kjedahl digestion and total P, Mg^{+2}, Zn^{+}, Cu^{+}, Fe^{+3}, S, Na^{+}, B and Mo using nitric acid/hydrogen peroxide digestion and ICP (AOAC 1990, B. Vaughan, personal communication 2007). Agsource Harris Laboratories participates in the North American Proficiency Testing (NAPT) program and quality control measures are defined and measured with a Standard Operating Procedure. Soil types, parent materials, physical properties (percent clay, sand and silt), and drainage class for each road or plot pair (if soil types differed on the same road) were determined by using the Natural Resources Conservation Survey Web Soil Survey (Soil Survey Staff 2008) (Table 2.2).

Statistical analysis. Data were analyzed by fitting random and fixed effects using The Mixed Procedure, SAS 9.1 (Copyright 2002-03 by SAS Institute Inc., Cary, NC). Fixed effects included distance and distance intervals, slope position from the road (upslope or downslope), $MgCl_2$ application rates, summer precipitation, drainage impact class and the drainage surface area that potentially moved water into the plots. Random effects were transect, plot, road and county, which were pooled when not comparing roads or counties. Trees were fit into distance intervals and analyzed as repeated measures effects. Precipitation was held constant throughout analyses by the average summer (May-September) precipitation of the two counties, so that means were more comparable, although summer precipitation was not always a significant variable in models. Adjusted least square means (lsmeans) of soil and foliar ion concentrations and foliar damage were compared between fixed effects (distances and slope position) to determine how far damage and elevated ion concentrations occurred from roads using Fisher's Least Significant Difference (LSD) at $p \leq 0.05$. Concentrations were $\log_{10}$ transformed to stabilize the variance of ion concentrations and lsmeans and standard errors were back-transformed to present data. Back-transformed means are typically closer to the median of the data, but are still referred to as adjusted means throughout this publication. Drainage plots were grouped into fixed drainage impact classes of control (along non-treated roads), low, medium and high impact drainages (based on lengths of the plots). Lsmeans of soil and plant ion concentrations and foliar damage by distance and drainage impact classes were adjusted by holding summer precipitation and surface area values constant in drainage plots. Multiple regressions were used to compare average and total $MgCl_2$ application rates with variables like foliar and soil ion concentrations while holding other variables constant. Pearson Correlation Coefficients were used to compare simple linear regressions of plant and soil nutrients, damage agents, and distance with crown damage seen in roadside trees. The square of a Pearson correlation is the R^2 for the simple regression with the same two variables.

2.3. Results

$MgCl_2$ in roadside plot soils. Chloride and magnesium concentrations were higher in soils along roads treated with $MgCl_2$ than along control roads ($p < 0.0001$). Along treated roads, both ion concentrations were highest near the road at both slope positions and decreased as distance from the road increased (Figure 2.1a-b). Overall (combining counties, all roads, plots, both depths and both years of sampling), chloride appeared to move downslope into roadside soils from treated roads to 6.1 m from the road and magnesium moved 3.0 m. At these distances, mean ion concentrations were similar between upslope and downslope plots and chloride concentrations were similar to concentrations measured along control roads (< 30 ppm) (Figure 2.1a-b). See Appendix B: Table B1 for upslope and downslope soil chloride and magnesium concentrations averaged by study road. In plots sampled for two consecutive years, significant accumulations of soil chloride were not measured from year to year when samples from both slopes and all distances were combined. Only directly off the road shoulder, chloride increased in upslope soils from 2004 to 2005 (Appendix C: Figure C1). No yearly increases in chloride were measured at any distance from the road in downslope plots, although magnesium concentrations increased downslope through 6.1 m from 2004 to 2005. When all data were combined, soil chloride and magnesium concentrations were similarly distributed between upper (0 to 30.5 cm) and lower (30.5 to 61.0 cm) soil horizon samples (Appendix C: Figures C2a-b). A change in chloride distribution occurred in plots sampled for two consecutive years. In 2004, soil chloride was significantly higher in the lower soil profile when compared to the upper profile (Appendix C: Figure C3a). In 2005, soil chloride was significantly higher in the upper soil profile (Appendix C: Figure C3b). The most important site factors explaining soil chloride concentrations were: $MgCl_2$ application rate, distance and slope position from the road. Soil physical properties such as percent clay, silt and sand were not significantly related to the distribution or concentration of chloride in roadside soils, although they did vary between roads (Table 2.2). Site factors specific to each plot, including difference in percent slope and average summer precipitation, did not explain chloride concentrations along treated roads. Chloride concentrations were similar between low (0 to 10%), medium (10 to 20%) and high (+20%) slope plots (Appendix C: Figure C4). Magnesium was slightly higher closest to the roads in low slope plots (Appendix C: Figure C5).

Using 369 g anhydrous $MgCl_2$ / liter of dust suppression solution applied as the active ingredient weight/solution ratio, the average rate of $MgCl_2$ applied to study roads ranged from 0 – 12,600 $kg \cdot km^{-1} \cdot yr^{-1}$ of anhydrous $MgCl_2$ through 2005 (3,600 $kg \cdot km^{-1} \cdot yr^{-1}$). The total $MgCl_2$ applied ranged from 0 to 76,000 $kg \cdot km^{-1}$ through 2005 (37,600 $kg \cdot km^{-1}$) (Appendix E). Roadside soil chloride concentrations increased as total and average application rates of $MgCl_2$ (total $kg \cdot km^{-1}$ and average $kg \cdot km^{-1} \cdot yr^{-1}$) increased on roads (Figure 2.2a-b). Greater concentrations were measured in downslope soils than in upslope soils (Figure 2.2a), so only these data are presented in Figure 2.2b. The largest increase in downslope chloride was directly off the road shoulder at 0 m (Figure 2.2b). When only downslope concentrations were correlated with $MgCl_2$ application rates, the average amount of $MgCl_2$ applied was the best predictor of soil chloride directly off the road shoulder at 0 m ($r = 0.57$, $p < 0.0001$) and at 3.0 m ($r = 0.54$, $p < 0.0001$).

Aside from increased $MgCl_2$ ions, nutritional and physical changes to soils along treated roads were generally negligible and were confined to 0 to 6.1 m from the road. Along treated roads, electrical conductivity (EC) was highest close to the road (2.02 deciSiemens per meter [$dS \cdot m^{-1}$]) and decreased as distance from the road increased, returning to the control plot average (0.25 $dS \cdot m^{-1}$) at 6.1 m from the road (Appendix C: Figure C6). Treatment of roads with $MgCl_2$ did not alter the pH of roadside soils, with mean pH along control roads ranging from 5.5 to 6.5, and soils along treated roads ranging from 6.4 to 6.8. Along both treated and control roads, percent soil organic matter was lowest directly off the road shoulder (0.97% at 0 m) and increased as distance from the road increased (Appendix C: Figure C7).

High concentrations of magnesium in soils appeared to displace exchangeable calcium (Ca^{+2}) and potassium (K^{+}) close to treated roads at both slope positions and lowered cation ratios (Appendix C: Figures C8c-d). Typical ratios in soils along control roads (Ca:Mg = 10.94, K:Mg = 1.0) were significantly higher than cation ratios directly off treated roads at 0.0 m (Ca:Mg = 3.5, K:Mg = 0.3). Concentrations of sodium, sulfur and boron increased in soils as the total and average rate of $MgCl_2$ applied increased. All three elements were highest close to treated roads and decreased with distance from the road (Appendix C: Figures C9a-c). Mean sodium concentrations ranged from 22.5 ppm directly off treated roads to 11.7 directly off the shoulder of control roads (Appendix C: Figure C9c). Sulfur concentrations decreased from 15.5 ppm in soils close to treated roads, compared to 4.5 ppm along control roads (Appendix C: Figure C9a). Soil boron concentrations were highest at 1.2 to 1.4 ppm along treated road shoulders and were 0.7 ppm along control roads (Appendix C: Figure C9b). Concentrations of the micronutrients zinc, iron, and manganese did not significantly differ in soils between treated and control roads, while copper was slightly higher along treated roads (0.6 ppm), when compared to control roads (0.5 ppm) (Appendix C: Figures C10a-d).

$MgCl_2$ in drainage plot soils. The length of a drainage plot (defined by the distance from the road where trees no longer displayed crown damage) was positively related to several main site factors. The best model to predict plot length in multiple regression, based on the highest R^2, included: amount of surface area which potentially drained water into the plot ($p < 0.0001$), total $MgCl_2$ application rate (total $kg \cdot km^{-1}$, $p < 0.0001$), average summer precipitation ($p = 0.04$), and average winter precipitation ($p = 0.008$) ($R^2 = 0.39$). The percent slope of each drainage plot was not a significant predictive factor of the length.

Chloride concentrations in drainage soils were related to distance from the road ($p < 0.0001$), surface area ($p = 0.03$), average $MgCl_2$ application rate ($p = 0.005$) and the maximum depth of sedimentation at each distance ($p = 0.0004$). Low, medium and high impact drainage plots had significantly more soil chloride than drainage plots along control roads. Along treated roads, soil chloride concentrations were similar at the first four distances sampled (0 to 12.2 m) between low, medium and high impact plots (Figures 2.3a-c). In low impact drainages, soil chloride concentrations decreased as distance from the road increased, and remained higher than control plots through 24 m (Figure 2.3a). All 19 medium impact plots and 7 of the 10 high impact plots had more soil chloride than typical control soils (20 to 30 ppm chloride) up to 61.0 m from the road, and three high impact drainage plots contained soil chloride higher than control concentrations through 98.0 m from the road (Figures 2.3b-c). Magnesium concentrations in drainage soils were related to surface area ($p = 0.003$) and average $MgCl_2$ application rate ($p = 0.002$), but no pattern was observed between magnesium and distance. More magnesium was present in treated road drainage soils than along control roads, and remained fairly constant through every distance along treated roads (Figures 2.3d-f). In high impact drainages, magnesium concentrations decreased where the majority of plots ended at 62 to 73.0 m from the road ($n = 7$ plots), but remained high in the three high impact plots that were 98.0 m long (Figure 2.3f).

Sediment, probably picked up from the road surface or moved with water through drainage ditches, occurred in drainage plots along both treated and control roads (Figures 2.3g-i). When compared to control drainages ($p = 0.08$), more sediment occurred in drainages along treated roads and the average depth increased as the total application rate of $MgCl_2$ increased ($p = 0.03$). More sediment occurred in drainages along treated roads compared to control drainages ($p = 0.08$) and the average depth increased as the total application rate of $MgCl_2$ increased ($p = 0.03$). Sediment depth generally decreased as distance from the road increased (Figures 2.3g-h). In high impact plots longer than 73 m, depth of sedimentation increased towards the end of the plots (Figure 2.3i). The best predictors of sedimentation depth were: surface area of the plot ($p = 0.01$), total application rate of $MgCl_2$ ($p = 0.01$), and concentrations of chloride and magnesium in drainage soils ($p < 0.0001$ and $p = 0.008$, respectively). As $MgCl_2$ ions increased in drainage plot soils, depth of sediment also increased.

Soil sulfur (Appendix C: Figure C11) and boron (Appendix C: Figure C12) were the only elements significantly higher in drainages along treated roads compared to control roads (treated = 11.6 ± 2.0 ppm sulfur and 1.2 ± 0.2 ppm boron; control = 3.0 ± 0.6 ppm sulfur and 0.5 ± 0.2 ppm boron). Both were in highest concentrations close to the road and decreased with distance (14.7 ± 1.7 ppm sulfur and 1.3 ± 0.3 ppm boron close to treated roads). Both elements increased as the amount of $MgCl_2$ applied increased along treated roads, but only boron increased as the surface area potentially draining water into the plot increased ($p = 0.03$).

Lodgepole pine in roadside plots. When compared to trees growing along control roads, lodgepole pine along treated roads had more crown damage (percentage of crown with needle tip burn, full needle necrosis, banding or chlorosis) and higher concentrations of both foliar chloride and magnesium (Figures 2.4a-c). Tip burn was the most prevalent type of symptomatic foliage on lodgepole pines. Mean crown damage (60%), foliar chloride (3,700 ppm) and foliar magnesium (2,000 ppm) were all highest in trees close to the road and decreased with distance from the road (Figures 2.4a-c). Lodgepole pines closest to and downslope from the road had the lowest health ratings, with an average rating of 3.1 (severely damaged).

In lodgepole pine sampled for two consecutive years, both foliar chloride ($p = 0.01$) and crown damage ($p = 0.003$) increased from year to year. Foliar chloride concentrations increased from 710 to 1350 ppm in upslope trees close to the road, and these trees increased from almost no damage (0.8% of crown) to a substantial mean portion of the crown with symptomatic foliage (18.9%). Downslope lodgepole pines closest to the road (0 to 3 m) also exhibited an increase in crown damage (46.6% in year one to 69.7% in year two) although foliar chloride concentrations stayed relatively similar (2,940 ppm and 2,860 ppm chloride).

Symptomatic lodgepole pine foliage from three different aged needles was sampled from three plots ($n = 9$ trees). Current-year needles had the lowest mean concentration of foliar chloride (5,670 ppm) and concentrations were similar between two-year old needles (8,630 ppm) and three-year old needles (9,000 ppm) (Appendix C: Figure C13b). The extent of mean severity (percent of needle with necrotic tissue) increased with needle age each year (ranging from 0% in current-year needles to 42% in three-year old needles) (Appendix C: Figure C13b). Magnesium increased with needle age to a similar extent as chloride, where two- and three-year old needles (2,400 and 2,600 ppm, respectively) were higher in magnesium than the current-years needles (1,450 ppm) (Appendix C: Figure C13a).

A strong positive relationship existed between lodgepole foliar chloride and average $MgCl_2$ application rates, and concentrations increased in roadside trees with the amount of $MgCl_2$ applied (Figure 2.5a). Downslope trees closest to the road had the strongest correlations with average $MgCl_2$ application ($r = 0.80$, $p < 0.0001$) and the relationship became weaker as distance from the road increased ($r = 0.58$ for trees 3.0 to 6.1 m). The lowest $MgCl_2$ application rate where lodgepole pine was sampled (besides control roads) was approximately 2,300 $kg \cdot km^{-1} \cdot yr^{-1}$ and roadside lodgepole pine tissue had approximately 4,000 ppm chloride and approximately 4,000 $kg \cdot km^{-1} \cdot yr^{-1}$ was associated with 6,000 ppm chloride (Figure 2.5a).

Lodgepole pine in drainage plots. With respect to damage, lodgepole pine trees in control drainages averaged 17% crown damage which included: 6% tip burn; 3% banded burn incidence, due to needlecast fungi; and 7% necrotic foliage (Appendix C: Figure C14a). Lodgepole in drainages along treated roads had 20 to 35% mean crown damage of which the majority was tip burn (Appendix C: Figure C14a). Damage fluctuated within drainage distance but generally decreased as distance from the road increased (data not shown). Foliar chloride concentrations were higher in drainages along treated roads, as compared to those along control roads; and mean chloride concentrations were similar between low, medium and high impact drainages (Figures 2.6a-c). Chloride concentrations were not related to the amount of surface area draining into the plot ($p = 0.29$), but did increase as the average $MgCl_2$ application rate increased ($p = 0.05$).

Foliar chloride varied with distance from the road but was highest close to the road ($p = 0.005$). In low impact plots, foliar chloride was extremely high close to the road and decreased as distance from the road increased (Figure 2.6a). In high impact drainages, concentrations were elevated through 61.0 m from the road, and trees between 62.0 and 85.0 m from the road had similar chloride concentrations as trees in control plots (Figures 2.6b-c). Though damage was apparent on trees past 62.0 m, most were not sampled because foliage was too high in several drainages. Foliar magnesium also varied with distance, was highest close to treated roads, and increased as the average rate of $MgCl_2$ increased ($p = 0.01$, Appendix C: Figures C15a-c).

Trembling aspen in roadside plots. In aspen, percent crown damage, foliar chloride and foliar magnesium concentrations were all highest close to and downslope from the road (Figures 2.4d-f). The most common symptom of foliar damage was necrosis of leaf margins, with a distinct separation between necrotic and green portions of the leaf. Along treated roads, mean crown damage (5 to 35%) and foliar chloride concentrations (7,000 to 17,000 ppm) were higher in trees downslope from the road, when compared to upslope trees through 9.1 m from the road (Figures 2.4d and 2.4f). Aspen leaves had low magnesium concentrations (2,000 ppm) past 3.0 m from the road (Figures 2.4e). At 12.2 m downslope and past 3.0 m upslope from the road, aspen crown damage returned to a typical amount of 0-5% damage and leaf chloride concentrations returned to typical control concentrations, ranging from 2,000 to 4,000 ppm. Aspen accumulated more chloride than any other tree sampled, although mean crown damage was lower than conifers at similar distances from the road (Figures 2.4d and 2.4f). However, aspen trees closest to and downslope from the road were in worse health than those further from the road ($p = 0.01$ and 0.03, respectively). The average health rating was 2.6, between mildly and severely damaged. In aspen plots sampled for two consecutive years, significant increases in foliar chloride concentrations or crown damage were not measured from year to year (Appendix C: Figures C16a-b).

Average application rate ($kg{\cdot}km^{-1}yr^{-1}$) was positively related to an increase in aspen foliar chloride and as the amount of $MgCl_2$ increased, the amount of foliar chloride increased ($p = 0.02$, Figure 2.5b). The largest increases in foliar chloride were in trees closest to the road, although there were increases in aspen leaf chloride with average application rate downslope through 9.1 m from the road (Figure 2.5b). The correlation between application rate and foliar chloride within the first 3.0 m from the road was similar to trees further (3.0 to 6.1 m) from the road ($r = 0.73$ and $r = 0.74$, respectively, both $p < 0.0001$). Trees between 6.1 and 9.1 m from the road still had high correlations with average $MgCl_2$ application rates ($r = 0.56$, $p < 0.0001$).

Trembling aspen in drainage plots. Mean aspen crown damage in treated road drainages ranged from 3% in low impact plots to 16% in high impact plots and less than 1% in control drainages (Appendix C: Figure C14b). In treated drainages almost all damage was marginal burning of leaves, and a major issue in these drainages was a lack of foliage on aspen trees that had recently died. When only drainages along treated roads were compared, aspen leaf chloride was in similar concentrations between drainage impact classes, with concentrations increasing as the amount of surface area increased ($p = 0.03$). Foliar chloride fluctuated with distance depending upon whether trees were in low, medium or high impact classes along treated roads. Due to high variation, chloride concentrations were not significantly different through the first 36 m from the road because of the high variation in chloride concentrations. However, aspen in high impact drainages averaged foliar chloride concentrations between 10,000 and 20,000 ppm through 49.0 m from the road (Figures 2.6d-f). There were no aspen trees to sample towards the end of high impact drainages (50.0 to 85.0 m) because they were dying or dead with no foliage, thus defoliated aspen trees may have had high concentrations of foliar chloride before the leaves dropped. Aspen foliar magnesium concentrations varied depending on the drainage impact class, with medium and high impact plots having higher concentrations than control or low impact drainages. Magnesium was not related to the distance interval from the road ($p = 0.20$), and fluctuated as distance from the road increased (Appendix C: Figures C17a-c). Like foliar chloride in aspen trees, magnesium appeared to remain high past the interval of sampled trees in high impact plots (Appendix C: Figure C17c). Magnesium concentrations did not increase with application rates ($p = 0.27$), but were positively related to the surface area potentially draining water into the plots ($p = 0.0009$).

Engelmann spruce and subalpine fir in roadside plots. Damage observed on Engelmann spruce and subalpine fir trees was frequently observed as both needle tip burn and full necrosis of needles. In both species, the most crown damage occurred downslope within the first 3.0 m from the road (Figures 2.4g and 2.4j). Crown damage in spruce and fir trees was higher in downslope plots compared to control trees through 6.1 m from the road (Figures 2.4g and 2.4j). In both species, trees downslope from the treated road had more than typical control chloride concentrations up to 6.1 m from the road (Figures 2.4i and 2.4l). In spruce trees, foliar magnesium fluctuated with distance and was consistently higher in trees along treated roads compared to control concentrations (500 to 1,500 ppm) at all distances from the road (Figure 2.4h). In fir trees, magnesium concentrations were similar in trees along both roads (Figure 2.4k). The average spruce health rating within the first 3.0 m from the road was 2.8, between mildly and severely damaged. Subalpine fir in the first 3.0 m from the road were rated an average of 2.6, also between mildly and severely damaged. Neither species accumulated more foliar chloride or increased in damage between the first and second year sampled (Appendix C: Figures C18 and C19).

Engelmann spruce and subalpine fir in drainage plots. There were no high impact drainages sampled for spruce trees. Mean crown damage ranged from 11 to 17% in treated road drainages and was less than 3% in control drainages (Appendix C: Figure C14d). Crown damage was a mix of fully necrotic tissue and tip burn. Needle chloride concentrations in Engelmann spruce trees varied by drainage impact class, and control plots had less foliar chloride than trees in low and medium impact drainages ($p = 0.02$) (Figures 2.6g-h). In treated road drainages, foliar chloride concentrations past 24.0 m were comparable to control trees (Figure 2.6g-h). Foliar magnesium also decreased with distance from the road (Appendix C: Figures C20a-b). As the surface area directing water towards the plot increased along the treated road, concentrations of foliar chloride and magnesium in Engelmann spruce both increased ($p = 0.06$ and 0.04).

In subalpine fir drainages, mean crown damage was less than 2% in control drainages, ranged from 14 to 32% in treated drainages, and was a mix of fully necrotic tissue and tip burn (Appendix C: Figure C14c). Foliar magnesium concentrations generally declined in all drainages as distance from the road increased and was highest in trees in medium impact drainages (Appendix C: Figures C21a-b). Foliar chloride concentrations in subalpine fir were variable depending on drainage impact class, and all foliage sampled along treated roads contained higher concentrations than those in control drainages (Figures 2.5i-j). Needle chloride decreased with distance from the road ($p = 0.01$) and average foliar chloride was higher in medium impact plots, when compared to low impact plots ($p = 0.01$). Along the treated road, foliar chloride and magnesium increased as the surface area draining into the plot increased ($p = 0.02$ and 0.01).

Other elements in tree foliage. Potassium, calcium, total nitrogen, phosphorus, sulfur, boron, copper and manganese were all higher in lodgepole pine foliage in roadside vegetation health plots along treated roads when compared to control roads (Table 2.3, Appendix C: Figures C22a-d, C23 and C24). Foliar boron was highest close to and downslope from the road (80 ppm), as compared to control concentrations (10 ppm) (Appendix C: Figure C24). Boron and sulfur both increased in needle tissue as the total and average $MgCl_2$ application rate increased. Foliar boron and manganese were higher in drainage plot lodgepole along treated roads, and only boron increased as application rate of $MgCl_2$ increased. Foliar boron was higher in treated road drainages (low impact: 57.6 ppm, medium: 45.0 ppm, high: 46.6 ppm) when compared to control (5.3 ppm) drainage plots, though concentrations fluctuated over distance (Appendix C: Table C5). Low and high impact drainages contained the highest concentrations of foliar manganese (946 and 1,000 ppm) compared to 431 ppm along control roads.

Aspen leaf boron was in higher concentrations along treated roads (65.5 ppm) compared to control roads (3.8 ppm) (Appendix C: Figure C25). In drainages, aspen foliar manganese and boron were the only elements significantly higher along treated roads than control roads (treated: 197 to 487 ppm manganese and 39.6 to 52.5 ppm boron; control: 9.2 ppm manganese and 24.4 ppm boron) (Appendix C: Table C5). Both ions increased with total $MgCl_2$ application rates (both $p = 0.001$), but only boron increased as the amount of surface area increased ($p = 0.04$).

Potassium, phosphorus, sulfur, nitrogen, boron, manganese, zinc and iron were all in higher concentrations in Engelmann spruce foliage sampled along the treated road when compared to the control road (Table 2.3, Appendix C: Figures C26a-d and C27a-c). With the exception of total foliar nitrogen, which was highest close to the road (Appendix C: Figure C26d) and formed a negative relationship with distance, no macronutrient concentration had any consistent pattern with road distance or slope position. Foliar boron concentrations (0.02 ppm) were much lower than in control trees in the treated road drainages, and the highest concentrations were in trees growing in medium impact drainages (41.3 ppm) (Appendix C: Table C5). Manganese was also higher in medium impact drainages (2,810 ppm) as compared to low (679 ppm) and control (199 ppm) impact plots (Appendix C: Table C5). Both boron and manganese were in highest concentrations close to the road and decreased with distance from the road, although manganese concentrations fluctuated with distance. Sulfur, copper, zinc and iron were also significantly higher in subalpine fir trees along the treated road than the control road (Table 2.3) (Appendix C: Figures C28 and C29a-c). In drainages, iron was the only micronutrient in higher concentrations in fir foliage along the treated road (201 to 282 ppm) than the control road (99.7 ppm) (Appendix C: Table C5).

Relationships between crown damage and ion concentrations in study trees.

When all trees from roadside and drainage vegetation health plots were combined foliar chloride, boron and magnesium were all strongly correlated with crown damage in lodgepole pine ($r = 0.74, 0.66$, and 0.56, $p < 0.0001$) (Appendix C: Tables C2 and C6). Needle chloride concentrations were consistently higher than twig chloride concentrations and were better correlated with crown damage (Appendix C: Tables C2 and C6). Concentrations of other essential plant nutrients had weaker correlations with damage ($r = {}^{-}0.27$ to 0.47). Soil chloride and magnesium concentrations did not correlate well with plant tissue concentrations. In lodgepole pine plots, correlations between soil and foliar chloride and magnesium ranged from 0.18 to 0.31. Soil sedimentation occurred in all drainage impact classes, including control plots, but sediment depth was not strongly correlated with lodgepole pine crown damage ($r = 0.12$ to 0.15) (Appendix C: Table C6).

In aspen trees, foliar chloride correlated strongly with the percent crown damage and percent marginal burn (both $r = 0.65$, $p < 0.001$). Foliar magnesium ($r = 0.59$, $p < 0.0001$) and boron concentrations ($r = 0.55$, $p < 0.0001$) were also highly correlated with crown damage in aspen (Appendix C: Tables C2 and C6). Foliar potassium and phosphorus formed weak negative correlations with damage observed in aspen ($r = {}^{-}0.15$ to ${}^{-}0.24$) (Appendix C: Tables C2 and C6). Sedimentation measured in aspen drainages positively correlated with aspen crown damage although these relationships were not as strong as those between foliar ions and crown damage ($r = 0.33$ to 0.40, $p < 0.0001$) (Appendix C: Table C6).

Needle chloride and boron concentrations both strongly correlated with total damage observed in Engelmann spruce ($r = 0.72$ and 0.64, $p < 0.0001$) (Appendix C: Table C2 and C6). Magnesium correlations were weaker than both chloride and boron ($r = 0.44$, $p < 0.0001$). Manganese also correlated with total damage in Engelmann spruce ($r = 0.39$, $p < 0.0001$), but not as well with just tip burn ($r = 0.24$, $p < 0.0001$). Needle chloride had the strongest correlation with both crown damage and tip burn in subalpine fir (both $r = 0.53$, $p < 0.0001$). Needle boron had the highest correlation with just tip burn ($r = 0.57$, $p < 0.0001$). Needle magnesium was also correlated to total crown damage and tip burn in fir trees ($r = 0.50$ and 0.47, $p < 0.001$) (Appendix C: Tables C2 and C6).

Other damages to study trees. Roadside trees were assessed for incidence and severity of any biotic or abiotic damage agents, and correlations between damage agents and crown damage were investigated. Many damage agents were apparent on roadside lodgepole pine including: stem and limb canker fungi (western gall rust and Comandra blister rust), foliar needlecast fungi, dwarf mistletoe, sucking insects such as aphids and mites, bark beetles, mechanical damage and abiotic damage from winter conditions (frost, snow, etc.) (Appendix C: Table C3). Aspen, on treated and non-treated roads, were affected by fungal stem and branch cankers, foliar diseases, and gall-makers and defoliators such as aphids, mites and tent caterpillars (Appendix C: Table C3). Engelmann spruce and subalpine fir were both affected by foliar diseases, stem cankers, and defoliating insects (Appendix C: Table C3). Spruce and fir also had high incidence of stand competition in the lower canopy that caused damage (Table C3). All agents recorded were considered fairly common on these species in the Rocky Mountain region (Cranshaw et al. 2000). Correlations between severity of known damage agents and crown damage were weak and generally not significant ($r < 0.20$) (Appendix C: Tables C4 and Table C7).

“Unknown damage,” which was generally symptomatic of drought, dehydration or salinity damage formed the strongest correlations with total crown damage and tip burn in all species. Lodgepole pine total damage and tip burn incidence were highly correlated with “unknown damage” in roadside vegetation health plots ($r = 0.55$ and 0.52, $p < 0.0001$) (Appendix C: Table

C4) and drainage vegetation health plots ($r = 0.63$ and 0.47, $p < 0.0001$) (Appendix C: Table C7). In aspen trees, the “unknown” category correlated with damage and marginal burn in roadside ($r = 0.49$ and 0.51, $p < 0.0001$) and drainage plots (both $r = 0.86$, $p < 0.0001$) (Appendix C: Tables C4 and C7). “Unknown” was also the strongest correlate with total crown damage in spruce and fir combined data ($r = 0.49$, $p < 0.0001$), as well as and tip burn and total crown damage in drainage plots ($r = 0.42$ and 0.25, $p < 0.0001$) (Appendix C: Tables C4 and C7).

Woody and herbaceous ground cover. The most common shrubs in roadside and drainage plots were *Rosa* species (generally Woods’ rose [*Rosa woodsii* Lindl.]), common juniper (*Juniperus communis* L.), kinnikinik (*Arctostaphylos uva-ursi* [L.] Spreng.), blueberry and whortleberry species (*Vaccinium* L.), rabbitbrush (*Chrysothamnus nauseosus* [Pall. ex Pursh] Britton), buffaloberry (*Shepherdia canadensis* [L.] Nutt.), and big sagebrush (*Artemisia tridentata* Nutt.). Species were rated for health on a 1 to 4 scale, 1 being healthy with <5% damage and a status of 4 given to dead plants (Appendix A: Table A16). Rose species and buffaloberry both had significantly lower health status (1.27 and 1.44, respectively) close to the road when compared to plants further away from the road (1.14 and 1.12, respectively) (Appendix C: Table C8). Common juniper was in worse health along treated roads (1.43) than along non-treated roads (1.04) (Table C8). Kinnikinik was in worse health downslope from the road (1.27), when compared to upslope areas (1.05) (Appendix C: Table C8). The major grass and sedge genera in roadside vegetation health plots were: Carex (*Carex* L.) species, *Poa* species including Kentucky bluegrass (*P. pratensis* L.) and alpine bluegrass (*P. alpina* L.), smooth brome (*Bromus inermis* Leyss.), fescue (*Festuca* L.) species, blue grama (*Bouteloua gracilis* [Willd. ex Kunth] Lag. ex Griffiths), and *Phleum* species including field Timothy (*P. pratense*

L.). Several grasses and forbs only occurred directly off the road shoulder and were not distributed well enough to compare health status between road treatments, slope positions or distances, although there were health discrepancies within some genera (Appendix C: Table C9). In non-forested plots, the major shrub was rabbitbrush (*C. nauseosus*) and there was no difference in health status by distance or slope position from the road. There were also no health discrepancies between distance or slope position for the highest occurring grasses in non-forested plots (smooth brome and blue grama).

2.4. Discussion

$MgCl_2$ ions in roadside soils. Chloride and magnesium concentrations at ten to twenty times typical background amounts were measured in roadside soils along roads treated with $MgCl_2$-based dust-suppression products within the first 6.1 m from the road edge. Taking into consideration the high concentrations of magnesium and chloride in the products applied to non-paved roads (Table 2.1), a fairly low percentage of these ions accumulated in roadside soils; and along road segments not influenced by culverts or drainages, ion movement from the road was fairly limited. Differences in ion properties influenced their mobility in roadside soils. Chloride ions do not readily volatize, precipitate or form complexes with other ions in the soil (White and Broadley 2001). Positively charged ions in the soil solution, such as magnesium, interact with the solid phase of the soil most heavily at exchange complexes and may exchange with other cations on exchange complexes (Fisher and Binkley 2000, Norrstrom and Bergstedt 2001). These properties help explain why magnesium slightly increased in the soil from year to year and did not move as far as chloride. Despite high concentrations of both ions in roadside soils and the exchanging capacity of magnesium, changes in the overall nutrient status of roadside soils were negligible. A decrease in calcium and potassium was only measured immediately off treated road shoulders; sodium, boron and sulfur were in highest concentrations close to treated roads because these chemicals are components of dust suppressant products used (Table 2.1); and pH was not significantly altered.

Although chloride and magnesium were both extremely high close to roads, both were dramatically lower 3.0 m away from the road. The majority of ions likely remained in the road base with $MgCl_2$ treatments and a large proportion of those that did move off treated roads were either likely taken up by plant roots or moved further down into the soil profile than our sampling depths (>61.0 cm). The upper and lower soil profiles had similar chloride and magnesium concentrations directly off the road shoulder indicating a substantial downward ion movement. These findings raise concerns of ion movement down the soil profile, and additional sampling should be done to determine if ions move far enough to affect water table ion concentrations.

Site factors are important determinants of the amount and distribution of chloride salt movement from treated roads into roadside systems. Westing (1969) correctly suggested that soil concentrations of chloride will be influenced by the amount of deicing salt applied, efficiency of roadside ditching, soil texture and chemistry, precipitation, slope and the amount of runoff prior to soil thawing. A major contrast between this work and previous studies on deicing salts is the distance of ion movement from road segments not influenced by drainages or culverts. Recent work on $MgCl_2$ and NaCl deicing application in Colorado indicated ions can move several hundred feet from the road via roadside splash zones and aerial dispersal generated by fast moving traffic (Trahan and Peterson 2007). On the other hand, our data indicate that when $MgCl_2$ moves from the road base through the soil matrix, only about 6.1 m of roadside environments are affected. Previous studies have also shown that soils and foliage upslope from the road base do not receive the amount of deicing salt compared to downslope sides (Hofstra and Hall 1971, Fleck et al. 1988, Piatt and Krause 1974) and upslope trees can have high foliar ion concentrations mainly due to aerial spray generated from vehicles traveling on treated highways. Dust suppression products are unlikely to be aerially sprayed onto roadside vegetation foliage with traffic in the same manner as wet roads treated with deicers. We measured high foliar ion concentrations in some upslope trees along non-paved roads most likely because of extended root systems into roadside ditches or under the road base, where they were exposed to chloride and magnesium ions in the soil matrix.

In areas where drainages channel water into roadside environments, we measured high soil concentrations of $MgCl_2$ ions much further from the road than along straight segments. Along straight segments, ion concentrations were high (400 to 500 ppm) close to the road and were dramatically lower (<100 ppm) 3.0 m from the road (Figure 2.1a-b). In high impact drainages, for example, chloride concentrations ranged from 200 to 400 ppm up to 85.0 m from the road (Figure 2.3c). Soil magnesium consistently occurred in high concentrations (>400 ppm) throughout drainage soils in medium and high impact drainages, although background concentrations were generally below 200 ppm. The sediment in drainages may have carried the disassociated magnesium and chloride ions or the associated $MgCl_2$ compound with water or road base material to such distances. The sediment in drainage areas was most likely washed from the road and picked up in the ditches that run alongside non-paved roads, and the amount of surface area that potentially emptied water into a drainage was a good predictor of sediment depth, chloride and magnesium concentrations. The longer the ditch length, the steeper the ditch slope and the greater the area of road base that drained water towards the ditch were positively related to the amount of sediment and $MgCl_2$ ions in the drainage. This, in turn, likely influenced how far ions and sediment occurred away from the road in drainage plots. $MgCl_2$ may build up in drainages due to the lack of ion mobility downward when sediment accumulates on top of existing organic matter. Though control drainages did contain some sediment, it was generally higher along treated roads and occurred at all distances from the road (Figure 2.3g-i).

$MgCl_2$ ions in roadside trees. Magnesium and chloride ions were taken up by roadside trees and accumulated in twig and foliar tissue to elevated concentrations. Twig concentrations were consistently lower than leaves from the same tree and had lower correlations with crown damage than foliar chloride in all species. While there were some discrepancies between shrub and herbaceous ground cover health by road treatment, slope and distance from road, the impact that high soil $MgCl_2$ concentrations had on ground cover vegetation health appears much less dramatic than the visible damage observed on tree species in this study. In previous research investigating NaCl, ions accumulated in leaves of deciduous and evergreen trees and caused injury to an extent often directly related to foliar levels of total salt or an ionic component (Hofstra and Hall 1971, Hall et al. 1972, Hall et al. 1973). Although chloride is an essential plant micronutrient, excess amounts can cause specific ion toxicities or wide osmotic gradients in cells, leading to leaf injury (Westing 1969, Shortle and Rich 1970, Bernstein 1975, White and Broadley 2001, Raveh and Levy 2005). Many roadside studies have shown that the chloride ion is most highly correlated with the toxic effects found on roadside vegetation (Bogemans et al.

1989, Hofstra and Hall 1971, Hall et al. 1972, Hall et al. 1973, Trahan and Peterson 2007). In our study, foliar chloride correlated most consistently and significantly with the incidence of crown damage in all species. Foliar magnesium concentrations correlated significantly and positively with crown damage in all study species to a lesser extent than chloride.

Surprisingly, soil chloride did not correlate well with foliar chloride or crown damage for any species. Trahan and Peterson (2007) also did not find strong correlations between soil chloride and foliar chloride or damage. They did, however, find positive correlations between the less mobile sodium ion and foliar damage in roadside conifers, while foliar chloride was the strongest correlate with foliar damage (Trahan and Peterson 2007). They speculated that a significant portion of crown damage observed was due to aerial drift of $MgCl_2$ and NaCl deicing salts, which would help explain the low correlations between soil and foliar chloride (Trahan and Peterson 2007). We speculate that our correlations were low not because of aerial drift, but because chloride fluctuates in soils with season, soil type and precipitation events; therefore the soil concentration at the time of sampling does not necessarily correlate well with foliar content. We did not measure water stress or transpiration rates of roadside trees, though it appears that trees do not necessarily accumulate foliar chloride directly proportional to how much soil chloride is available under field conditions.

It is generally reported that leaf injury occurs when leaf chloride reaches 10,000 ppm in deciduous tree species and 5,000 in conifer species (Westing 1969, Bernstein 1975, Dobson 1991), although variations of these concentrations exist in the literature on NaCl deicing studies. Using foliar concentrations from deicing studies can be misleading, because the total ionic concentration often includes any surface salts aerially deposited onto needles or leaves. Deicing and dust suppression application practices differ, and the potential for aerial drift of dust suppression chemicals is limited. However, the possibility of aerial drift was considered as factor in this study. The foliar ion concentrations of trees in this study were likely via root absorption and translocation, as no dust particles, crystallized salt deposits or damage associated with aerial spray was observed on roadside trees (including more severe damage on the side of the tree facing the road) (Strong 1944, Trahan and Peterson 2007). Our leaf tissue was also washed with distilled water in order to measure foliar ion content within the leaf, not on the surface. Trahan and Peterson also observed very low correlations between crown damage and distance from the road, as well as evidence of needle surface deposits in off-road conifers as far as 115 m from the road (2007). However, we observed high negative correlations between damage and distance from the road along straight segments of road. Also, necrotic flecks on foliar tissue that have been recorded on trees lightly covered with dust containing $CaCl_2$ (Strong 1944) were not observed in our roadside plots. The foliar crown damage observed on roadside trees in this study was otherwise comparable to recorded symptoms of roadside deicing salt damage, including tip and marginal necrosis and complete leaf or needle death (Hofstra and Hall 1971, Hall et al. 1972, Dobson 1991, Trahan and Peterson 2007).

Since most of our study roads have been treated with $MgCl_2$ for different time periods, and because of the short duration of this study, we cannot accurately predict the time required to completely defoliate crowns or cause irreversible damage to these species with the application rates that have been used. However, we can predict the concentration of foliar chloride related to various incidences of crown damage in each species. Roadside lodgepole pines appear to be the most sensitive species in this study, exhibiting tip burn or necrosis on approximately 50 to 60% of the crown at foliar chloride levels as low as 3,000 to 4,000 ppm (0.3 to 0.4% d.w.); with complete necrosis of the crown related to 8,000 ppm chloride when all needle ages were combined. Engelmann spruce and subalpine fir had different background concentrations of needle chloride and magnesium, with each species accumulating ions to a different extent. Spruce trees exhibited about 50% crown damage when concentrations were 6,000 to 7,000 ppm, and full crown necrosis occurred at approximately 9,000 ppm chloride. Subalpine fir trees exhibited 50% crown damage around 5,000 ppm chloride and approximately 6,200 ppm chloride led to more than 90% crown damage. We collected only crown severity data (percent of tree crown with affected needles) on conifers and believe that additional needle severity data (average percent of needle area affected) would lead to stronger correlations and closer estimations of toxicity thresholds. In some roadside lodgepole pines, foliar chloride concentrations almost doubled from the previous year's amount with an associated increase in crown damage, although spruce and fir foliar chloride concentrations stayed relatively similar from year to year. It is extremely difficult to predict uptake and distribution of chloride into needle tissue because it likely varies with moisture stress, root morphology and transpiration rates. It is not plausible to conclude that foliar concentrations should continue to increase at similar rates each year from only two years of sampling.

Chloride concentrations necessary to cause damage to conifers in this study appear lower than in previous work sampling damaged roadside conifers, most likely due to the limitation of aerial drift or foliar uptake of salt ions in this study. In this research, roadside trees were also exposed to ambient Colorado temperatures and precipitation patterns and were most likely water-stressed, which could exacerbate damage caused by high chloride concentrations in needles and leaves. Chloride concentrations of 10,000 ppm (1.0% d.w.) in the needles of red pine (*Pinus resinosa* Ait.) and eastern white pines *(Pinus strobus* L.) were associated with extensive plant injury in a previous roadside study (Hall et al. 1972). Severely injured white pines sampled along a NaCl treated highway that were 70 - 90% necrotic had chloride concentrations as high as 13,600 ppm in green tissue and 17,600 ppm in brown tissue (Hall et al. 1972). In another study, complete death of white pine needles was associated with chloride concentrations of approximately 10,000 ppm (Hofstra and Hall 1971). Trahan and Peterson (2007) found that extensive necrosis occurred on lodgepole and ponderosa pine when foliar concentrations exceeded 10,000 ppm. To our knowledge, none of these foliar samples were rinsed with distilled water, and reported levels could include residual surface salt deposits. In addition, several of these studies took place in eastern United States, which receives greater and more consistent precipitation than north-central Colorado.

Deciduous species generally accumulate more foliar chloride than conifers (Westing 1969, Bernstein 1975, Dobson 1991). In a plantation study where young Norway maples were treated with soil applications of $CaCl_2$ or NaCl, extensive defoliation did not occur until chloride reached 15,000 ppm (Walton 1969). In littleleaf linden (*Tilia cordata* L.) trees along urban roads where NaCl had been applied, damage symptoms were observed as marginal necrosis and chlorosis when leaf tissue averaged 16,100 ppm chloride and trees became severely damaged at 21,000 ppm chloride (Czerniawska-Kusza et al. 2004). In our study, roadside aspen trees accumulated more chloride than conifers but exhibited the lowest incidence of visible damage. Mean background foliar concentrations in aspen leaves were generally less than 2,000 ppm chloride and trees along treated roads were measured with over 30,000 ppm. When leaf chloride concentrations reached 16,000 ppm, roadside aspen trees exhibited mean marginal necrosis on approximately 30% of the crown, though we also observed damage to over 90% of the crown when chloride concentrations were this high. Generally, 20,000 ppm chloride caused 50% crown damage on roadside aspen trees. This indicates that high soil chloride may take several years to cause measurable declines in aspen health, as the new leaves appeared to accumulate the same amount of chloride as previous season's leaves, with crown damage remaining fairly consistent from year to year. We did observe that while roadside aspen trees did not exhibit as much damage as conifers, many aspen trees growing in drainage plots were recently killed or dying. The combination of the sediment on top of aspen roots and $MgCl_2$ ions in the soil may cause more damage than $MgCl_2$ ions alone. Further monitoring of these plots over the next few years is needed to determine aspen mortality rate relationships with foliar chloride concentrations.

Predicting soil and foliar chloride with application rates. As $MgCl_2$ application rates increased along non-paved roads (either through applying a higher rate per application or by applying a constant rate of a product more than once a spring or summer) soil and foliar chloride concentrations close to and downslope from the road increased. Foliar chloride is a better predictor variable for quantifying the movement of $MgCl_2$ into roadside environments than soil concentrations. Concentrations in both roadside lodgepole and aspen foliage had stronger correlations with application rates than soil ion concentrations. Thus, accurate estimations of how far $MgCl_2$ ions have moved into roadside environments can still be made with $MgCl_2$ application rates, even in the absence of foliar concentration data. The lowest rate of $MgCl_2$ application where lodgepole pine was sampled was approximately 2,300 $kg \cdot km^{-1} \cdot yr^{-1}$, and lodgepole pine tissue along that road had approximately 4,000 ppm chloride. On average, 50 to 60% mean crown damage was observed on lodgepole pine with these concentrations of foliar chloride. A rate of approximately 4,000 $kg \cdot km^{-1} \cdot yr^{-1}$ was associated with 6,000 ppm chloride in lodgepole pines along that road. It may be a more cost effective method to use $MgCl_2$ application rates to estimate ion concentrations and crown damage in roadside lodgepole pine, as opposed to foliar samples and chemical analysis. The relationships between soil and foliar chloride and $MgCl_2$ application rates do show that lower concentrations in roadside soils and plants can be achieved with decreased application rates of $MgCl_2$.

$MgCl_2$ distribution in different aged foliage. Magnesium and chloride were in highest concentrations in the oldest needles of roadside lodgepole pines although a significant accumulation had already begun in the current-year's flush of needles when sampled at the end of the growing season. The oldest needles also had the highest severity of necrotic tissue, while the newest needles were still green. By the next growing season these needles also appeared symptomatic. This indicates that a physiological change occurs during winter or early spring months, where the new flush of needles begins to turn necrotic at the tips if they contain high concentrations of magnesium and chloride ions. The processes of salt uptake and accumulation into leaf cells during the winter months are not known. Trahan and Peterson also observed less necrosis on the newly flushed needles in lodgepole and ponderosa pines when compared to older needles, and needle retention was reduced in conifers exposed to $MgCl_2$ and NaCl salts (2007). Along Japanese highways treated with NaCl, Kayama et al. (2003) measured an increase in chloride with needle age in both healthy looking and damaged roadside trees, although damage levels were not reported by needle age.

Other ions in roadside soils and trees. Roadside environments can be affected by a variety of anthropogenic stresses, including contamination of the soil by pollution and metals. Salt ions (particularly the calcium and magnesium components) may have the potential to displace and mobilize heavy metals in roadside soils (Amrhein and Strong 1990, Norrstrom and Bergstedt 2001). While other studies on $MgCl_2$ deicers have expressed concern over the ability for $MgCl_2$ to mobilize heavy metals into roadside environments, measurements of trace metals (micronutrients) along non-paved roads were negligible in this study, and low in comparison with previously reported levels along more frequently traveled roads (Amrhein and Strong 1990, Trahan and Peterson 2007). No micronutrient had strong correlations with damage in roadside trees.

The leaching of calcium and potassium from roadside soils did not translate into deficiencies of these nutrients in roadside trees; in both lodgepole pine and spruce trees excessive amounts of foliar potassium and calcium were measured in areas where these soil cations were in low concentrations. An increase in certain cations, such as calcium, can help amend the detrimental effects of high NaCl by mitigating the toxic effects of sodium ions (Rengel 1992, Bressnan et al. 1998). Cells may also respond to salinity stress by increasing potassium uptake; in studies investigating NaCl toxicities to plants, adequate potassium to sodium ratios were necessary for cellular function during saline stress conditions (Serrano et al. 1999, Crowley and Arpaia 2000). An increase in calcium and potassium uptake by our study trees may have occurred in response to high magnesium concentrations in soil or foliar tissue, indicating that high concentrations of $MgCl_2$ may cause cellular and whole plant responses similar to NaCl. Further studies of the effects of $MgCl_2$ on foliar concentrations of essential plant elements in these tree species are needed to clarify these proposed relationships.

Sulfur, a component of the applied lignin sulfonate and $MgCl_2$ dust suppression products (Table 2.1) was also elevated in conifer foliar tissue of trees growing along treated roads; but was not a strong correlate with crown damage in any species sampled. Foliar sulfur was also high in roadside lodgepole and ponderosa pines growing along highways treated with NaCl and $MgCl_2$ deicing salts (Trahan and Peterson 2007). However, these high concentrations presumably arose from vehicular emissions and Trahan and Peterson (2007) did not conclude sulfur was a primary damage agent to roadside vegetation. Boron (linked to the brine from the ocean or salt lakes where $MgCl_2$ originates) frequently appeared as a significant correlate with crown damage in this study and was elevated in roadside soils and plants. The critical deficiency and the toxicity levels of boron are known to be very close to each other (Mengel and Kirkby 2001, Marschner 2002, Tester and Davenport 2003). For example, less than 25 ppm boron is considered a deficiency in citrus crops, while more than 200 ppm may be toxic (Bennet 1993). In stone fruit crops (peaches and nectarines), anything over 100 ppm is excessive (Bennet 1993). Boron concentrations in lodgepole pine stayed below 100 ppm, and 140 ppm of boron was measured in aspen trees very close to the road. Concentrations averaged 20 to 30 ppm boron in foliar tissue of Engelmann spruce and subalpine fir. Unfortunately, little is known about the mechanisms of transport and toxicity thresholds of boron, especially in woody species (Tester and Davenport 2003). However, it is thought that boron behaves similarly to chloride within the plants (both elements are governed by the transpiration stream via the xylem and rarely phloem mobilized), and boron may be associated with damage to leaves because it is similar in mobility and to storage as chloride

(Marschner 2002). Excess boron is known to cause brownish, resinous pustules on the undersides of citrus leaves and chlorosis and necrosis that is confined to the midribs and main veins in stone fruit, apple and pear leaves (Bennet 1993). However, none of these symptoms were observed on leaves in our study indicating that boron was below toxic levels. Further studies are necessary to determine the toxic effects of boron, especially in combination with chloride, on roadside vegetation.

2.5. Conclusions

Magnesium and chloride ions moved downslope of road segments not affected by culverts or drainages to approximately 3.0 to 6.1 m into soils and roadside trees. When concentrations were high, ions were evenly distributed between the upper and lower soil profiles. Further $MgCl_2$ movement was measured into roadside drainages where both chloride and magnesium remained elevated in soils through 98.0 m from the road, causing foliar damage. Trees along roadsides and in drainage areas took up magnesium and chloride ions from the soil solution and accumulated them over time, often to toxic concentrations, which led to severe damage of foliar tissue. Chloride appears to be the ion responsible for the majority of damage in roadside trees. Concentrations phytotoxic to trees varied with species, especially between conifer and deciduous species. Lodgepole pine appears to be the most sensitive conifer to $MgCl_2$, while aspen appears to be the most tolerant of all study species, but because study species accumulated chloride to such diverse concentrations their levels of $MgCl_2$ tolerance cannot be accurately compared. Leaf chloride, magnesium and boron concentrations all correlated strongly with crown damage, and no known biotic damage agent correlated well with the damage observed to roadside vegetation.

Trees in these plots were measured and sampled for only two growing seasons, therefore conclusively determining the time it takes to cause irreversible damage and mortality to roadside trees is beyond the scope of this study. However, high correlation values, yearly accumulation of chloride, and increases in chloride and damage by needle age indicate that the chloride component in $MgCl_2$-based dust-suppression products induced the crown damage observed on roadside trees, which lead to the death of some proportion of trees in this study. While strong correlations between foliar chloride and leaf necrosis were apparent, other abiotic factors cannot be completely ruled out as contributors to the observed crown damage in addition to chloride toxicity. Although drought and dehydration effects may have potentially worsened stress caused by $MgCl_2$ ions, this study was not designed to address the influences of these factors. Further long term research is needed in the field and in controlled settings, with yearlong observations of symptoms and measurements of foliar and soil ion contents, in order to establish the specific interactions over time of the various processes that contribute to damage and mortality associated with $MgCl_2$ applications.

2.6. Section 2 Figures and Tables

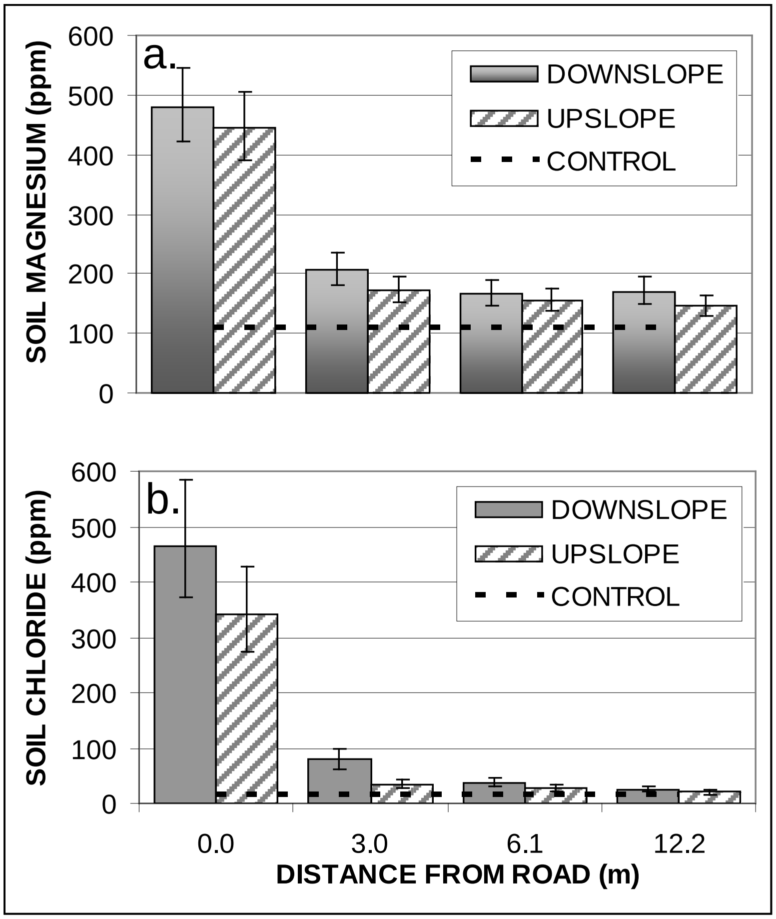


Figure 2.1a-b. Soil (a) chloride and (b) magnesium adjusted mean concentrations along roads in Larimer and Grand Counties, Colorado at four distances, both soil sampling depths, and both slope positions from the road (1429 total soil samples, *n* = 171 to 195 samples collected at each sampling distance separated by slope). Dotted line indicates control plot soil concentrations at each distance combining both slope positions (225 total soil samples, *n* = 53 to 58 samples collected at each distance). NOTE: Concentrations back-transformed from $\log_{10}$ values and error bars indicate ± 1.4 back-transformed standard errors (approximately ± ½ Fisher's Least Significant Difference [LSD]).

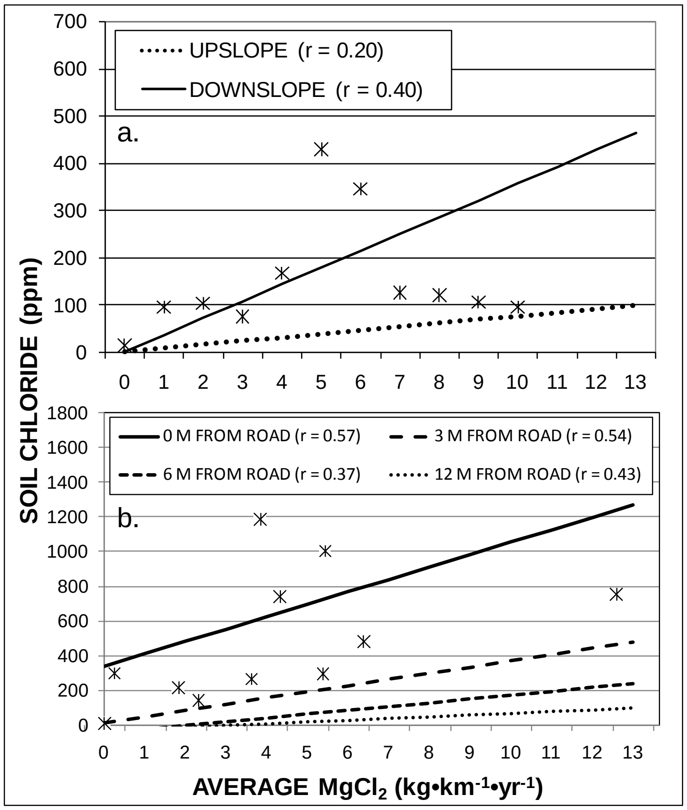


Figure 2.2a-b. Modeled increase in soil chloride concentration with average $MgCl_2$ applied to roads in Larimer and Grand Counties, Colorado at (a) two slope positions from the road (1694 total soil samples, *n* = 819 samples upslope and *n* = 875 samples downslope) and (b) in downslope plots only at four distances from the road (875 total soil samples, *n* = 212 – 225 samples per distance from the road). Asterisks indicate lsmeans of downslope soil chloride at all distances from the road for each study road (averaged across all distances, transects and plots for each study road) in Figure 3a and lsmeans of downslope soil chloride at 0 m from the road for each study road (averaged across all transects and plots for each study road) in Figure 3b, used in statistical modeling. NOTE: chloride concentrations modeled using least adjusted mean chloride concentrations from plots sampled in 2004 and 2005 using the Solution Function (The Mixed Procedure, SAS 2001). All Pearson correlation coefficients (r) reported are significant at $p < 0.0001$. Soil concentrations were not $\log_{10}$ transformed to create predictive models.

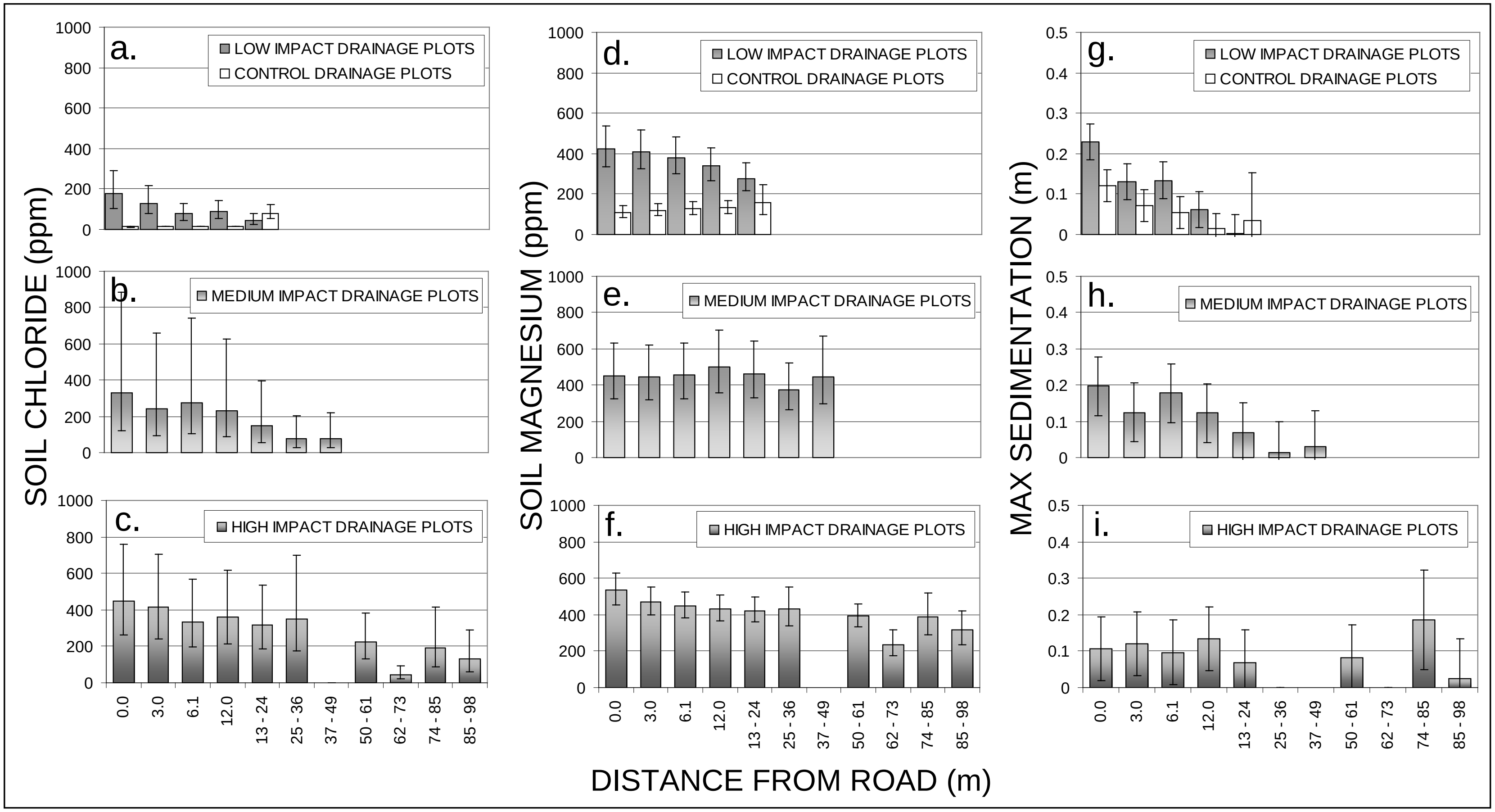


Figure 2.3a-i. Soil (a-c) chloride, (d-f) magnesium, and (g-i) maximum sedimentation adjusted means measured in control (*n* = 26), low (*n* = 24), medium (*n* = 19) and high (*n* = 10) impact drainage plots along roads in Larimer and Grand Counties, Colorado sampled in 2005 or 2006. NOTE: Concentrations back-transformed from $\log_{10}$ values and error bars indicate ± 1.4 back-transformed standard errors (approximately ± ½ Fisher's Least Significant Difference).

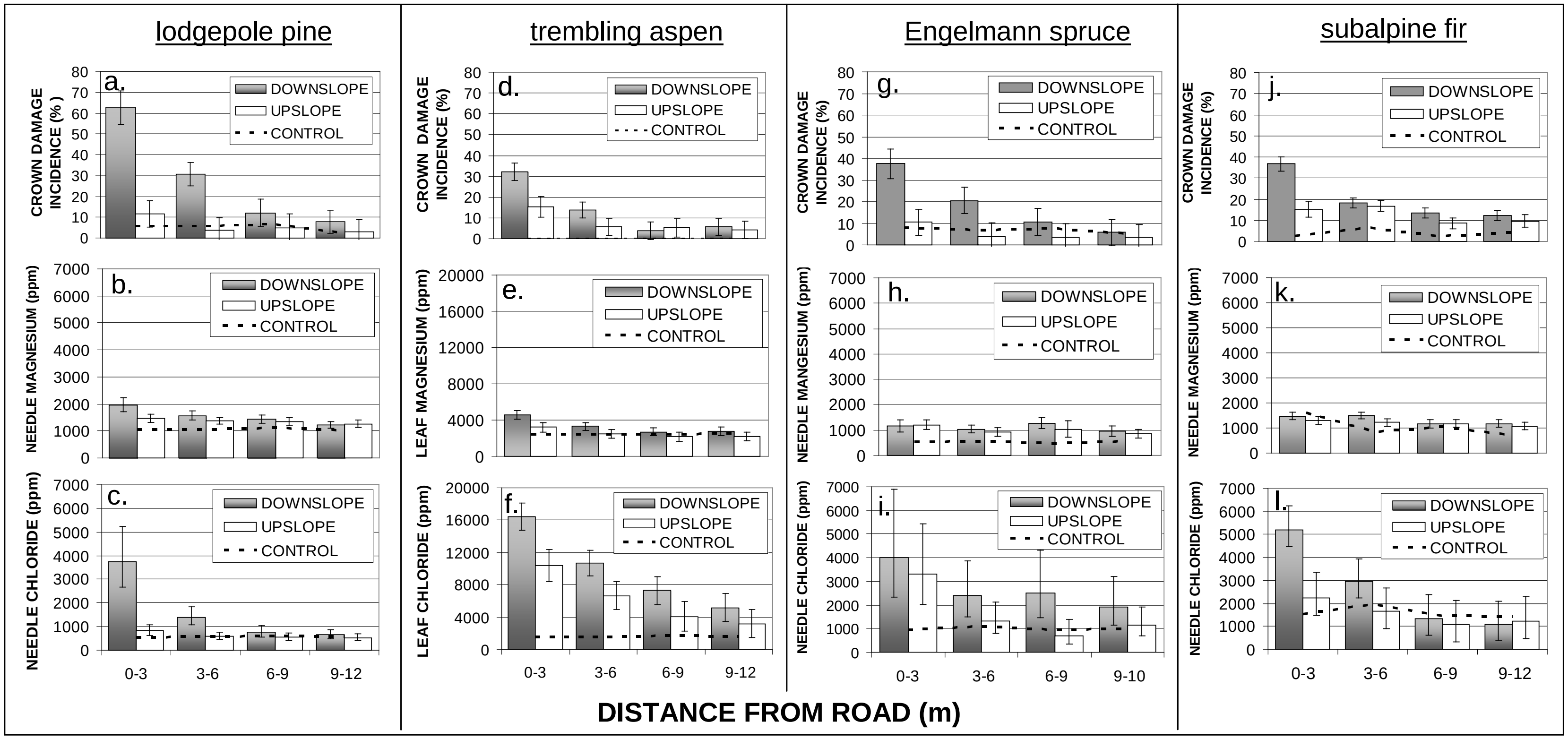
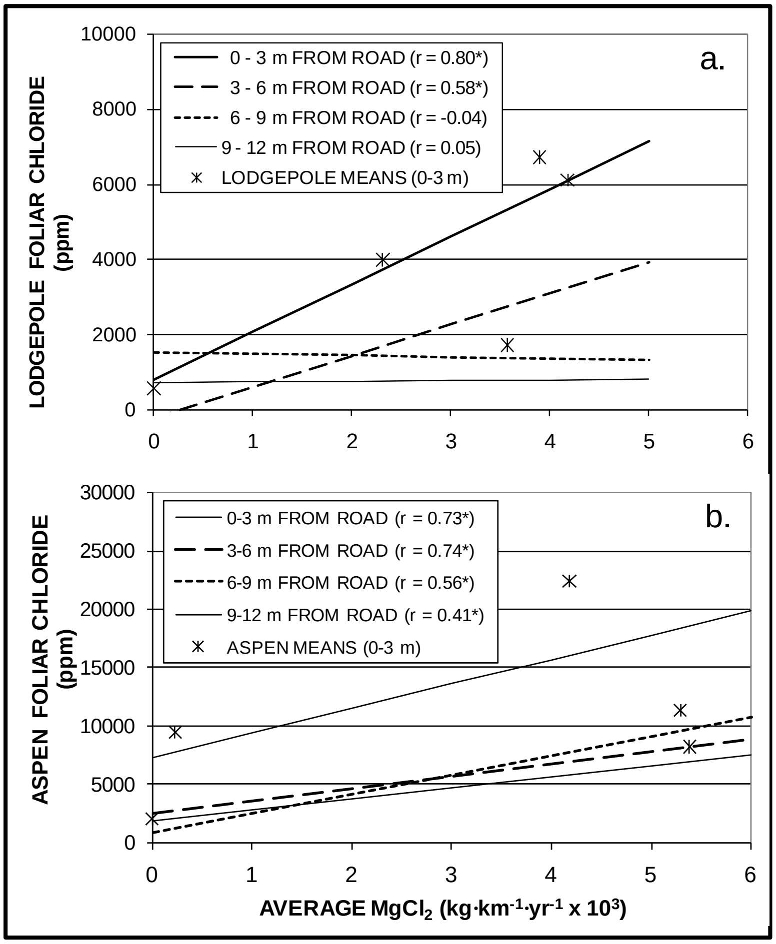


Figure 2.4a-l. Lodgepole pine (a-c, n = 2024 trees visually assessed along treated roads and 487 trees along control roads, n = 471 treated road foliar samples collected and n = 141 control road foliar samples, respectively), trembling aspen (d-f, n = 2851 and 521 trees and n = 420 and 42 samples), Engelmann spruce (g-i, n = 1748 and 55 trees and n = 68 and 27 samples) and subalpine fir (j-l, n = 431 and 96 trees and n = 207 and 13 samples) adjusted mean crown damage incidence, foliar magnesium and foliar chloride along roads in Larimer and Grand Counties, Colorado. Dotted lines indicate crown damage incidence, foliar magnesium and foliar chloride concentrations measured in control plots. NOTE: Concentrations back-transformed from $\log_{10}$ values and error bars indicate ± 1.4 back-transformed standard errors (approximately ± ½ Fisher's Least Significant Difference).



Figures 2.5a-b. Modeled increase in (a) lodgepole pine and (b) aspen foliar chloride concentrations with increasing average $MgCl_2$ applied to roads in Larimer and Grand Counties, Colorado in downslope plots only at four distance intervals from the road. Asterisks indicate means of foliar chloride for each species at 0 to 3 m downslope from the road along each study road (averaged across all samples, transects and plots on each road), used in statistical modeling. NOTE: Chloride concentrations modeled using least adjusted mean chloride concentrations from plots sampled in 2004 and 2005 using the Solution Function (The Mixed Procedure, SAS 2001). Pearson correlation coefficients (r) reported with a (*) are significant at $p < 0.0001$. Foliar concentrations were not $\log_{10}$ transformed to create predictive models.

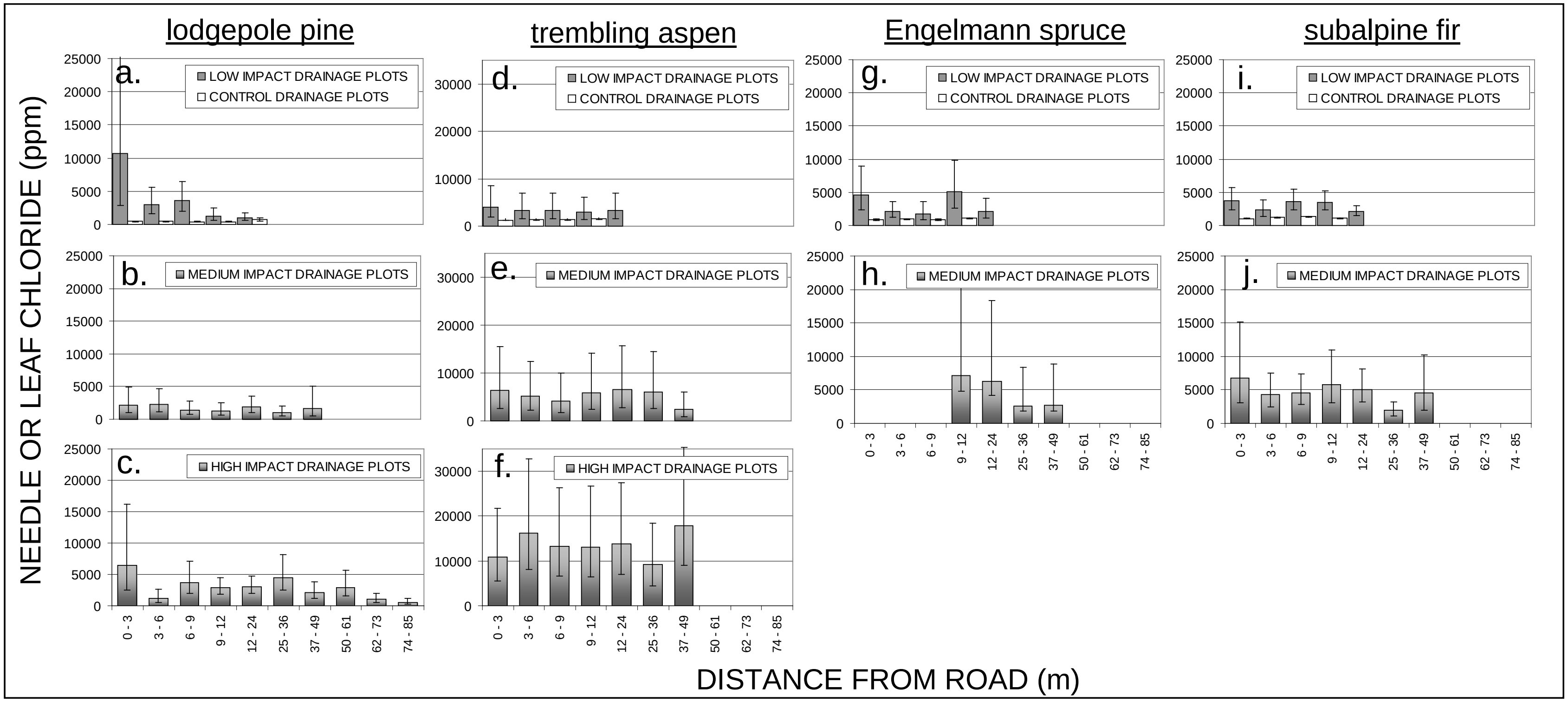


Figure 2.6a-j. Lodgepole pine (a-c) adjusted foliar chloride means at various distance intervals in control (a. 82 foliar samples), low (a. 43 samples), medium (b. 73 samples), and high (c. 49 samples) drainage plot impact classes. Trembling aspen (d-f) adjusted foliar chloride means at various distance intervals in control (d. 49 samples), low (d. 64 samples), medium (e. 50 samples), and high (f. 21 samples) drainage plot impact classes. Engelmann spruce adjusted foliar chloride means at various distance intervals in control (g. 25 samples), low (g. 12 samples), and medium (h. 7 samples) impact drainage plots classes. Subalpine fir adjusted foliar chloride means at various distance intervals in control (i. 28 samples), low (i. 43 samples), and medium (j. 32 samples) impact drainage plots. Drainage plots sampled in Grand and Larimer Counties, Colorado in 2005 and 2006. Means back-transformed from $\log_{10}$ data transformations, error bars indicate ± 1.4 back-transformed standard errors (± approximately ½ Fisher's Least Significant Difference).

Table 2.1. Chemical composition of lignin sulfonate and $MgCl_2$-based dust suppression products[4] applied in Larimer and Grand Counties, Colorado.

	LIGNIN SULFONATE SOLUTION			MAGNESIUM CHLORIDE SOLUTION		
	MEAN[1]	STANDARD DEVIATION (n = 3)[2]	RANGE	MEAN[1]	STANDARD DEVIATION (n = 4)[2]	RANGE
pH[3]	4.17	0.06	4.1 – 4.2	8.8	0.05	8.8 – 8.9
Electrical Conductivity[3]	1.84	0.005	1.83 – 1.84	6.7	0.16	6.5 – 6.8
SAR	0.08	0	0.08 – 0.08	0.16	0.01	0.15 – 0.17
Magnesium	2,100	100	2,000 – 2,200	95,000	1,730	93,000 – 97,000
Chloride	9,820	85	9,740 – 9,910	252,000	4,240	249,000 – 258,000
Boron	16.7	5.7	10 – 20	190	14.1	180 – 210
Sodium	200	0	200 – 200	1,325	50	1,300 – 1,400
Potassium	700	0	700	1150	370	900 – 1700
Calcium	933	57.7	900 – 1,000	150	57.7	100 – 200
Phosphate	63.3	5.7	60 – 70	72.5	20.6	50 – 100
Sulfate	130,000	4,120	126,000 – 134,200	8,000	424	7,600 – 8,600
Ammonia	45,000	551	44,000 – 45,500	126.45	51.6	86.8 – 202
Nitrate	460	13.6	445 – 469	1.18	0.37	1.0 – 1.7
Iron	30	0	30 – 30	7.75	4.5	1 – 10
Manganese*	< 0.1	-	-	< 0.1	-	-
Copper*	< 0.1	-	-	< 0.1	-	-
Aluminum*	0.12	0.03	0.1 - 0.15	< 0.1	-	-
Zinc*	< 0.1	-	-	< 0.1	-	-

1. All means reported in mg/L except pH and electrical conductivity ($dS \cdot m^{-1}$).
2. Sample size (n) denotes the number of replications of each solution from the same source.
3. 1:100 dilutions used to analyze lignin solution, 1:1,000 dilution used to analyze $MgCl_2$ solution.
4. $MgCl_2$ solution provided by Larimer County Road and Bridge Department (Larimer County, CO). Lignin solution provided by EnviroTech Services (Greeley, CO) (http://www.envirotechservices.com, 1-800-369-3878)

* Elements below reported detection limits in one or both solutions

Table 2.2. Road dust suppression treatment and roadside soil data information of study roads in Grand and Larimer Counties, Colorado.

COUNTY	ROAD	FIRST YEAR OF TRT.[1]	TRT. PRODUCT[2]	GENERAL SOIL TYPE	PARENT MATERIAL	HYDRO. SOIL GROUP[3]	% CLAY	% SAND	% SILT
Grand	1	1993	$MgCl_2$	Quander stoney loam	Colluvium and/or glacial drift	B	23.6	39.6	36.6
Grand	4	2002	$MgCl_2$	Herd-Goosepeak families, sandstone substratum complex	Residuum weathered from mudstone	C	35.0	27.2	37.9
Grand	6	1985	$MgCl_2$	Leighcan family till substratum	Residuum and/or till derived from igneous and metamorphic rock	A	10.6	48.9	40.5
Grand	8	1989	$MgCl_2$	Cowdry loam	Glacial drift	C	37.0	31.3	31.7
Grand	30	1998	$MgCl_2$	Newcomb gravelly sandy loam	Glacial till	A	11.2	62.8	14.0
Grand	50	-	-	no soil data available	-	-	-	-	-
Grand	55	1997	$MgCl_2$	Uinta sandy loam	Glacial drift derived from metamorphic rock	B	24.0	58.8	17.2
Grand	235/555	-	-	no soil data available	-	-	-	-	-
Grand	83	1992	$MgCl_2$	Cowdry loam	Glacial drift	C	37.0	31.3	31.7
Grand	85	1996	$MgCl_2$	Upson stony sandy loam	Highly weathered granite	C	12.8	67.6	19.5
Larimer	37.023	2001	$MgCl_2$ + Lignin	Kirtley-Purner complex	Material weathered from reddish brown sandstone and shale	C	23.6	37.8	38.6
Larimer	37.023	2001	$MgCl_2$ + Lignin	Connerton-Barnum complex	Mixed alluvium derived from sandstone and shale	B	20.0	48.3	31.7
Larimer	44H.34	-	-	Cypher-Ratake families complex	Colluvium and/or residuum derived from igneous and metamorphic rock	B	11.8	75.0	18.3
Larimer	73C	1993	$MgCl_2$ + Lignin	Bullwark-Catamount families-Rubble land complex	Residuum and/or slope alluvium derived from igneous and	B	69.3	22.8	12.2
Larimer	80C.1	2001	$MgCl_2$ + Lignin	Breece coarse sandy loam	Alluvium derived from granite	B	14.4	67.0	18.6
Larimer	80.062	1995	$MgCl_2$ + Lignin	Haplustolls-Rock outcrop complex	Cobbly to stony colluvium	D	19.8	41.7	38.5

Larimer	80.030	1997	$MgCl_2$ + Lignin	Haplustolls-Rock outcrop complex	Cobbly to stony colluvium	D	19.8	41.7	38.5
Larimer	63E.029	2006	$MgCl_2$	Cypher-Ratake families complex	Colluvium and/or residuum derived from igneous and metamorphic rock	B	11.8	75.0	18.3
Larimer	80C	-	-	Supervisor family	Alluvium and/or residuum derived from interbedded sedimentary rock	B	17.1	54.7	28.3
Larimer	103	1995	$MgCl_2$ + Lignin	Leighcan family till substratum	Residuum and/or till derived from igneous and metamorphic rock	A	10.6	48.9	40.5
Larimer	139	-	-	Leighcan-Catamount families moist complex	Residuum and/or slope alluvium derived from igneous and metamorphic rock	A	10.6	48.9	40.5
Larimer	162D	-	-	Leighcan family	Residuum and/or till derived from igneous and metamorphic rock	A	10.6	48.9	40.5
Larimer	162.234	1994	$MgCl_2$ + Lignin	Redfeather sandy loam	Material weathered from granite	D	16.5	64.5	18.9
Larimer	163	2004	$MgCl_2$	Redfeather sandy loam	Material weathered from granite	D	16.5	64.5	18.9
Larimer	190	1996	$MgCl_2$ + Lignin	Supervisor-Passar-Howlett families complex	Alluvium and/or residuum derived from interbedded sedimentary rock	B	17.1	54.7	28.3

1. First year of treatment and application information gathered from estimations and documentation gathered by county road and bridge departments. (-) indicates no $MgCl_2$ treatment has ever occurred on road.

2. Product use changed from year to year of treatment. Treatment products reported here are the most commonly used.

3. Hydrologic soil groups are based on estimates of runoff potential. Group A: Soils with a high infiltration rate (low runoff potential) when thoroughly wet. Group B: Soils with a moderate infiltration rate when thoroughly wet. Group C: Soils having a slow infiltration rate when thoroughly wet. Group D: Soils with a very slow infiltration rate (high runoff potential) when thoroughly wet (Soil Survey Staff 2008).

Table 2.3. Mean foliar ion concentrations in four tree species along treated and control study roads.

		MEAN CONCENTRATIONS[1] (ppm)											
		K	**Ca**	**P**	**Na**	**S**	**N (%)**	**B**	**Cu**	**Mn**	**Zn**	**Fe**	**Mo**
lodgepole pine	control roads (*n* = 141)	2710	3840	772	99.8	544	0.8	8.8	2.3	365	43.0	198	1.2
	SE	260	220	40.0	1.1	37	0.0	4.3	0.5	87.3	3.0	41.2	1.5
	treated roads (*n* = 471)	4540	4360	986	102	797	1.0	32.3	4.3	632	42.5	241	3.5
	SE	156	132	24.9	0.6	22.3	0.0	2.6	0.3	52.7	1.7	24.5	0.9
	* $p < 0.05$, ** $p<0.0001$	**	**	**		**	**	**	**	**			
trembling aspen	control roads (*n* = 42)	18600	7570	4940	100	2060	3.3	3.8	7.5	56.5	108	201	1.6
	SE	2200	2070	319	7.0	223	0.3	14.6	1.5	615	19.4	116	3.2
	treated roads (*n* = 420)	11100	11400	1780	107	1650	2.2	65.5	7.4	335	84.3	133	6.0
	SE	768	718	113	2.6	78.4	0.1	5.4	0.7	300	7.2	56.8	1.2
	* $p < 0.05$, ** $p<0.0001$	*		**			*	**					
Engelmann spruce	control roads (*n* = 27)	3500	10150	888	103	355	0.7	4.5	1.5	837	29.2	28.3	6.9
	SE	240	1496	55	7.6	43.5	0.1	10.1	0.6	468	8.6	26.9	4.7
	treated roads (*n* = 68)	4390	13060	1080	105	656	0.9	26.1	3.5	2090	59.8	117	6.8
	SE	135	920	30.4	4.1	24.9	0.0	5.2	0.3	252	4.7	13.8	2.5
	* $p < 0.05$, ** $p<0.0001$	*		*		**	*			*	*	*	
subalpine fir	control roads (*n* = 13)	4100	10600	1100	101	536	1.0	9.4	1.7	1390	31.7	63.9	5.2
	SE	254	1059	100	6.14	68.0	0.1	6.0	0.6	309	4.9	17.5	3.0
	treated roads (*n* = 270)	4170	11000	1180	104	776	1.1	21.9	3.9	1570	42.5	166	7.1
	SE	249	493	47.4	2.0	33.7	0.04	2.6	0.3	139.5	2.2	5.7	1.1
	* $p < 0.05$, ** $p<0.0001$					*			*		*	**	

1. Least square means adjusted to include all application rates, plots, transects, distance intervals and slope positions for each species in roadside plots.

2.7. SECTION 2 APPENDICES

Appendix A. Detailed plot information and methods for roadside and drainage vegetation health plots.

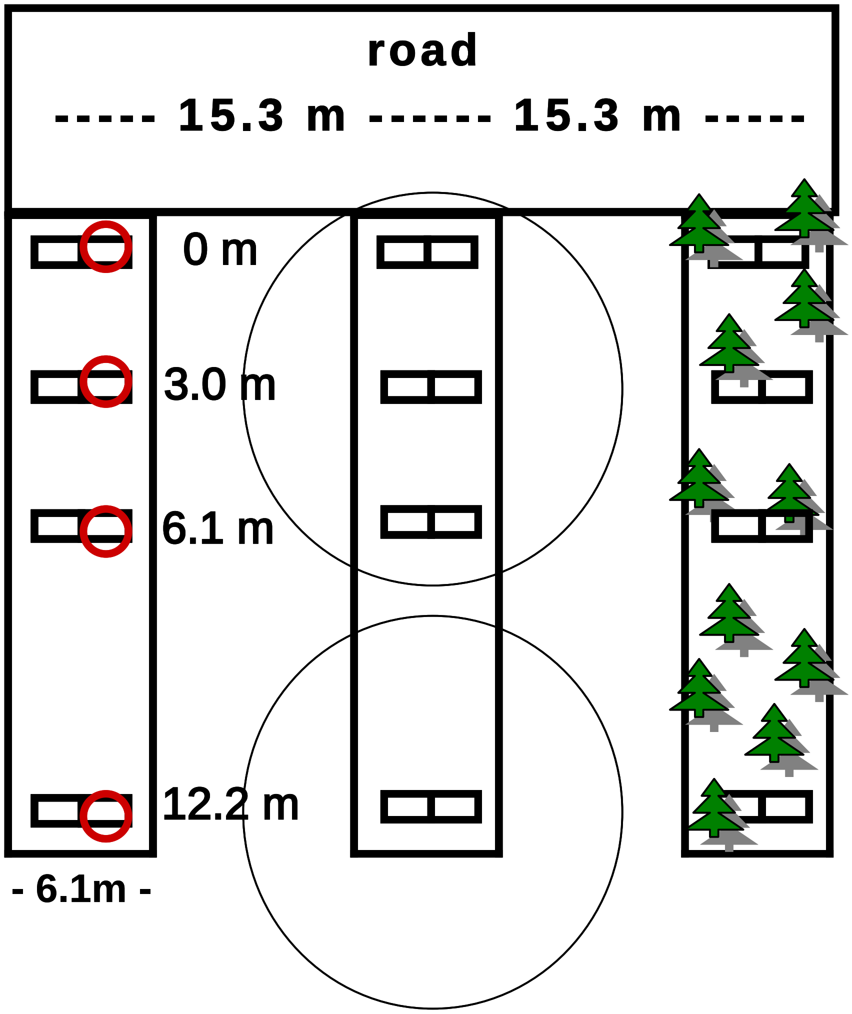


Figure A1. Plot Type 1: Roadside vegetation health plot design established and sampled along treated and control roads in Larimer and Grand Counties, Colorado in 2004 and 2005 (n = 60). Plots paired as upslope and downslope plots from the road edge in similar habitats, slopes and stand structures. Large rectangles perpendicular to road = subplots. Small rectangles inside subplots parallel to roads = ground cover plots. Large circles within subplot = 11.5 m radius shrub cover subplots. Small, red circles inside subplots = soil sampling locations.

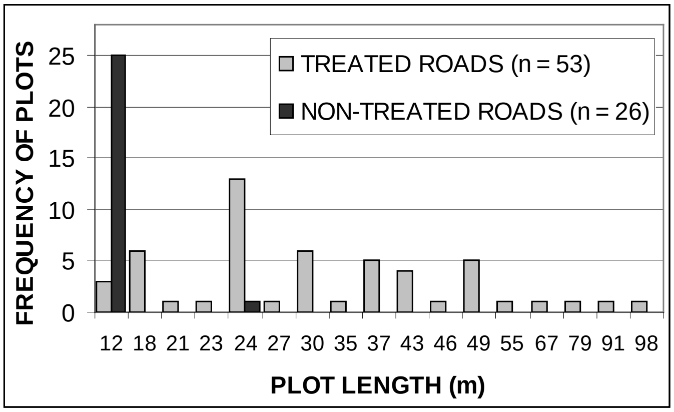


Figure A2. Frequencies of drainage vegetation health plot lengths along non-paved roads both treated and control with $MgCl_2$ based dust suppression products in Larimer and Grand Counties, Colorado in all habitat types. Plots were established and sampled in summers 2005 and 2006.

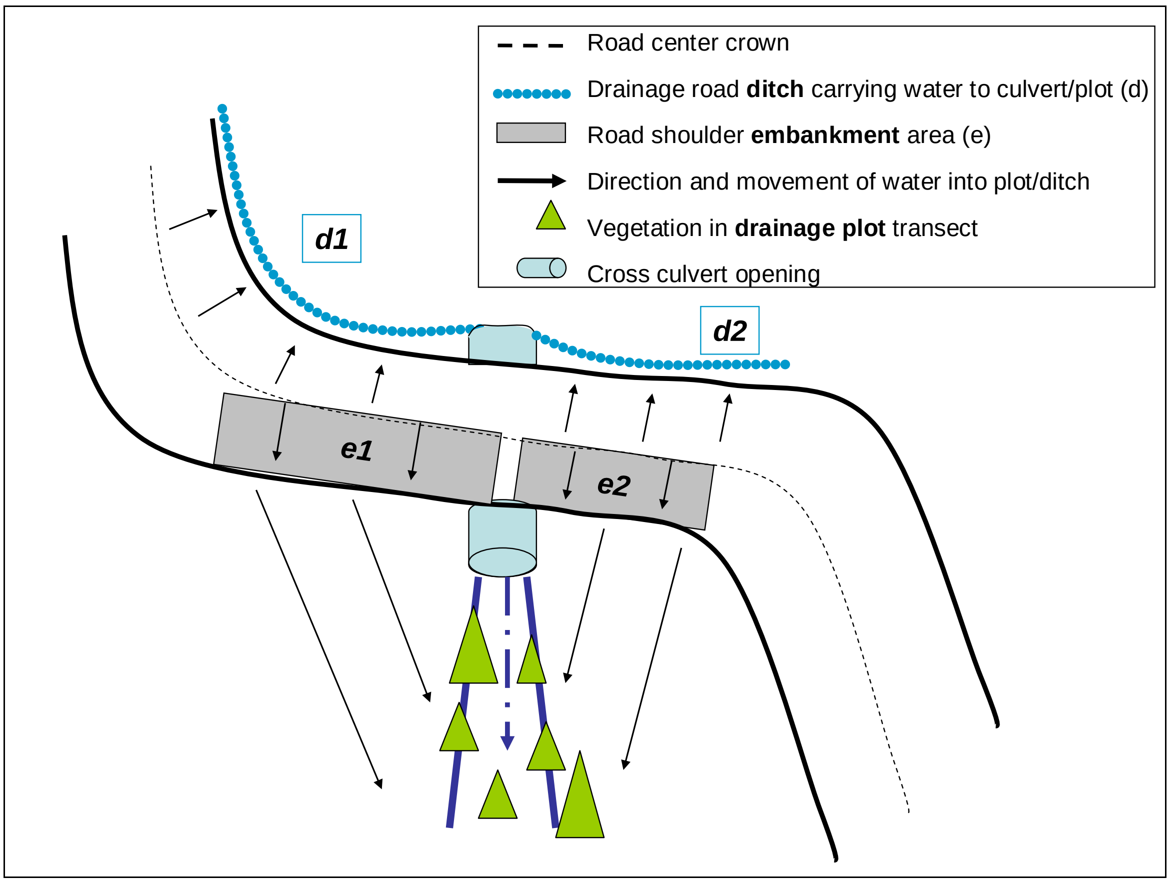


Figure A3. Illustration of potential water movement due to drainage plot surface area from non-paved roads impacted by ditches (d1 and d2) and embankments (e1 and e2) into downslope culvert channels and Plot Type 2: Drainage vegetation health plots.

Figure A3 illustrates measurements taken to obtain surface area values for drainage vegetation health plots. These measurements included the amount of road surface area draining into the plot and the length and slope of roadside ditches that drained into the plot. The amount of road surface area potentially dictating water movement into the plot was measured from the point in the road where the peak, or road crown, occurred multiplied by the width of the embankment or length of the ditch associated with it. The potential surface area of road drainages (d1 and d2) was calculated by multiplying road area and the slope (%) of the ditch depending on where it began (either at the crest of a hill or where another culvert broke up the continuous ditch). If the ditch did not flow directly into the culvert, that area was subtracted from the total ([length] [width]). The surface area of drainages 1 and 2 (d1 and d2) of Figure A3 was calculated as follows:

d1 = ([drainage length][road width][slope of ditch]) – distance(width) to culvert
d2 = ([drainage length][road width][slope of ditch]) – distance(width) to culvert

The potential amount of surface area from embankments (e1 and e2 in Figure A3) was calculated by measuring the road area draining into the plot and subtracting the calculated area between the road and the plot ([0.5][length][width]). The potential amount of surface area of embankments 1 and 2 (e1 and e2) in Figure A3 were calculated as follows:

e1 = shoulder width x road width – distance(width) to drainage plot
e2 = shoulder width x road width – distance(width) to drainage plot

The total surface area was calculated by adding up the individual totals for any combination of ditches and embankments that potentially impacted water movement into the plot. The ditches and embankments in Figure A3 would be calculated as: ***d1 + d2 + e1 + e2*** = total potential surface water flow to drainage vegetation health plot.

Table A1. Plot Type 1: Roadside vegetation health plots in each habitat type sampled along both treated and control roads in Grand and Larimer Counties, Colorado in 2004 and 2005.

Dominant Species	Roadside Plots on $MgCl_2$-treated Roads	Roadside Plots on Non-treated (Control) Roads
lodgepole pine	25	6
trembling aspen	13	2
Engelmann spruce & subalpine fir	6	2
various shrubs, grasses and forbs	6	-
Plot totals	**50**	**10**

Table A2. Plot Type 2: Drainage vegetation health plots in each habitat type sampled along both treated and control roads in Grand and Larimer Counties, Colorado in 2004 and 2005.

Dominant Species	Drainage Plots on $MgCl_2$-treated Roads	Drainage Plots on Non-treated (Control) Roads
lodgepole pine	21	9
trembling aspen	15	10
Engelmann spruce & subalpine fir	10	7
various shrubs, grasses and forbs	7	-
Plot totals	**53**	**26**

Appendix A (cont.) Detailed methods and code sheets used to define study sites in roadside and drainage vegetation health plots.

Table A3. Habitat Types Defined in Study Sites. Record habitat type dominating landscape**.**

1	Forested/Wooded
2	Meadow
3	Riparian zone
4	Shrubland
5	Wetland
6	Rangeland
7	Rock/Cliff

Slope: Record the slope, in percent. Average the down slope and upslope measurements from plot center. Slope is defined as the ratio of vertical rise divided by the horizontal distance.

Aspect: Record the direction, in degrees, which the plot faces. Aspect may be determined by taking compass readings directly down slope from plot center. Aspect is the way the land or slope faces.

Table A4. Slope Position: Record the plot position on the landscape. Slope position definitions are from: National Soil Survey Handbook (Title 430-VI). USDA Soil Conservation Service, 1993.

Code	Description
SU	**Summit/Ridgetop/Plateau**. The topographically highest hillslope position of a hillslope profile and exhibiting a nearly level surface.
SH	**Shoulder**. The hillslope position that forms the uppermost inclined surface near the top of a hillslope. It comprises the transition zone from backslope to summit.
BS	**Backslope**. The hillslope position that forms the steepest inclined surface and principal element of many hillslopes. In profile, backslopes are commonly steep, linear, and bounded by a convex shoulder above and descending to concave footslope. They may or may not include cliff segments. Backslopes are commonly erosional forms produced by mass movement and running water.
FS	**Footslope**. The hillslope position that forms the inner, gently inclined surface at the base of a hillslope. In profile, footslopes are commonly concave. It is a transition zone between upslope sites of erosion and transport.
TS	**Toeslope**. The hillslope position that forms the gently inclined surface at the base of a hillslope. Toeslopes in profile are commonly gentle and linear, and are constructional surfaces forming the lower part of a hillslope continuum that grades to valley bottom.
VB	**Valley Bottom**. Wide valley bottom beyond influence of toeslope.

Slope Position Visual Aid

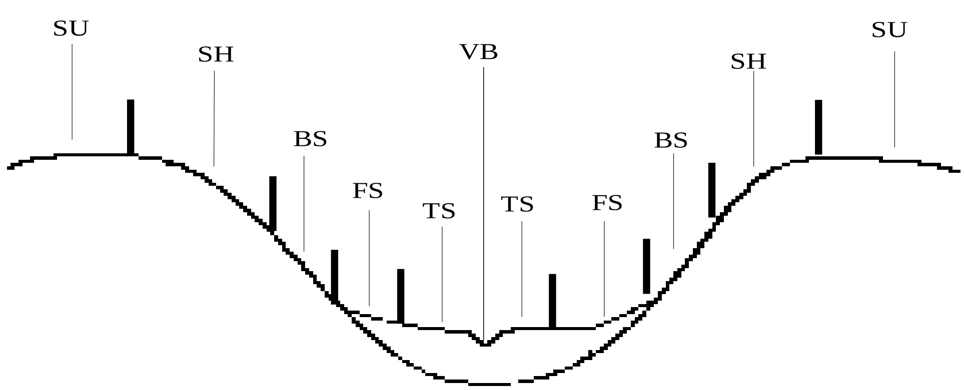


Table A5. Topographic Configuration: Record the micro-site configuration of the plot.

Code	Description
BR	**Broken**. Cliffs, knobs and/or benches interspersed with steeper slopes generally characterized by sharp, irregular breaks. A marked variation of topography, or an irregular and rough piece of ground.
CC	**Concave.** The gradient decreases down the slope. Runoff tends to decelerate as it moves down the slope, and if it is loaded with sediment the water tends to deposit the sediment on the lower parts of the slope. The soil on the lower part of the slope also tends to dispose of water less rapidly than the soil above it.
CV	**Convex**. The gradient increases down the slope and runoff tends to accelerate as it flows down the slope. Soil on the lower part of the slope tends to dispose of water by runoff more rapidly than the soil above it. The soil on the lower part of a convex slope is subject to greater erosion than that on the higher parts.
LL	**Linear or Planar.** Substantially a straight line when seen in profile at right angles to the contours. The gradient does not increase or decrease significantly with distance (level or little relief).
UN	**Undulating**. One or more low relief ridges or knolls and draws within the plot area.

Table A6. Stand Structure: Record structure as a description of the distribution of tree height classes within stand.

Code	Description
CCSS	**Closed Canopy Single-story** - A single even canopy characterizes the stand. The greatest number of trees are in a height class represented by the average height of the stand; there are substantially fewer trees in height classes above and below this mean.
CCMS	**Closed Canopy Multi-storied** - At least two height size classes are commonly represented in the stand. Generally, the canopy is broken and uneven although multiple canopy levels may be distinguishable. The various size classes tend to be uniformly distributed throughout the stand.
OCMS	**Open Canopy Multi storied**– Woodland, open canopy, trees are dispersed throughout stand, two distinct age or height classes commonly represented. Generally, the canopy is broken and uneven although multiple canopy levels may be distinguishable. The various size classes tend to be uniformly distributed throughout the stand.
OCSS	**Open Canopy Single Storied**– Woodland, open canopy, trees are dispersed throughout stand, the greatest number of trees are in a height class represented by the average height of the stand; there are substantially fewer trees in height classes above and below this mean.
MO	**Mosaic** - At least two distinct height size classes are represented and these are not uniformly distributed, but are grouped in small repeating aggregations, or occur as stringers less than two chains wide, throughout the stand.

Table A7. Land Use Descriptions: Record information about the land use of the area.

Code	Description
1	Forest/open land (no bldgs, etc.)
2	Residential (houses, etc)
3	Ranch/Farmland (livestock, etc).
4	Recreation
5	Intersection
6	Other

Table A8. Disturbances: Record information about activities that occurred on, or affected the plot. Multiple codes may be entered if more than one event is observed.

Code	Description
1	Artificial Regeneration
2	Tree cutting
3	Fire
4	Mining
5	Land Clearing
6	Grazing/Livestock
7	Other Human Disturbances
8	Mowing/landscaping along road
9	Road maintenance

Table A9. Dominant Tree Species: Record 4 letter code (ex. *Pinus contorta* = PICO) for each tree in plot.

Species Code	**Scientific Name**	**Common Name**	**Family**
ABLA	Abies lasiocarpa	Subalpine fir	Pinaceae
PIEN	Picea engelmannii	Engelmann spruce	Pinaceae
PIGL	Picea glauca	White spruce	Pinaceae
PIAL	Pinus albicaulis.	Whitebark pine	Pinaceae
PICO	Pinus contorta Dougl..	Lodgepole pine	Pinaceae
PIFL2	Pinus flexilis	Limber pine	Pinaceae
PIPO	Pinus ponderosa	Ponderosa pine	Pinaceae
POTR5	Populus tremuloides.	Quaking aspen	Salicaceae
PSME	Pseudotsuga menziesii	Douglas-fir	Pinaceae
PIAR	Pinus aristata	Bristlecone pine	Pinaceae
PODE	Populus deltoides	Plains/Southern Cottonwood	Salicaceae
JUSC	Juniperus scopulorum	Rocky Mountain juniper	Cupressaceae
PIPU	Picea pungens	Colorado blue spruce	Pinaceae
PIED	Pinus edulis	Pinon pine	Pinaceae

Table A10. DBH Classes (Diameter at Breast Height = 4.5 feet, 1.37 meters)**:**

Code	**Diameter at Breast Height (DBH)**
1	< 2 inches, < 5.1 centimeters
2	2-6 inches, 5.1 – 15.2 centimeters
3	6.1-12 inches, 15.3 – 30.5 centimeters
4	>12 inches, > 30.5 centimeters

Table A11. Crown Class: Record the crown class for all live trees. Crown class is the description of the relative position of the tree crown with respect to competing vegetation surrounding the tree.

Code	**Description**
1	Dominant, full sunlight from above and partially from sides.
2	Codominant, full sunlight from above but little from sides.
3	Intermediate, sunlight only from holes in canopy.
4	Overtopped, understory tree, barely any sunlight.
5	Open grown, crown receives optimal sunlight from above and sides.

Table A12. Tree Health Classes: Record for each tree in plot (including those below dbh).

Code	**Health Class**	**Description**
1	Healthy	No visual damage to crown or stem up to 5% damage
2	Slightly affected	6-50% of crown or stem circumference showing symptoms of damage
3	Severely affected	> 50% of crown or stem circumference showing symptoms of damage
4	New dead	No green needles, has red needles, fine twigs still present
5	Old dead	No fine twigs or needles.
6	Stump	Cut or decayed stump

Table A13. Biotic Damage Agent Incidence Codes. Record up to three major damage agents' incidence and rate severity (Table A14) for each tree in plot.

Code	Description	Code	Description
11	bark beetles	27	broom rust
12	defoliators	28	sunscald
14	sucking insects	30	fire
15	boring insects	41	wild animals
16	seed/cone/flower/fruit insects	42	domestic animals
17	gallmaker insects	50	unknown abiotic
18	insect predators	54	dead/missing top
20	branch cankers	55	lightning
21	root/butt disease	56	hail
22	stem decay/cankers	57	frost damage
23	parasitic plants	58	winter injury
24	dieback	60	competition
25	foliage disease	90	unknown
26	stem rust	98	twig beetles
		99	mechanical damage

Table A14. Biotic damage code severity ratings. Record severity for biotic damage incidence for each tree in plot..

Damage	Severity	Description
23 (see below for Hawksworth rating explanation*)	1	Hawksworth tree DMR rating = 1; light infection
	2	Hawksworth tree DMR rating = 1; light infection
	3	Hawksworth tree DMR rating = 1; medium infection
	4	Hawksworth tree DMR rating = 1; medium infection
	5	Hawksworth tree DMR rating = 1; heavy infection
	6	Hawksworth tree DMR rating = 1; heavy infection
ALL other damages	0	0-9% affected
	1	10-19% affected
	2	20-29% affected
	3	30-39% affected
	4	40-49% affected
	5	50-59% affected
	6	60-69% affected
	7	70-79% affected
	8	80-89% affected
	9	90-100% affected

***DMR (Dwarf Mistletoe Rating):** Hawksworth 0-6 Class System

- Divide crown into thirds
- Rate each third
- 0= no mistletoe infection
- 1= <50% branches have infection
- 2= >50% branches have infection
- Add each third for a total between 0-6.

Additional Information Collected for Each Tree in Plot:

- **Transect number:** 1-3, left to right (facing stand from road)
- **Tree Number:** Start at beginning of road and work your way away from road. One number for each tree, if tree is tagged record corresponding tag number**.Percent Crown**: Record percent crown as the length of the crown divided by tree height. Crown is assessed from the uppermost leader or branch to the lowest branch. Visually adjust large openings in the crown or lopsided crowns by transferring lower branches to fill in the holes. Compressing the crown length because the crown appears sparse or contains unhealthy foliage is not appropriate. For our purposes, all crown (even dead crown) counts as a part of the 100% total. Dead branches (with no fines or dead needles) do not count.
- **Height**: Measure height if tree is below standard breast height (4.5 feet, 1.37 meters) and above 1.0 foot (30.5 centimeters).
- **Date**: Record the date the sample of the foliage was collected from this tree.
- **Sample Damage**: Record the percentage of sample with tip or marginal burn, banded burning, or full necrosis or chlorosis.

Table A15. Ground Cover: Layout squares at 0, 3.1, 6.1, and 12.2 meters away from the road on both sides of each transect with edge of square lined up with middle line subplot tape. Start shrub plots at 3.1 and 12.2 meters on the tape and use measuring tape to draw a circular plot 11.5 meters radius.

Code	Description	Definition
		WOODY PIECES
WOOD	Wood	Woody material, slash and debris; any woody material, small and large woody debris, regardless of depth. Litter and non-continuous litter are not included (for example, scattered needles over soil is classified as BARE).
		ROADS
ROAD	Road	Improved roads, paved roads, gravel roads, improved dirt roads and off-road vehicle trails regularly maintained or in long-term continuing use. Generally constructed using machinery. Includes cutbanks and fills.
BARE	Bare soil (soil particles < 2 mm)	Bare soil, not covered by rock, cryptogams or organic material. Does not include any part of a road (see definition for road).
		MOSS, LICHEN, FUNGI
CRYP	Cryptogamic crust	Thin, biotically dominated ground or surface crusts on soil in dry rangeland conditions, e.g. cryptogamic crust (algae, lichen, mosses or cyanobacteria).
FUNG	Fungus	Fruiting bodies of basidiomycetes and ascomycetes.
LICH	Lichen	Lichens: an organism generally recognized as a single plant that consists of a fungus and an alga or cyanobacterium living in a symbiotic association. For lichen growing on bare soil in dry rangeland conditions, see cryptogamic crusts.
MOSS	Moss	Nonvascular, terrestrial green plants including mosses, hornworts and liverworts - always herbaceous. This code does not apply to moss growing on bare soils in dry rangeland conditions. For rangeland conditions, see cryptogamic crusts.
		DUFF AND LITTER
LITT	Litter and duff	Leaf and needle litter, and duff not yet incorporated into the decomposed top humus layer. Non-continuous litter is not included (for example, scattered needles over soils is classified a BARE).

Table A16. Ground Cover Plant Health: Record the plant health for all species in the square.

Code	Health Class	Description
1	Healthy	No visual damage to crown or stem up to 5% damage
2	Declining	6-50% of crown showing symptoms of damage
3	Dying	> 50% of crown showing symptoms of damage
4	Dead	No green foliage, dead.

APPENDIX B. Soil magnesium and chloride means along individual study roads.

Table B1. Mean magnesium and chloride soil concentrations in roadside vegetation health plots by each study road sampled. Three transects combined for mean concentrations by distance and yearly data combined for plots sampled for two years. Least square means back transformed from $\log_{10}$ values, ± back-transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

County	Road (Number: Name/Description)	Slope Position	Distance from Road (m)	Soil Chloride (ppm)	1.4 SE (½ LSD)	Soil Magnesium (ppm)	1.4 SE (½ LSD)
Larimer	37.023: Red Mountain Granite Canyon	Up	0.0	230.1	153.1	380.0	145.1
			3.0	32.9	22.2	144.1	55.4
			6.1	20.1	13.5	150.8	57.8
			12.2	18.6	12.4	128.6	49.1
		Down	0.0	615.5	409.4	371.5	141.8
			3.0	246.3	163.9	159.2	60.8
			6.1	163.6	108.9	163.6	62.4
			12.2	61.0	40.9	180.6	69.2
Larimer	80.031: 287 to County Line East	Up	0.0	107.7	38.3	439.1	89.0
			3.0	13.4	4.8	294.2	59.6
			6.1	13.8	4.9	337.8	68.4
			12.2	9.4	3.3	337.2	68.3
		Down	0.0	439.9	156.4	433.1	87.7
			3.0	35.4	12.6	202.8	41.1
			6.1	13.1	4.6	201.6	40.8
			12.2	12.4	4.4	256.4	51.9
Larimer	103: Larimie River Road	Up	0.0	479.2	158.9	405.8	41.8
			3.0	29.8	9.9	128.0	13.1
			6.1	25.0	8.2	125.1	12.7
			12.2	19.0	6.3	121.3	12.3
		Down	0.0	225.9	74.9	437.0	45.0
			3.0	42.3	14.1	158.0	16.4
			6.1	28.9	9.6	147.2	15.2
			12.2	18.1	6.0	128.4	13.3
Larimer	162.234: Bellaire Lakes	Up	0.0	306.4	84.8	465.3	68.8
			3.0	34.1	9.1	163.0	23.6
			6.1	26.3	6.8	139.4	19.9
			12.2	20.3	5.3	126.2	18.0
		Down	0.0	703.7	198.8	540.9	96.6
			3.0	116.2	32.6	246.0	39.2
			6.1	39.4	10.8	170.7	26.9
			12.2	26.8	7.4	171.0	27.0
Larimer	190: Stub Creek	Up	0.0	1235.9	301.0	549.3	79.3
			3.0	27.4	6.7	183.8	26.5
			6.1	22.6	5.5	180.0	26.0
			12.2	18.3	4.5	183.7	26.5
		Down	0.0	329.2	80.2	395.1	57.0
			3.0	19.6	4.8	156.0	22.5
			6.1	13.9	3.4	157.3	22.7
			12.2	14.2	3.5	168.7	24.3

Table B1 (cont).

County	Road (Number: Name/Description)	Slope Position	Distance from Road (m)	Soil Chloride (ppm)	1.4 SE (½ LSD)	Soil Magnesium (ppm)	1.4 SE (½ LSD)
Larimer	139: Crown Point	Up	0.0	11.1	3.0	155.0	22.9
			3.0	13.9	2.9	145.1	22.5
			6.1	15.7	3.0	138.1	22.9
			12.2	17.7	2.9	147.3	22.5
		Down	0.0	12.5	3.0	136.1	22.7
			3.0	14.7	2.9	116.5	22.3
			6.1	14.2	2.9	122.4	22.3
			12.2	13.4	2.9	103.9	22.3
Larimer	44.34: Pingree Park	Up	0.0	14.6	2.9	35.8	12.9
			3.0	15.8	2.9	40.5	12.9
			6.1	12.2	2.9	62.5	12.9
			12.2	12.1	2.9	66.7	12.9
		Down	0.0	13.7	2.9	56.0	12.9
			3.0	15.4	2.9	60.0	12.9
			6.1	20.8	2.9	78.3	12.9
			12.2	15.9	2.9	77.7	12.9
Grand	1: Trough	Up	0.0	325.2	83.0	411.7	50.0
			3.0	66.4	16.2	273.7	31.9
			6.1	37.2	9.1	246.1	28.6
			12.2	22.9	5.6	185.5	21.6
		Down	0.0	1230.8	300.1	650.3	75.7
			3.0	119.5	27.9	262.9	29.4
			6.1	42.7	10.4	215.9	25.1
			12.2	31.8	7.8	256.6	29.9
Grand	30: Upper Williams	Up	0.0	1362.0	2053.4	792.1	937.3
			3.0	64.2	96.8	196.9	236.7
			6.1	45.1	68.0	163.3	196.3
			12.2	30.3	45.7	149.8	178.6
		Down	0.0	398.7	601.2	559.3	672.5
			3.0	89.7	135.2	315.0	375.6
			6.1	45.9	69.1	188.1	222.6
			12.2	37.7	56.8	139.9	166.8
Grand	6: Monarch	Up	0.0	156.3	106.8	348.9	214.0
			3.0	49.6	33.9	140.2	86.0
			6.1	34.9	25.0	141.6	87.6
			12.2	30.2	22.3	130.1	81.0
		Down	0.0	316.5	162.8	438.1	210.3
			3.0	36.6	18.8	219.0	105.1
			6.1	24.7	12.5	185.7	88.9
			12.2	27.6	14.4	180.0	86.6
Grand	83: Devils Ranch	Up	0.0	764.2	221.4	719.3	11.3
			3.0	34.5	11.5	283.7	54.0
			6.1	42.4	13.1	200.5	34.1
			12.2	19.8	6.1	345.1	58.6
		Down	0.0	1341.8	388.8	505.6	78.2
			3.0	202.6	58.7	193.8	30.0
			6.1	47.9	14.7	137.0	23.3
			12.2	17.2	5.0	149.5	23.1

APPENDIX C: Supplemental soil and foliar chemistry results in roadside and drainage vegetation health plots.

Figures C1 – C28

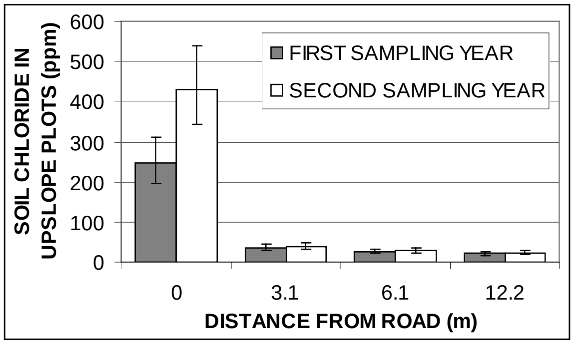
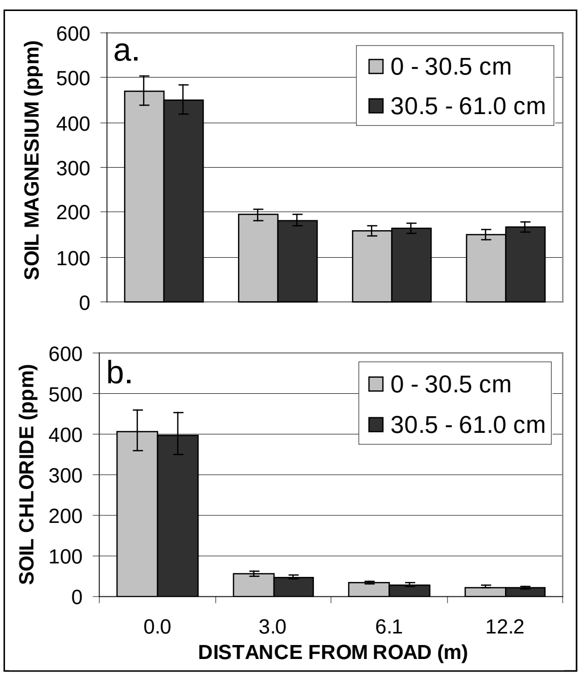
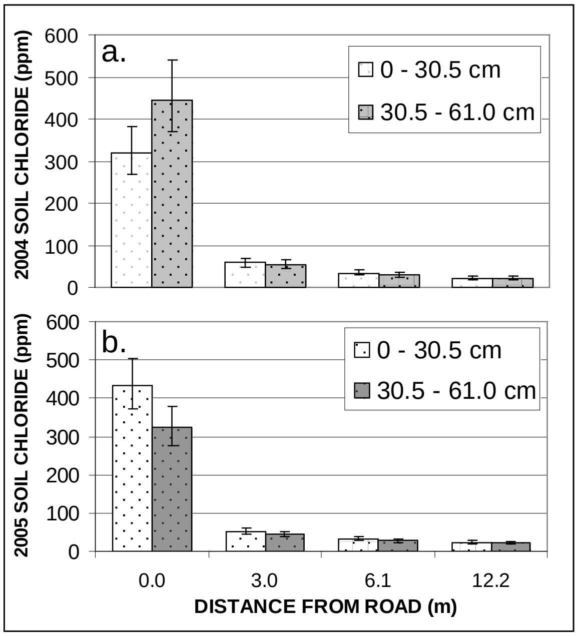


Figure C1. Soil chloride adjusted mean (lsmean) concentrations along roads treated with $MgCl_2$ based dust suppressants in Larimer and Grand Counties, Colorado in upslope plots only and four distances from the road (497 total soil samples in upslope plots, *n* = 58 to 61 samples per distance sampled in 2004 and *n* = 63 to 63 samples per distance sampled in 2005). Data only taken from plots sampled for two consecutive years. Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



Figures C2a-b. Soil (a) magnesium and (b) chloride adjusted mean (lsmean) concentrations along roads treated with $MgCl_2$ based dust suppressants at two sampling depths (0 to 30.5 cm and 30.5 to 61.0 cm) in Larimer and Grand Counties, Colorado at four distances from the road (1411 total soil samples, *n* = 194 to 197 at each distance in upper soil sampling depth and *n* = 159 to 182 at each distance in lower soil sampling depth with slope positions from the road combined at each distance). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



Figures C3a-b. Adjusted mean soil chloride concentrations in (a) 2004 and (b) 2005 along roads treated with $MgCl_2$ based dust suppressants at two sampling depths (0 to 30.5 cm and 30.5 o 61.0 cm) in Larimer and Grand Counties, Colorado at four distances from the road (upslope and downslope samples combined at each distance). Data only taken from plots sampled for two consecutive years. Soils sampled in late summers 2004 (523 total soil samples, n = 74 to 75 samples from upper sampling depth at each distance and n = 56 to 65 samples from lower sampling depth at each distance) and 2005 (583 total soil samples, n = 73 to 75 samples from upper sampling depth at each distance and n = 69 to 74 samples from lower sampling depth at each distance). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

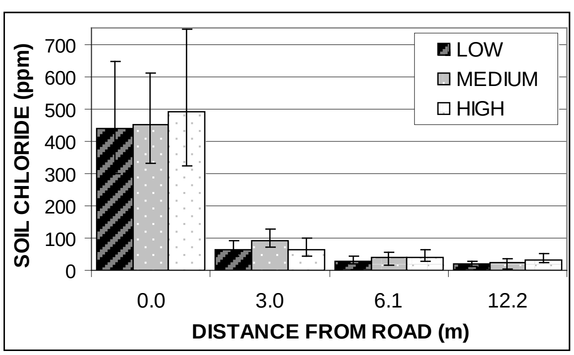


Figure C4. Soil chloride adjusted mean (lsmean) concentrations along roads treated with $MgCl_2$ based dust suppressants in Larimer and Grand Counties, Colorado separated by slope categories in downslope plots only at four distances from the road (720 total soil samples, n = 50 to 54 samples per distance in low slope plots, n = 93 to 99 samples per distance in medium slope plots and n = 68 to 74 samples per distance in high slope plots). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

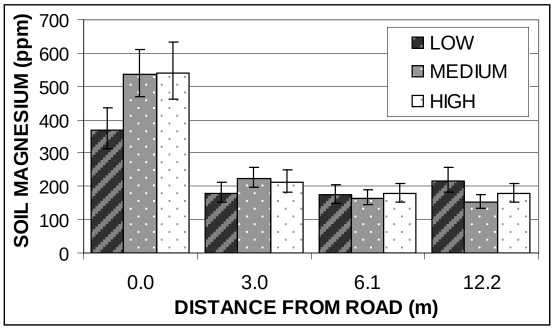


Figure C5. Soil magnesium adjusted mean (lsmeans) concentrations along roads treated with $MgCl_2$ based dust suppressants in Larimer and Grand Counties, Colorado separated by slope categories in downslope plots only at 4 distances from the road (720 total samples, n = 50 to 54 per distance in low slope plots, n = 93 to 99 per distance in medium slope plots and n = 68 to 74 per distance in high slope plots). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

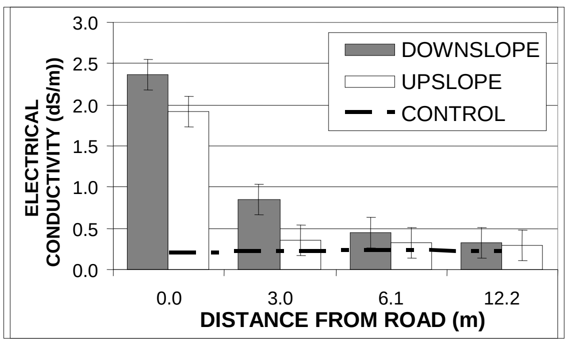


Figure C6. Soil electrical conductivity adjusted means (lsmeans) along roads treated with $MgCl_2$ based dust suppression products in Larimer and Grand Counties, Colorado at four distances and two slope positions from the road (1,411 total samples, n = 171 to 195 samples collected at each distance separated by slope). Dotted line indicates control soil concentrations of each ion (225 total soil samples, n = 26 to 30 samples collected at each sampling distance separated by slope, n = 53 o 58 samples collected at each distance). ± 1.4 standard error (approximately ± ½ Fisher's Least Significant Difference).

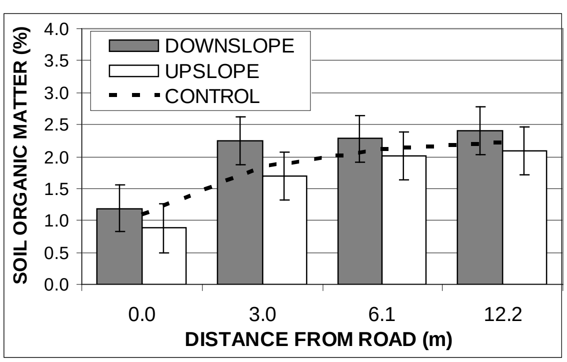
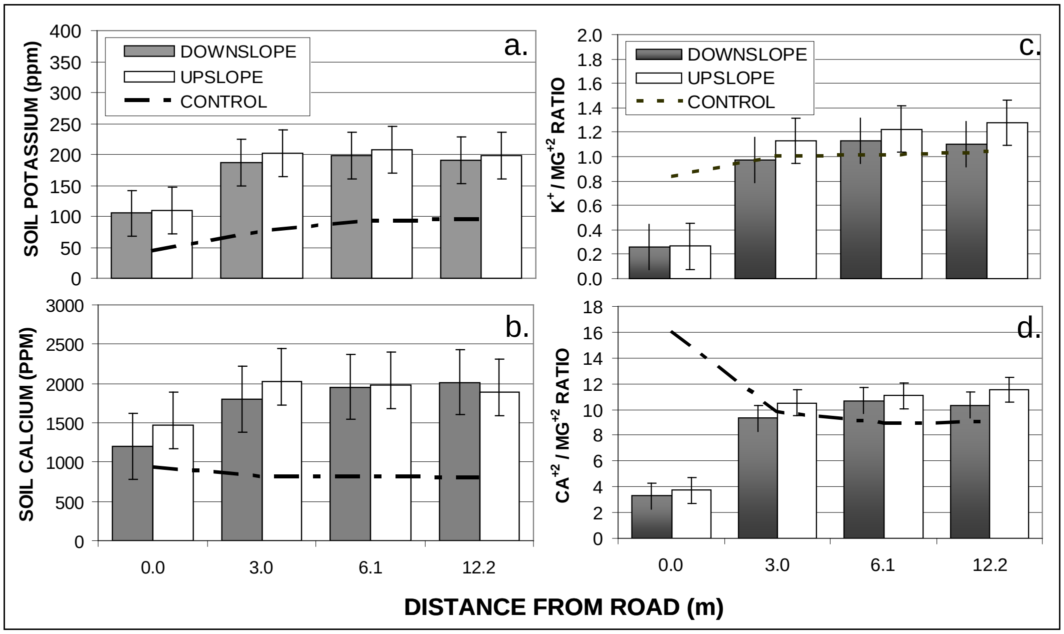
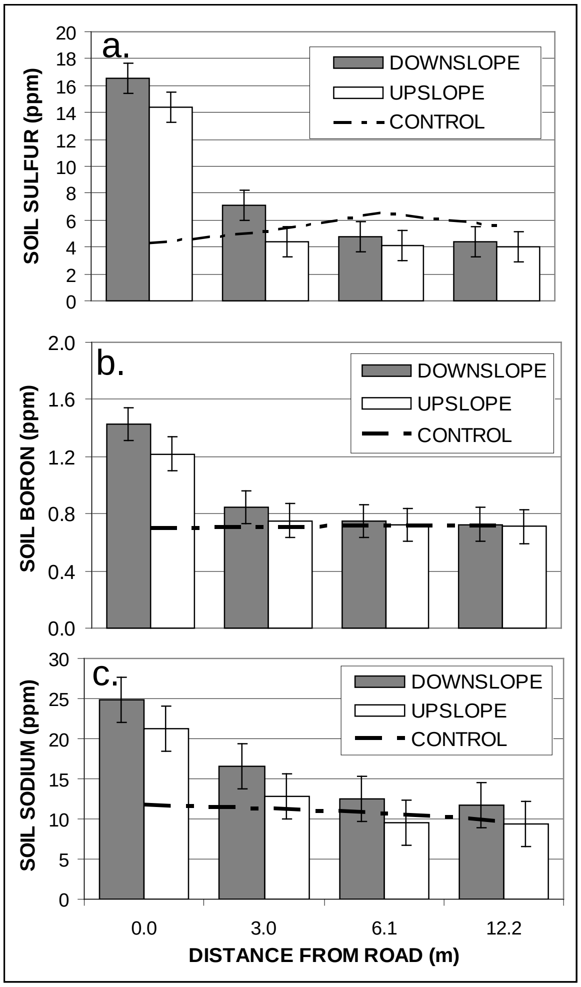


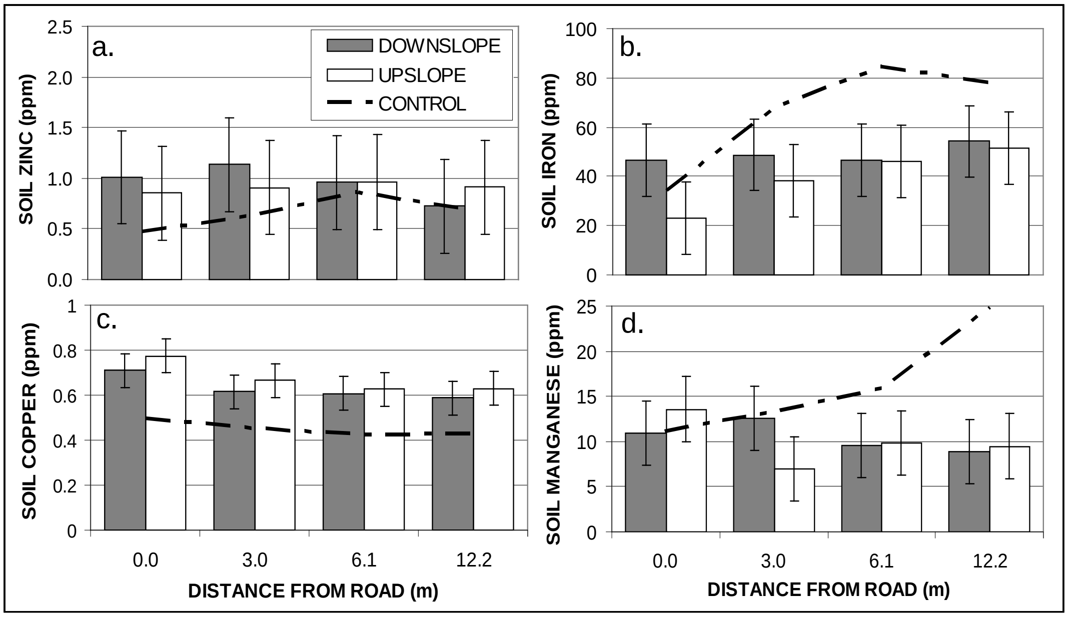
Figure C7. Soil organic matter adjusted means (lsmeans) along roads treated with $MgCl_2$ based dust suppression products in Larimer and Grand Counties, Colorado at four distances and two slope positions from the road (1,411 total samples, n = 171 to 195 samples collected at each distance separated by slope). Dotted line indicates control soil concentrations of each ion (225 total soil samples, n = 26 to 30 samples collected at each sampling distance separated by slope, n = 53 to 58 samples collected at each distance). ± 1.4 standard error (approximately ± ½ Fisher's Least Significant Difference).



Figures C8a-d. Exchangeable (a) potassium, (b) calcium, c) K/Mg , and (d) Ca/Mg ratios adjusted mean concentrations (lsmeans) along roads treated with $MgCl_2$ based dust suppression products in Larimer and Grand Counties, Colorado at four distances and two slope positions from the road (1,411 total soil samples, n = 171 to 195 samples collected at each sampling distance separated by slope). Dotted line indicative of control soil concentrations (225 total soil samples, n = 26 to 30 samples collected at each sampling distance separated by slope, n = 53 to 58 samples collected at each distance). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



Figures C9a-c. Soil (a) sulfur, (b) boron and (c) sodium adjusted mean concentrations (lsmeans) along roads treated with $MgCl_2$ based dust suppression products in Larimer and Grand Counties, CO at four distances and two slope positions from the road (1,411 total soil samples, *n* = 171 to 195 samples collected at each sampling distance separated by slope). Dotted line indicative of control soil concentrations (225 total soil samples, *n* = 26 to 30 samples collected at each sampling distance separated by slope, *n* = 53 to 58 samples collected at each distance). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



Figures C10a-d. Soil micronutrient (a) zinc, (b) iron, (c) copper and (d) manganese adjusted mean concentrations (lsmeans) along roads treated with $MgCl_2$ based dust suppression products in Larimer and Grand Counties, CO at four distances and two slope positions from the road (1,411 total soil samples, *n* = 171 to 195 samples collected at each sampling distance separated by slope). Dotted line indicative of control soil concentrations (225 total soil samples, *n* = 26 to 30 samples collected at each sampling distance separated by slope, *n* = 53 to 58 samples collected at each distance). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

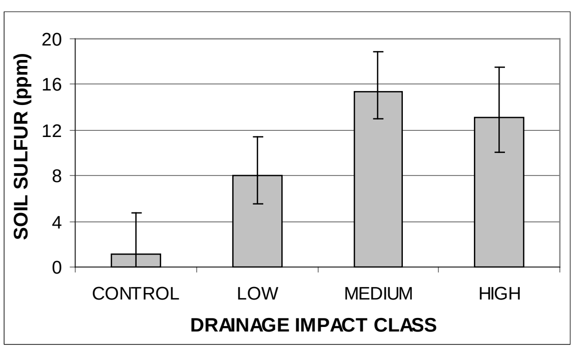


Figure C11. Soil sulfur adjusted means separated by drainage impact class in control (n = 101 soil samples), low (n = 116 samples), medium (n = 114 soil samples), and high (n = 70 soil samples) impact drainages on treated and control roads in Larimer and Grand Counties, Colorado sampled in 2005 or 2006. Means include all distance intervals and all plots in each class combined. Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

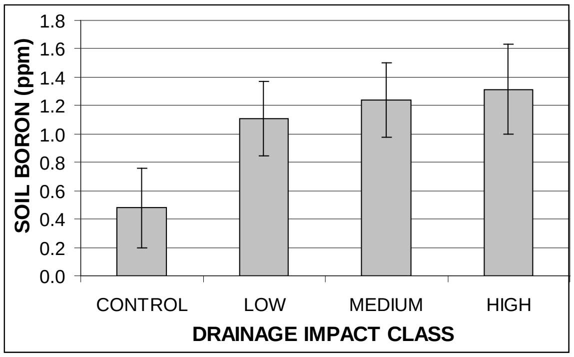
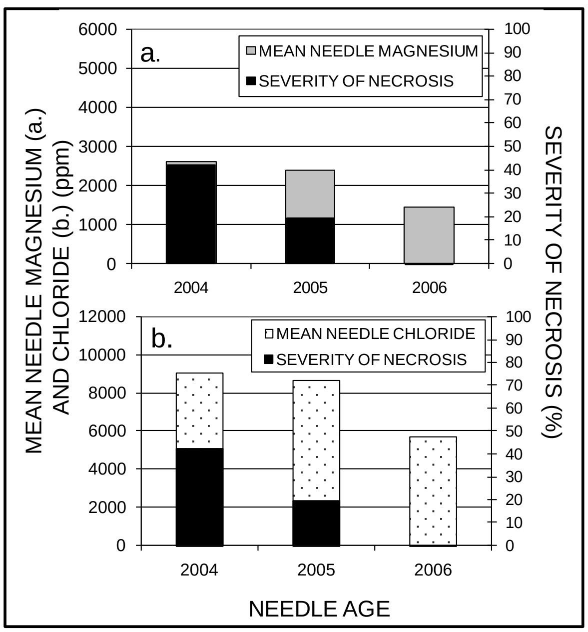
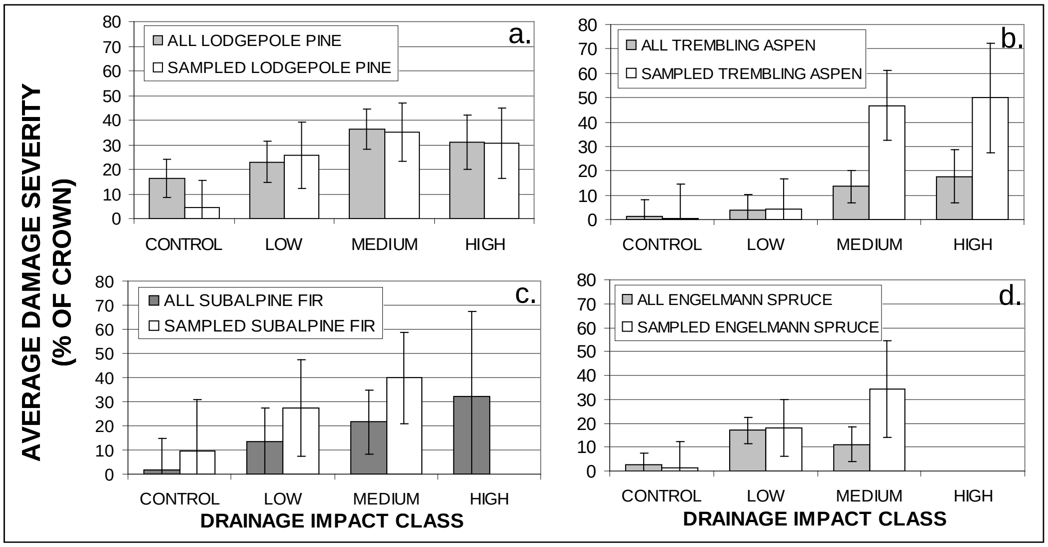


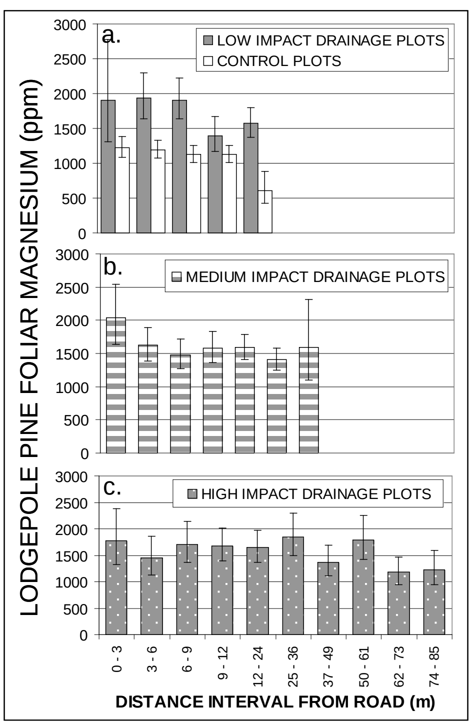
Figure C12. Soil boron adjusted means separated by drainage impact class in control (*n* = 101 soil samples), low (*n* = 116 samples), medium (*n* = 114 soil samples), and high (*n* = 70 soil samples) impact drainages on treated and control roads in Larimer and Grand Counties, Colorado sampled in 2005 or 2006. Means include all distance intervals and all plots in each class combined. Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



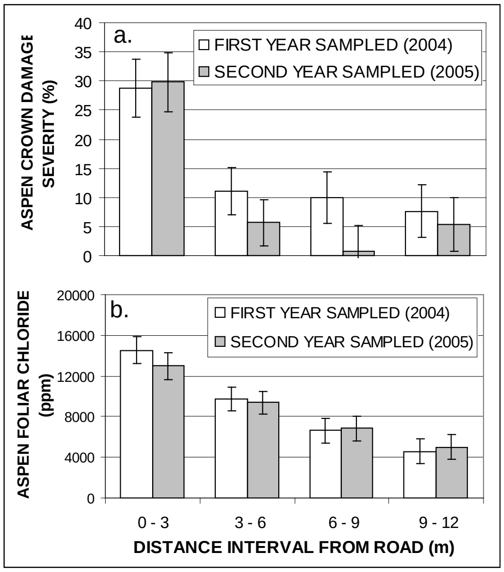
Figures C13a-b. Mean needle (a) magnesium concentrations, (b) chloride concentrations and severity of needle damage in three age classes of lodgepole pine needles sampled from three downslope plots along one non-paved road treated with $MgCl_2$ dust suppression products in Larimer County, Colorado (County Road 162.234). Nine trees samples with each of three different aged needles (2004, 2005 and 2006 flushed needles) for each age class.



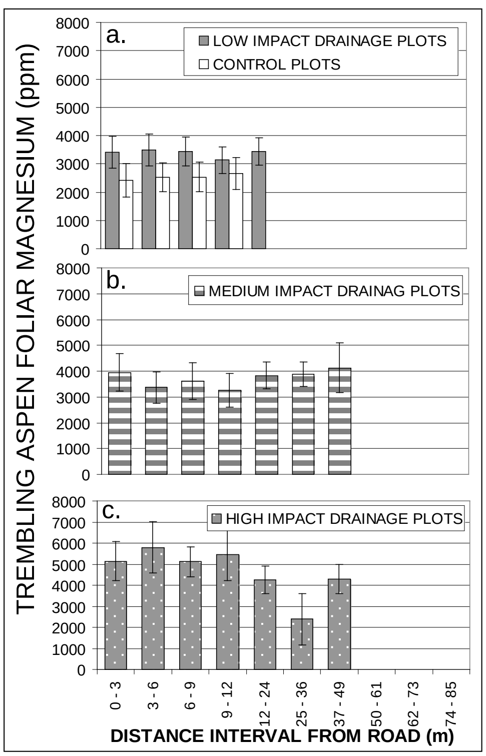
Figures C14 a-d. Mean crown damage severity in drainage plots separated by drainage impact class in all trees visually assessed (grey bars) and sampled for foliar ion content (white bars) of (a) lodgepole pine (n = 1,532 trees visually assessed and 247 trees sampled for ions), (b) trembling aspen (n = 2,292 trees and 192 sampled), (c) Engelmann spruce (n = 243 trees and 44 sampled), and (d) subalpine fir (n = 593 trees and 103 sampled). All roads, plots and distance intervals combined in each drainage impact class. No observations in high impact drainages for Engelmann spruce. Least square means ± 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



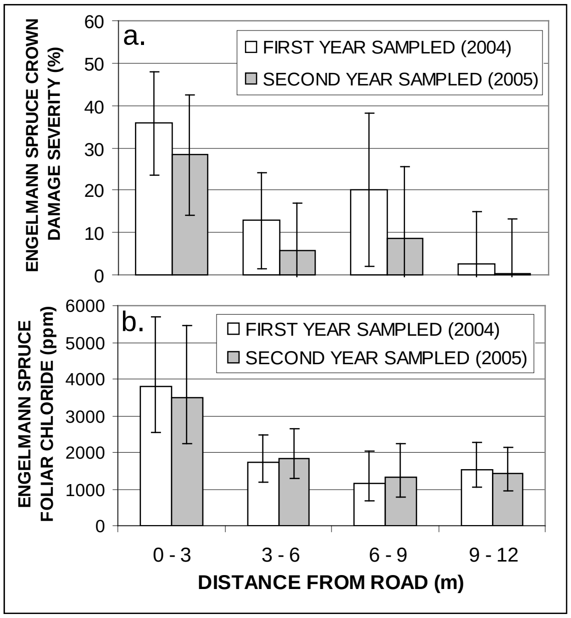
Figures C15a-c. Lodgepole pine adjusted foliar magnesium means (lsmeans) at various distance intervals in (a) control (n = 82 foliar samples), (a) low (n = 43 samples), (b) medium (n = 73 samples), and (c) high (n = 49 samples) drainage plot impact classes along $MgCl_2$ treated and control roads in Larimer and Grand Counties, Colorado Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



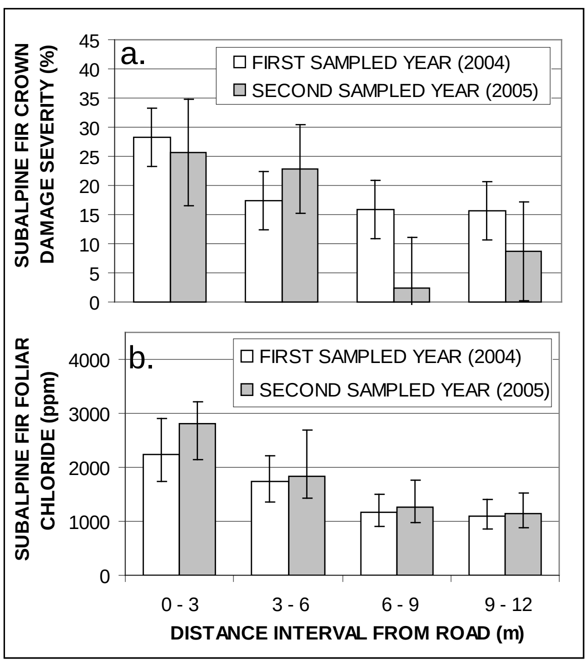
Figures C16a-b.Trembling aspen (a) crown damage and (b) chloride adjusted mean concentrations (lsmeans) along treated roads in Larimer and Grand Counties, Colorado at four distances and two slope positions in permanent plots sampled in 2004 and 2005. Two hundred eight-six total foliar samples and trees visually assessed, n = 51 to 103 samples in both years per distance interval from the road). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



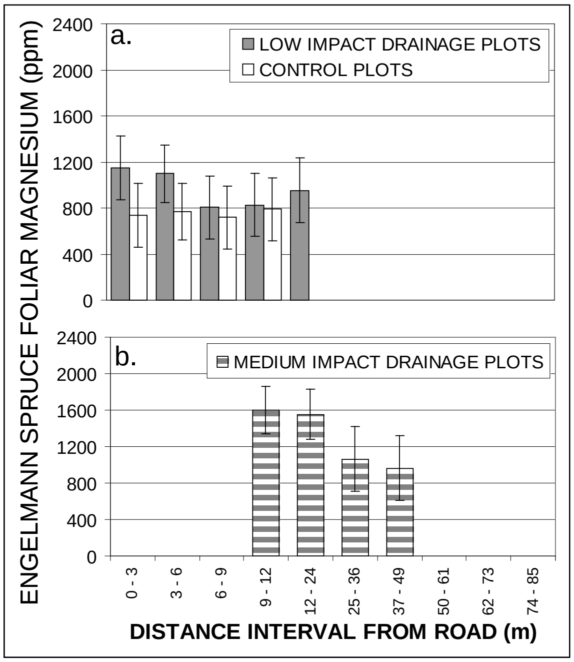
Figures C17a-c. Trembling aspen adjusted foliar magnesium means at various distance intervals in (a) control (n = 49 foliar samples), (a) low (n = 64 foliar samples), (b) medium (n = 50 foliar samples), and (c) high (n = 21 foliar samples) drainage plot impact classes along treated and control roads in Larimer and Grand Counties, Colorado sampled in 2005 or 2006. Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



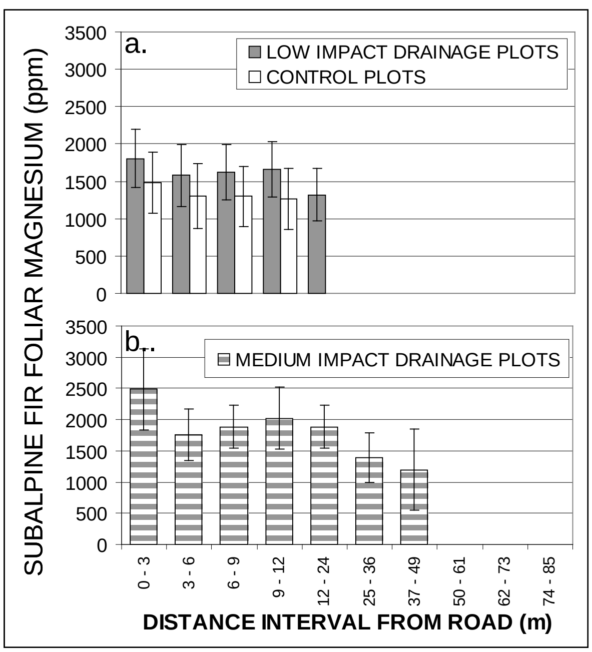
Figures C18a-b. Engelmann spruce (a) crown damage and (b) foliar chloride adjusted mean concentrations (lsmeans) along treated roads in Larimer and Grand Counties, Colorado. Sixty-eight total foliar samples and trees visually assessed, *n* = 8 to 28 foliar samples in both years per distance interval from the road). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



Figures C19a-b. Subalpine fir a) crown damage and (b) foliar chloride adjusted mean concentrations (lsmeans) along treated roads in Larimer and Grand Counties, Colorado. Two hundred six total foliar samples and trees visually assessed, *n* = 46 to 72 samples in both years per distance interval from the road). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



Figures C20a-b. Engelmann spruce adjusted foliar magnesium means at various distance intervals in (a) control (*n* = 25 foliar samples), (a) low (*n* = 12 foliar samples), and (b) medium (*n* = 7 foliar samples) impact drainage plots classes along treated and control roads in Larimer County, Colorado sampled in 2005 or 2006. Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



Figures C21a-b. Subalpine fir adjusted foliar magnesium means at various distance intervals in (a) control (*n* = 28 foliar samples), (a) low (*n* = 43 foliar samples), and (b) medium (*n* = 32 foliar samples) impact drainage plots classes along treated and control roads in Larimer County, Colorado sampled in 2005 or 2006. Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

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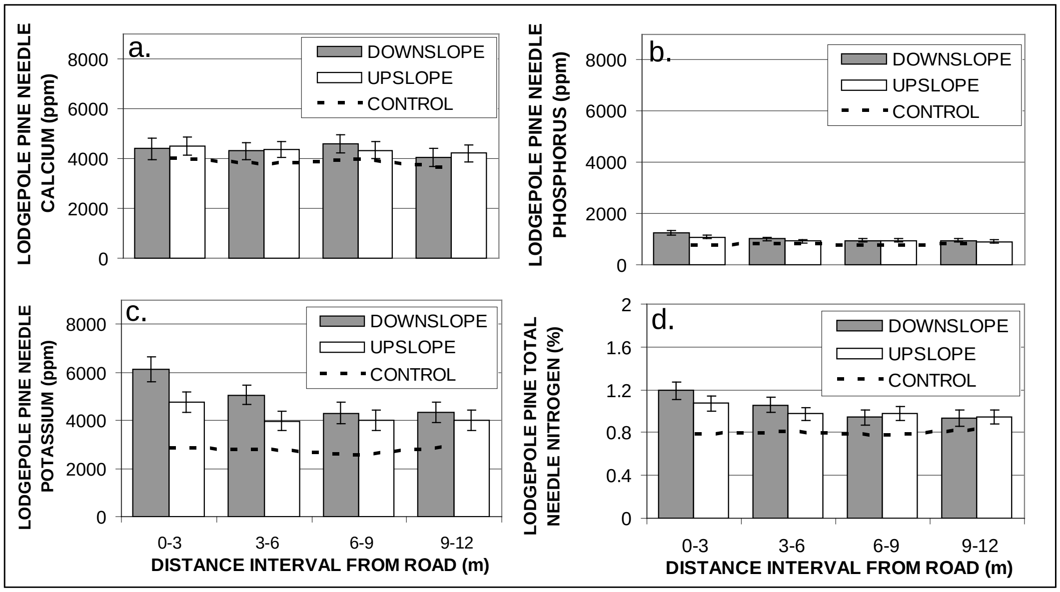


Figures C22a-d. Lodgepole pine needle (a) calcium, (b) potassium, (c) phosphorus and (d) and total nitrogen adjusted mean concentrations (lsmeans) at four distances and two slope positions from the road along $MgCl_2$ treated roads in Larimer and Grand Counties, Colorado (471 total samples collected, downslope plots ranged from 28 to 74 samples collected per distance interval, upslope plots ranged from 47 to 69 samples collected per interval). Dotted line indicative of control foliar concentrations (141 total foliar samples, 25 to 36 samples collected per distance interval). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

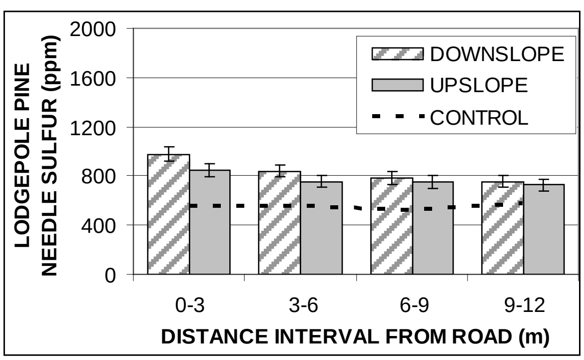


Figure C23. Lodgepole pine needle sulfur adjusted mean concentrations (lsmeans) at four distances and two slope positions along $MgCl_2$ treated roads in Larimer and Grand Counties, Colorado (471 total foliar samples collected, downslope plots ranged from 28 to 74 samples per distance interval, upslope plots ranged from 47 to 69 samples per distance interval). Dotted line indicative of control foliar concentrations (141 total foliar samples, n = 25 to 36 samples collected per distance interval). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

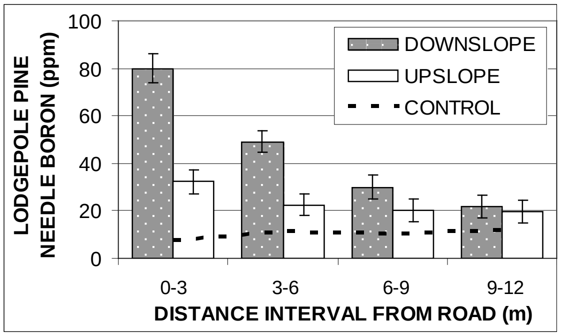


Figure C24. Lodgepole pine needle boron adjusted mean concentrations (lsmeans) at four distances and two slope positions along $MgCl_2$ treated roads in Larimer and Grand Counties, CO (471 total foliar samples collected, downslope plots ranged from 28 to 74 samples per distance interval, upslope plots ranged from 47 to 69 samples per distance interval). Dotted line indicative of control foliar concentrations (141 total foliar samples, *n* = 25 to 36 samples collected per distance interval). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

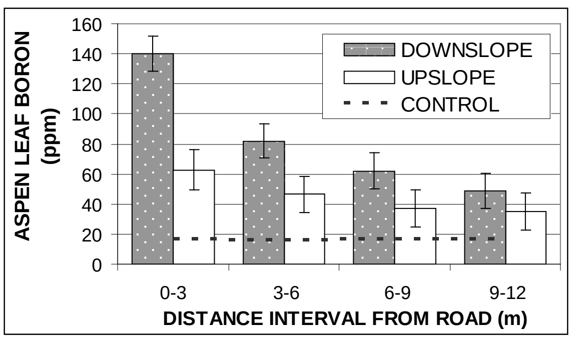
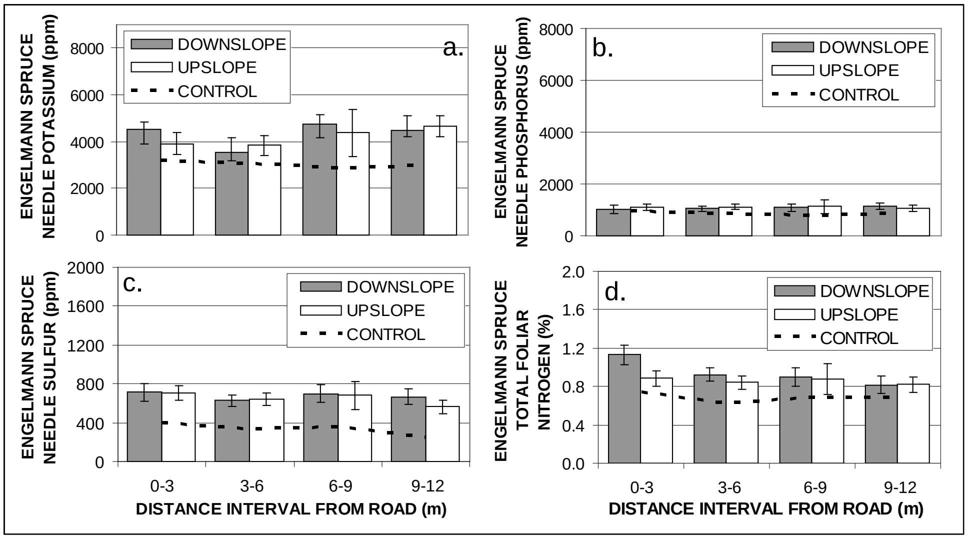
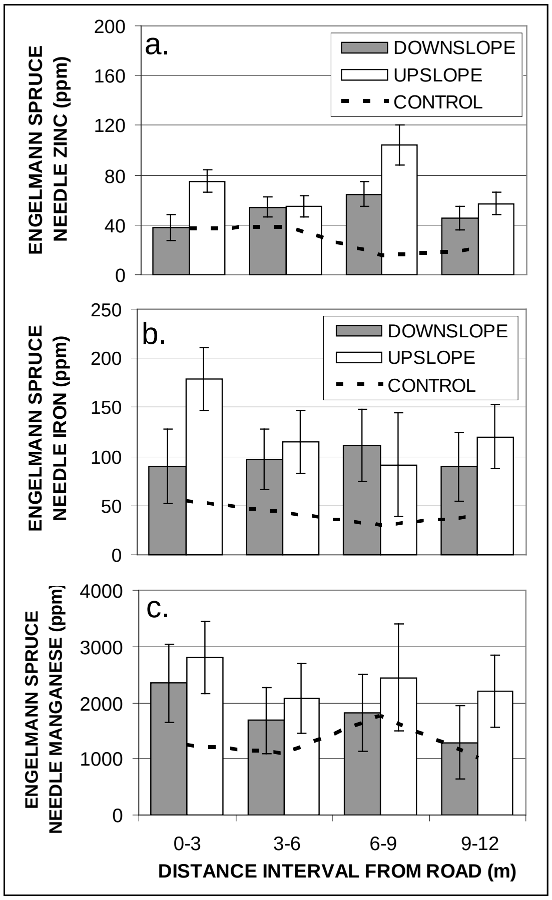


Figure C25. Trembling aspen leaf boron adjusted mean (lsmeans) concentrations, 420 total foliar samples collected, downslope plots ranged from 48 to 75 samples collected per distance interval, upslope plots ranged from 33 to 68 samples collected per interval along treated roads in Larimer and Grand Counties, Colorado. Dotted line indicative of control concentrations (42 total foliar samples, *n* = 3 to 9 samples collected per distance interval). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



Figures C26a-d. Engelmann spruce needle (a) potassium, (b) phosphorus, (c) sulfur, and (d) total foliar nitrogen adjusted mean (lsmeans) concentrations, 68 total foliar samples collected, downslope plots: 6 to 15 samples per distance interval, upslope plots: 2 to 13 samples per interval. Dotted line indicative of control concentrations of each ion (27 samples, *n* = 2 to 11 samples per distance interval). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



Figures C27a-c. Engelmann spruce needle (a) zinc, (b) iron and (c) manganese adjusted mean concentrations, 68 total foliar samples collected, downslope plots ranged from 6 to 15 samples collected per distance interval, upslope plots ranged from 2 to 13 samples collected per interval along treated road. Dotted line indicative of control concentrations of each ion (27 foliar samples, *n* = 2 to 11 samples collected per distance interval). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

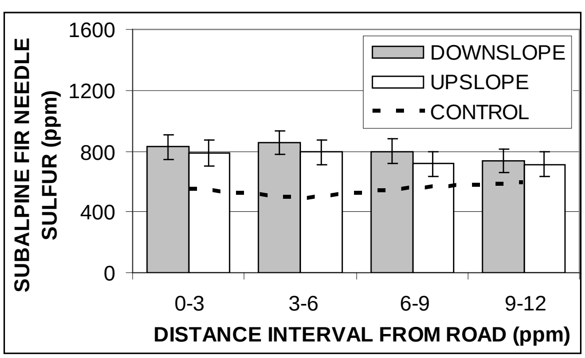
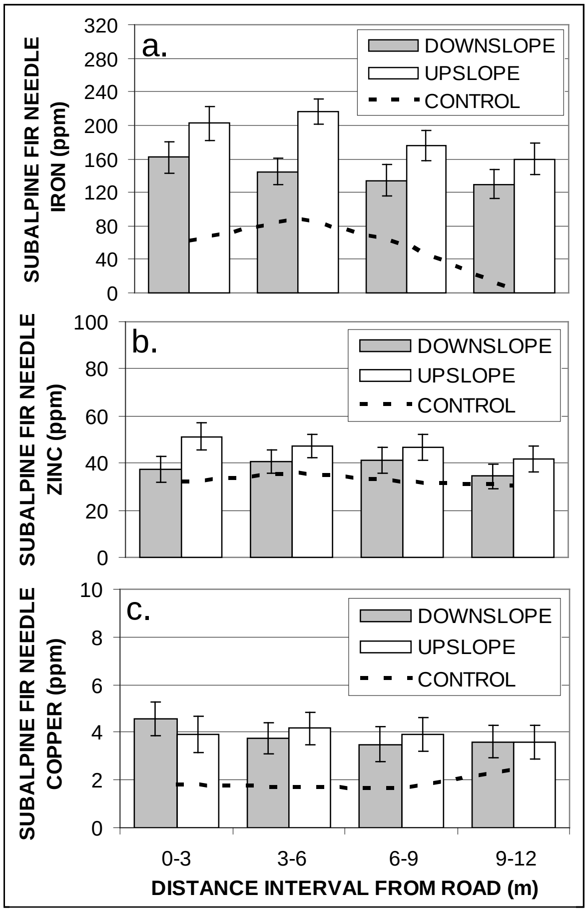


Figure C28. Subalpine fir needle sulfur adjusted mean (lsmean) concentrations, 207 total foliar samples collected, downslope plots: 21 to 34 samples collected per distance interval, upslope plots: 17 to 38 samples collected per interval along one treated road in Larimer County, Colorado. Dotted line indicative of background concentration (13 total foliar samples, *n* = 1 to 6 samples per distance interval). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).



Figures C29a-c. Adjusted mean needle (a) iron, (b) zinc and (c) copper in subalpine fir trees, 207 foliar samples collected, downslope plots: 21 to 34 samples per distance interval, upslope plots: n = 17 to 38 samples per interval along one treated road in Larimer County, Colorado. Dotted line indicative of control concentrations of each ion (13 foliar samples, n = 1 to 6 samples per distance interval). Least square means back transformed from $\log_{10}$ values, ± back transformed 1.4 standard errors (approximately ± ½ Fisher's Least Significant Difference).

Tables C1-C9

Table C1. Soil element concentrations and standard errors (SE) in drainage vegetation health plot soils along treated and control roads in Larimer and Grand Counties, Colorado, sampled in 2005 or 2006.

	MEAN CONCENTRATIONS[1] (ppm)									
	K	**Ca**	**P**	**Na**	**S**	**Zn**	**Fe**	**Cu**	**Mn**	**B**
control roads (n = 101)	116	1600	20.4	7.7	3.0	3.3	85.1	0.7	12.6	0.5
SE	14	223	4.4	3.9	2.6	3.6	15.0	0.2	5.3	0.2
treated roads (n = 300)	116	1500	22.7	15.1	11.6	5.1	75.9	0.9	23.7	1.2
SE	11	175	3.4	3.0	2.0	2.9	11.9	0.2	4.1	0.2
**p<0.0001, p<0.05[2]					*					*

1. Means combined for all distances, drainage impact classes, roads and plots for each road treatment (treated or control).
2. Significant difference between road treatments.

Table C2. Pearson correlation coefficients (r) between foliar and woody tissue elements and damage in 1) lodgepole pine (*n* = 612 foliar samples and *n* = 204 woody samples), 2) trembling aspen (479 foliar and 204 woody), 3) Engelmann spruce (102 foliar and 34 woody) and 4) subalpine fir (220 foliar and 113 woody) sampled along $MgCl_2$ treated and control roads in Larimer and Grand Counties, Colorado in 2004 and 2005.

	Pearson Correlation Coefficient (r)											
	lodgepole pine			**trembling aspen**			**Engelmann spruce**			**subalpine fir**		
FOLIAGE	**TOTAL DAMAGE (%crown)**	**TIP BURN (% crown)**		**TOTAL DAMAGE (% crown)**	**TIP BURN (% crown)**		**TOTAL DAMAGE (% crown)**	**TIP BURN (% crown)**		**TOTAL DAMAGE (% crown)**	**TIP BURN (% crown)**	
LEAF CHLORIDE	0.73	0.65	**	0.49	0.50	**	0.70	0.53	**	0.50	0.50	**
LEAF MAGNESIUM	0.52	0.39	**	0.51	0.52	**	0.42	0.38	**	0.48	0.43	**
LEAF CALCIUM	0.21	0.16	**	0.16	0.15	**	0.38	0.30	*	0.07	0.20	*
LEAF POTASSIUM	0.41	0.41	**	-0.03	-0.03	**	0.07	-0.01		-0.22	-0.16	*
LEAF PHOSPHORUS	0.42	0.33	**	-0.12	-0.10	**	0.04	-0.12		0.11	-0.05	
TOTAL NITROGEN (%)	0.38	0.37	**	0.38	0.37	**	0.47	0.14	**	0.25	0.23	*
LEAF SULFUR	0.41	0.33	**	0.18	0.12	*	0.40	0.15	**	0.19	0.06	
LEAF ZINC	0.02	0.01		0.12	0.17	*	0.28	0.20	*	-0.05	0.20	*
LEAF MANGANESE	0.12	0.16	*	0.27	0.30	**	0.46	0.26	*	0.30	0.33	**
LEAF BORON	0.66	0.72	**	0.53	0.58	**	0.66	0.57	**	0.47	0.61	**
LEAF COPPER	0.22	0.20	**	0.02	0.01		0.29	0.24	*	0.17	0.23	*
LEAF MOLYBDENUM	0.06	0.02		0.01	0.03		-0.01	-0.02		-0.02	-0.02	
LEAF SODIUM	0.05	-0.02		0.20	0.23	**	0.39	-0.05	**	0.09	-0.06	
WOODY TISSUE												
TWIG CHLORIDE	0.56	0.37	**	0.49	0.44	**	0.73	0.34	**	0.43	0.42	**
TWIG MAGNESIUM	0.27	0.09		0.45	0.45	**	0.11	0.01		0.24	0.20	*
TWIG CALCIUM	0.01	0.02		-0.09	-0.02		0.15	0.15		0.11	-0.11	
TWIG POTASSIUM	0.06	0.05		0.01	-0.06		-0.02	-0.02		0.09	0.11	
TWIG PHOSPHORUS	0.06	0.01		0.18	0.15	*	0.10	0.02		0.10	0.17	
TWIG SULFUR	0.39	0.22	*	0.34	0.28	**	0.25	0.24		0.23	0.10	
TWIG ZINC	0.00	-0.09		0.10	0.18		-0.03	0.13		-0.14	-0.15	
TWIG MANGANESE	-0.10	-0.02		0.13	0.17	*	0.53	0.10	*	0.33	0.44	*
TWIG BORON	0.05	0.09		0.38	0.41	**	0.50	0.32	*	0.22	0.21	*
TWIG COPPER	0.11	0.07		-0.07	-0.04		0.02	-0.03		0.35	0.24	*
TWIG MOLYBDENUM	-0.06	-0.08		-0.02	-0.01		-0.25	-0.17		-0.17	0.04	
TWIG SODIUM	0.00	-0.03		0.03	0.01		0.01	-0.07		-0.03	-0.12	

**p < 0.0001, *p < 0.05, significance of correlation for species to left

Table C3. Mean severity (mean percent of tree affected) or incidence (mean percent of all trees affected) and standard errors (SE) of common damage agents in roadside vegetation health plots in Larimer and Grand Counties, Colorado in 1) lodgepole pine plots: along treated (*n* = 2,169 trees) and control roads (*n* = 492 trees), 2) trembling aspen: along treated (*n* = 3,110 trees) and control roads (*n* = 521 trees), 3) Engelmann spruce and subalpine fir: along treated (*n* = 2,334 trees) and control (*n* = 593 trees) roads established and sampled in 2004 and 2005.

	Mean Damage Agent Severity or Incidence (%)														
	lodgepole pine					**trembling aspen**					**Engelmann spruce and subalpine fir**				
DAMAGE AGENT	**CONTROL ROADS**	**SE**	**TREATED ROADS**	**SE**		**CONTROL ROADS**	**SE**	**TREATE D ROADS**	**SE**		**CONTROL ROADS**	**SE**	**TREATED ROADS**	**SE**	
UNKNOWN	0.2	2.1	7.6	1.0	**	0.4	1.3	3.3	0.6	**	0.0	3.0	7.5	1.8	*
MECHANICAL DAMAGE	1.8	0.5	1.4	0.3		0.8	1.5	1.9	0.7		1.7	2.2	2.4	1.4	
STEM/BRANCH CANKERS AND ROOT ROT	4.6	1.1	3.2	0.6		22.8	3.1	7.0	1.4	**	4.1	4.4	2.4	2.8	
DEFOLIATING/SUCKING INSECTS	0.0	0.8	1.6	0.4		1.2	2.2	5.6	1.1		2.3	3.0	7.1	1.8	
ANIMAL DAMAGE	0.1	0.8	0.8	0.4		1.3	1.1	1.6	0.6		2.2	1.2	0.8	0.8	
ABIOTIC WEATHER DAMAGE	1.9	0.9	0.8	0.4		1.6	0.7	0.2	0.3		2.7	0.9	0.9	0.5	
FOLIAR DISEASES	5.3	1.0	0.4	0.5	**	0.1	3.2	5.0	1.4		9.9	2.4	0.2	1.7	*
STAND COMPETITION	0.6	1.0	1.8	0.6		0.6	0.3	0.2	0.1		0.3	3.3	4.0	1.8	
BARK/TWIG BEETLES (INCIDENCE)	2.2	1.8	3.6	1.0		0.0	0.4	0.4	0.2		0.5	2.3	1.9	1.5	
BORING INSECTS (INCIDENCE)	0.2	0.7	1.6	0.4		1.3	1.3	1.3	0.6		0.1	0.7	0.5	0.2	
DWARF MISTLETOE (INCIDENCE)	34.7	12.5	12.2	7.3		-	-	-	-		-	-	-	-	
BROOM RUST	-	-	-	-		-	-	-	-		0.4	0.4	0.5	0.2	

**p < 0.0001, *p < 0.05: significance between treated and control roads, corresponds to species at left

Table C4. Pearson correlation coefficients (r) between common biotic and abiotic damage agent severity (percent of tree affected) or incidence (percent of all trees affected) and crown damage in 1) lodgepole pine trees along treated (*n* = 2,169 trees) and control roads (*n* = 492 trees), 2) trembling aspen trees along treated (*n* = 3,110 trees) and control roads (*n* = 521 trees) and 3) Engelmann spruce and subalpine fir trees along treated (*n* = 2,334 trees) and control (*n* = 593 trees) roads in roadside vegetation health plots along $MgCl_2$ treated and control roads in Larimer and Grand Counties, Colorado in 2004 and 2005.

	Pearson Correlation Coefficients (r)								
	lodgepole pine			**trembling aspen**			**Engelmann spruce and subalpine fir**		
DAMAGE AGENT	**TOTAL DAMAGE (% CROWN)**	**TIP BURN (% CROWN)**		**TOTAL DAMAGE (% CROWN)**	**TIP BURN (% CROWN)**		**TOTAL DAMAGE (% CROWN)**	**TIP BURN (% CROWN)**	
UNKNOWN	0.55	0.52	**	0.49	0.51	**	0.49	0.14	**
MECHANICAL DAMAGE	0.09	0.05	*	0.07	0.03	*	0.06	0.03	
STEM/BRANCH CANKERS AND ROOT ROT	0.11	0.06	*	0.01	-0.01		0.12	-0.07	*
DEFOLIATING/SUCKING INSECTS	0.05	0.06	*	0.11	0.07	**	0.00	0.08	*
ANIMAL DAMAGE	0.02	0.02		0.04	0.02	*	0.08	0.07	*
ABIOTIC WEATHER DAMAGE	0.00	-0.01		-0.02	-0.02		-0.04	-0.03	
FOLIAR DISEASES	0.11	-0.03	*	0.04	0.06	*	0.05	-0.01	*
STAND COMPETITION	0.15	0.08	*	-0.01	-0.02		0.04	-0.13	
BARK/TWIG BEETLES (INCIDENCE)	0.16	0.02		0.01	0.00		0.18	-0.01	**
BORING INSECTS (INCIDENCE)	0.07	-0.02		0.00	-0.01		0.04	-0.01	**
DWARF MISTLETOE (INCIDENCE)	0.02	-0.04		-	-		-	-	
BROOM RUST	-	-		-	-		0.03	0.04	

**p < 0.0001, *p < 0.05, significance of correlation for species to left

Table C5. Mean major and minor foliar nutrient concentrations and SE in drainage vegetation health plots along treated and control roads in Larimer and Grand Counties, Colorado sampled in 2005 and 2006.

		MEAN ION CONCENTRATIONS[1] (ppm)									
		K	**Ca**	**P**	**S**	**N (%)**	**Zn**	**Mn**	**B**	**Cu**	**Fe**
lodgepole pine	control drainages (n = 82)	2420	3760	729	650	8380	48.2	431	5.3	2.9	113.4
	SE	473	463	80	47	504	4.5	142	7.1	0.4	17.9
	low impact drainages (n = 43)	4490	5200	1020	680	11000	45.1	946	57.6	3.4	76.5
	SE	594	591	98	59	604	5.8	179	9.4	0.6	23.0
	medium impact drainages (n = 73)	4250	4460	995	806	11300	51.4	630	45.0	4.6	113.7
	SE	497	503	81	49	518	4.9	158	7.9	0.5	19.5
	high impact drainages (n = 49)	3510	4680	893	816	9120	55.0	1000	46.6	2.9	142.4
	SE	573	663	91	58	575	6.6	216	11.7	0.7	26.1
	*p<0.05, **p<0.0001[2]	*		*	*	*		*	**		
trembling aspen	control drainages (n = 49)	15700	10700	2800	1820	26200	123.6	9	24.0	6.8	65.6
	SE	1940	1270	664	175	3530	21.5	99	16.4	1.2	26.6
	low impact drainages (n = 64)	14300	10300	2500	1940	26800	151.6	197	52.5	7.7	89.5
	SE	1730	1110	550	150	3000	18.1	80	14.3	1.0	22.8
	medium impact drainages (n = 50)	11200	11000	2390	1890	24300	120.4	318	83.4	7.8	146.2
	SE	1920	1260	561	173	3110	20.9	96	14.8	1.1	25.9
	high impact drainages (n = 21)	8480	9580	2130	1470	23000	96.0	487	39.6	5.4	154.4
	SE	2910	1960	616	269	3660	32.2	148	17.6	1.5	40.2
	*p<0.05, **p<0.0001[2]							*	*		
Engelmann spruce	control drainages (n = 25)	5400	12400	1260	561	8620	63.6	199	0.0	3.2	75.9
	SE	1010	2640	244	99	1490	12.2	346	5.9	0.6	56.0
	low impact drainages (n = 12)	4350	11400	786	576	8790	49.6	679	20.4	1.9	125.7
	SE	1280	3510	310	125	1900	13.3	396	7.3	0.7	75.6
	medium impact drainages (n = 7)	7298	11400	1949	852	13400	63.0	2810	41.3	5.8	133.5
	SE	1610	3650	392	159	2400	13.3	426	8.6	0.9	78.0
	*p<0.05, **p<0.0001[2]							*	*		
subalpine fir	control drainages (n = 28)	9814	4830	1260	644	9170	61.7	944	12.3	3.4	99.7
	SE	1637	431	120	76	1050	21.1	632	11.1	0.9	61.9
	low impact drainages (n = 43)	11817	4280	1200	812	12100	69.6	1943	33.0	3.3	201.4
	SE	1357	283	81	52	704	17.5	392	6.9	0.6	51.3
	medium impact drainages (n = 32)	13470	3840	1070	770	10900	63.7	1471	34.0	4.4	281.2
	SE	1219	272	82	54	711	15.8	379	6.8	0.6	46.6
	*p<0.05, **p<0.0001[2]										*

1. Means combined for all distances, drainage impact classes, roads and plots for each road treatment (treated or control).
2. Significant difference between road treatments.
NOTE: no Engelmann spruce or subalpine fir not sampled in any high impact drainage plots.

Table C6. Pearson correlation coefficients (r) between percent crown damage and percent tip burn, foliar ion concentrations and site factors in 1) lodgepole pine, 2) trembling aspen, 3) Engelmann spruce and 4) subalpine fir trees sampled in all drainage impact classes along treated and control roads in Larimer and Grand Counties, Colorado in 2005 or 2006 (*n* = 247 lodgepole pine foliar samples, *n* = 184 aspen foliar samples, *n* = 44 Engelmann spruce samples, *n* = 103 subalpine fir samples).

	Pearson Correlation Coefficient (r)											
	lodgepole pine			**trembling aspen**			**Engelmann spruce**			**subalpine fir**		
FOLIAR ELEMENT	**TOTAL DAMAGE (% crown)**	**TIP BURN (% crown)**		**TOTAL DAMAGE (% crown)**	**TIP BURN (% crown)**		**TOTAL DAMAGE (% crown)**	**TIP BURN (% crown)**		**TOTAL DAMAGE (% crown)**	**TIP BURN (% crown)**	
CHLORIDE	0.73	0.71	**	0.76	0.76	**	0.80	0.79	**	0.61	0.53	**
MAGNESIUM	0.59	0.59	**	0.62	0.61	**	0.56	0.58	**	0.56	0.46	**
CALCIUM	0.09	0.06		0.41	0.41	**	-0.06	-0.08		0.27	0.07	*
POTASSIUM	0.55	0.50	**	-0.29	-0.28	**	0.55	0.46	*	-0.18	0.01	
PHOSPHORUS	0.38	0.39	**	-0.41	-0.40	**	0.55	0.39	*	0.22	0.30	*
TOTAL NITROGEN (%)	0.45	0.46	**	-0.47	-0.47	**	0.70	0.63	**	0.25	0.31	*
SULFUR	0.39	0.38	**	-0.06	-0.06		0.70	0.61	**	0.35	0.24	*
ZINC	-0.04	0.05		-0.06	-0.06		0.04	0.04		0.32	0.22	*
MANGANESE	0.22	0.28	*	-0.06	0.21	*	0.22	0.25		0.10	0.37	*
BORON	0.64	0.71	**	0.53	0.52	**	0.65	0.70	**	0.40	0.50	**
COPPER	0.14	0.10		-0.41	-0.40	**	0.57	0.51	*	0.34	0.24	*
MOLYBDENUM	0.01	0.02		-0.13	-0.14		-0.13	-0.10		0.46	0.05	**
SODIUM	-0.03	-0.02		-0.04	-0.03		-0.03	-0.05		0.16	0.19	
SITE FACTOR VARIABLE												
MAX. SEDIMENTATION	0.15	0.13		0.40	0.39	**	0.29	0.27	*	0.41	0.16	**
AVG. SEDIMENTATION	0.12	0.12	*	0.33	0.33	**	0.33	0.31	*	0.41	0.11	**
DISTANCE	0.08	0.06		0.30	0.30	**	-0.04	-0.04		-0.09	-0.03	
SLOPE (%)	0.12	0.10		0.12	0.12		0.05	0.03		0.13	0.13	
DRAINAGE SURFACE AREA	0.02	0.06		0.41	0.40	**	0.17	0.28		0.30	-0.07	**

**p < 0.0001, *p < 0.05, significance of correlation for species to left

Table C7. Pearson correlation coefficients (r) between common biotic and abiotic damage agent severities (percent of tree affected) and incidences (percent of all trees affected) and damage to crown in 1) lodgepole pine trees (*n* = 449 trees along treated roads and 141 trees along control roads), 2) trembling aspen (*n* = 427 trees along treated roads and *n* = 45 trees along control roads), and 3) Engelmann spruce and subalpine fir (*n* = 285 trees along treated roads and *n* = 44 trees along control roads) in drainage vegetation health plots in Larimer and Grand Counties, Colorado in 2005 and 2006.

	Pearson Correlation Coefficients (r)								
	lodgepole pine			**trembling aspen**			**Engelmann spruce and subalpine fir**		
Damage Agent	**Total Damage (% of crown)**	**Tip Burn (% of crown)**		**Total Damage (% of crown)**	**Tip Burn (% of crown)**		**Total Damage (% of crown)**	**Tip Burn (% of crown)**	
UNKNOWN	0.63	0.47	**	0.86	0.86	**	0.42	0.25	**
DEFOLIATING/ SUCKING INSECTS	-0.03	-0.01		0.04	0.04		-0.03	0.08	
STEM/BRANCH/ ROOT CANKERS OR ROT	-0.02	-0.02		0.12	0.11	**	0.09	-0.01	*
FOLIAR DISEASE/ NEEDLECAST	0.04	0.03		-0.05	-0.08	*	0.08	0.23	**
WEATHER/ WINTER DAMAGE	0.02	-0.01		0.00	0.00		0.00	-0.04	
ANIMAL DAMAGE	0.00	-0.03		0.06	0.05	*	0.05	0.03	
MECHANICAL DAMAGE	0.07	0.02		0.02	0.03		0.24	0.06	
COMPETITION	0.04	0.01		0.06	0.07	*	0.09	0.20	*
BARK/TWIG BEETLES (incidence)	0.17	-0.09	**	0.06	-0.01		0.28	-0.04	**
BORING INSECTS (incidence)	0.08	-0.05		-0.01	-0.01		0.16	-0.01	**
DWARF MISTLETOE	-0.04	0.00		-	-		-	-	
BROOM RUST	-	-		-	-		0.02	0.05	*

**p < 0.0001, *p < 0.05: significance of correlation for species to left.

Table C8. Common woody shrub species percent cover and health in roadside vegetation health plots along non-paved roads both treated and non-treated with $MgCl_2$ dust suppression products in Larimer and Grand Counties, Colorado in 2004 and 2005. Distance estimates combine both slope positions and road treatments, slope position estimates combine all distances, and road treatment estimates combine distances and slope positions by road treatment.

Genus or species	DISTANCE FROM ROAD (m)	PERCENT COVER		HEALTH STATUS			SLOPE POSITION	HEALTH STATUS			ROAD TREATMENT	HEALTH STATUS		
		MEAN	**SE**	**MEAN**	**SE**			**MEAN**	**SE**			**MEAN**	**SE**	
Rosa species	3.0	6.4	4.09	1.3	0.09	**	UP	1.1	0.10		CONTROL	1.3	0.17	
	12.2	6.2	4.09	1.1	0.09		DOWN	1.3	0.10		TREATED	1.1	0.04	
Juniperus communis	3.0	10.3	1.81	1.2	0.10		UP	1.2	0.10		CONTROL	1.0	0.17	**
	12.2	11.5	1.76	1.2	0.10		DOWN	1.3	0.09		TREATED	1.4	0.07	
Arctostaphylos uva-ursi	3.0	12.0	3.02	1.2	0.09		UP	1.1	0.09	**	CONTROL	1.2	0.13	
	12.2	19.3	2.99	1.1	0.08		DOWN	1.3	0.09		TREATED	1.2	0.07	
Vaccinium species	3.0	21.9	6.93	1.1	0.06		UP	1.1	0.05		CONTROL	1.0	0.08	
	12.2	32.3	6.87	1.0	0.06		DOWN	1.0	0.06		TREATED	1.1	0.04	
Sheperdia canadensis	3.0	8.3	3.93	1.4	0.11	**	UP	1.2	0.12		CONTROL	-	-	
	12.2	9.7	3.81	1.1	0.11		DOWN	1.3	0.12		TREATED	1.3	0.08	
Artemisia tridentata	3.0	7.5	2.46	1.5	0.18		UP	1.2	0.18		CONTROL	-	-	
	12.2	5.3	2.81	1.4	0.21		DOWN	1.6	0.26		TREATED	1.4	0.16	

***$p < 0.0001$, **$p < 0.05$, *$p < 0.10$ denotes significance of health status in relationship to variable at left.

Table C9. Common grass, forb and sedge genera percent cover and health in roadside vegetation health plots along non-paved roads both treated and non-treated with $MgCl_2$ dust suppression products in Larimer and Grand Counties, Colorado in 2004 and 2005. Distance estimates combine both slope positions and road treatments, slope position estimates combine all distances, and road treatment estimates combine distances and slope positions by road treatment.

	DISTANCE FROM ROAD (m)	**PERCENT COVER**		**HEALTH STATUS**			**SLOPE POSITION**	**HEALTH STATUS**			**ROAD TREATMENT**	**HEALTH STATUS**		
Genera		**MEAN**	**SE**	**MEAN**	**SE**			**MEAN**	**SE**			MEAN	SE	
Poa	0.0	8.6	2.26	1.1	0.07	**								
	3.0	9.7	2.44	1.0	0.08		UP	1.03	0.1		CONTROL	1.0	0.12	
	6.1	7.2	2.55	1.0	0.08									
	12.2	10.0	2.64	1.0	0.08		DOWN	0.98	0.1		TREATED	1.1	0.05	
Carex	0.0	7.7	2.84	1.2	0.10									
	3.0	12.2	2.08	1.2	0.08		UP	1.13	0.1		CONTROL	1.3	0.15	
	6.1	11.4	2.04	1.2	0.08									
	12.2	11.0	1.97	1.1	0.08		DOWN	1.20	0.1		TREATED	1.1	0.05	
Bromus	0.0	24.2	4.18	1.7	0.17	**								
	3.0	13.2	5.87	1.3	0.17		UP	1.30	0.2		CONTROL	-	-	
	6.1	29.2	7.75	1.0	0.22									
	12.2	8.7	23.94	1.0	0.43		DOWN	1.05	0.2		TREATED	1.2	0.17	
Taraxacum	0.0	8.4	1.25	1.2	0.13									
	3.0	10.8	1.07	1.3	0.13		UP	1.29	0.2		CONTROL	-	-	
	6.1	7.7	1.15	1.1	0.13									
	12.2	7.5	1.42	1.1	0.15		DOWN	1.08	0.1		TREATED	1.2	0.11	
Achillea	0.0	6.2	2.02	1.2	0.13									
	3.0	4.7	1.86	1.1	0.12		UP	1.01	0.1		CONTROL	1.1	0.23	
	6.1	5.9	1.88	1.0	0.12									
	12.2	4.0	1.86	1.0	0.12		DOWN	1.09	0.1		TREATED	1.0	0.04	
Arnica	0.0	8.4	6.64	1.0	0.36	**								
	3.0	9.6	2.75	1.4	0.20		UP	1.19	0.2		CONTROL	1.0	0.36	
	6.1	6.9	2.78	1.1	0.20									
	12.2	4.8	2.73	1.1	0.20		DOWN	1.14	0.2		TREATED	1.5	0.17	

***$p < 0.0001$, **$p < 0.05$, *$p < 0.10$ denotes significance of health status in relationship to variable at left.

APPENDIX D. Location and stand characteristics of vegetation health plots in Grand and Larimer Counties, Colorado.

Table D1. Roadside vegetation health plots locations and stand characteristics.

County	Road	Name	Plot	Northing	Easting	Dominant Species	Elevation (m)	Slope
GRAND	6.000	Monarch Road	1.0	4442858	427547	PICO	2553	-17
GRAND	6.000	Monarch Road	3.0	4442585	428820	PICO	2560	16
GRAND	6.000	Monarch Road	4.0	4442740	429108	PICO	2553	-66
GRAND	6.000	Monarch Road	5.0	4441627	434847	PICO	2542	12
GRAND	30.000	Upper Williams	6.0	4413137	407229	PICO	2673	-8
GRAND	8.00	Frasier to Ranch	7.0	4422255	433873	PICO	2694	22
GRAND	8.00	Frasier to Ranch	8.0	4422740	432276	PICO	2682	-9
GRAND	4.000	stillwater	9.0	4453152	424144	PICO	2724	22
GRAND	4.000	stillwater	10.0	4452648	424494	PICO	2697	-23
GRAND	4.000	stillwater	11.0	4453035	454419	PICO	2696	-24
GRAND	4.000	stillwater	12.0	4451919	424601	PICO	2629	9
GRAND	8.00	Frasier to Ranch	13.0	4422730	432293	PICO	2691	5
GRAND	83.00	Devils Thumb Road	14.0	4426225	431531	PICO	2603	-9
GRAND	83.00	Devils Thumb Road	15.0	4424865	432601	PICO	2604	33
GRAND	1.000	Trough Road	16.0	4428088	374539	POTR	2504	-9
GRAND	55.000	Cottonwood Pass	18.0	4433916	412025	POTR	2739	-13
GRAND	1.000	Trough Road	19.0	4428138	374314	POTR	2485	15
GRAND	30.000	Upper Williams	20.0	4417488	406118	POTR	2569	-12
GRAND	30.000	Upper Williams	21.0	4417448	406110	POTR	2579	25
GRAND	6.000	Monarch Road	22.0	4444029	426680	PICO	2541	-23

Table D1 (cont). Roadside vegetation health plots locations and stand characteristics.

County	Road	Name	Plot	Northing	Easting	Dominant Species	Elevation (m)	Slope
LARIMER	162.234	Bellaire Lakes	1.0	4514240	448949	LODGEPOLE/ASPEN	2612	12
LARIMER	162.234	Bellaire Lakes	1.1	4514230	448958	LODGEPOLE	2613	14
LARIMER	162.234	Bellaire Lakes	2.0	4514246	448964	LODGEPOLE PINE	2618	-7
LARIMER	162.234	Bellaire Lakes	3.0	4511729	448141	LODGEPOLE PINE	2633	25
LARIMER	162.234	Bellaire Lakes	3.1	4512488	448302	LODGEPOLE PINE	2651	16
LARIMER	162.234	Bellaire Lakes	4.0	4511787	448172	LODGEPOLE PINE	2655	-11
LARIMER	162.234	Bellaire Lakes	5.0	4511230	448220	LODGEPOLE PINE	2673	9
LARIMER	162.234	Bellaire Lakes	6.0	4511117	448319	LODGEPOLE PINE	2686	-13
LARIMER	162.234	Bellaire Lakes	7.0	4510186	449251	ASPEN	2676	42
LARIMER	162.234	Bellaire Lakes	7.1	4509267	449307	ASPEN	2589	14
LARIMER	162.234	Bellaire Lakes	8.0	4510197	449260	ASPEN	2672	-32
LARIMER	162.234	Bellaire Lakes	8.1	4510631	448959	ASPEN	2708	-11
LARIMER	162.234	Bellaire Lakes	9.0	4310169	449253	LODGEPOLE PINE	2669	38
LARIMER	162.234	Bellaire Lakes	10.0	4510149	449288	LODGEPOLE PINE	2676	-14
LARIMER	103.000	Laramie River Road	11.0	4500119	427151	ENGELMANN SPRUCE & SUBALPINE FIR	2682	5
LARIMER	103.000	Laramie River Road	12.0	4500114	427158	ENGELMANN SPRUCE & SUBALPINE FIR	2682	-10
LARIMER	103.000	Laramie River Road	13.0	4501390	427226	ENGELMANN SPRUCE & SUBALPINE FIR	2691	4
LARIMER	103.000	Laramie River Road	14.0	4501436	427235	ENGELMANN SPRUCE & SUBALPINE FIR	2627	-35
LARIMER	103.000	Laramie River Road	15.0	4495323	428219	ENGELMANN SPRUCE & SUBALPINE FIR	2847	8
LARIMER	103.000	Laramie River Road	16.0	4500409	427098	ENGELMANN SPRUCE & SUBALPINE FIR	2670	-14
LARIMER	162.234	Bellaire Lakes	17.0	4513050	448486	ASPEN	2649	-9
LARIMER	162.234	Bellaire Lakes	18.0	4511576	448039	ASPEN	2656	8
LARIMER	37.023	Granite Mountain	19.0	4529844	476880	SHRUBS	2083	10
LARIMER	37.023	Granite Mountain	20.0	4530035	476853	SHRUBS	2099	-3
LARIMER	80.031	287 to county line (east)	21.0	4519983	487492	SHRUBS	1753	10
LARIMER	80.031	287 to county line (east)	22.0	4519885	487573	SHRUBS	1752	-8
LARIMER	37.023	Granite Mountain	25.0	4529432	476636	SHRUBS	2049	15
LARIMER	37.023	Granite Mountain	26.0	4529455	476669	SHRUBS	2048	-10
LARIMER	190.000	Stub Creek	28.0	4516657	425241	ASPEN	2535	-11
LARIMER	190.000	Stub Creek	29.0	4516663	425246	ASPEN	2531	17
LARIMER	162.000	Deadman	30.0	4517036	445141	LODGEPOLE PINE	2725	-15
LARIMER	162.000	Deadman	31.0	4517045	444991	LODGEPOLE PINE	2734	33
LARIMER	44.340	Pennock Pass	33.0	4490594	450442	LODGEPOLE PINE	2745	23
LARIMER	44.340	Pennock Pass	34.0	4491063	450376	LODGEPOLE PINE	2736	-18
LARIMER	139.000	Crown Point	35.0	4501629	448149	LODGEPOLE PINE	2746	16
LARIMER	139.000	Crown Point	36.0	4501098	447080	LODGEPOLE PINE	2847	-34
LARIMER	139.000	Crown Point	37.0	4501795	450882	ASPEN	2572	39
LARIMER	139.000	Crown Point	38.0	4501985	448749	ASPEN	2716	-45
LARIMER	139.000	Crown Point	39.0	4499962	440651	ENGELMANN SPRUCE & SUBALPINE FIR	3200	28
LARIMER	139.000	Crown Point	40.0	4499986	440787	ENGELMANN SPRUCE & SUBALPINE FIR	3211	-20

Table D2. Drainage vegetation health plots locations and stand characteristics.

COUNTY	ROAD	PLOT	NORTHING	EASTING	DOMINANT TREE	TOPOGRAPHY	ELEVATION (m)	SLOPE	LENGTH (m)
GRAND	6.00	D01	4442723	429089	LODGEPOLE	CC	2591	-37	24.4
GRAND	6.00	D02	4442739	431361	LODGEPOLE	UN	2558	-17	24.4
GRAND	6.00	D03	4442022	434037	LODGEPOLE	CC	2554	-6	36.6
GRAND	6.00	D04	4442045	434059	LODGEPOLE	UN	2542	-14	36.6
GRAND	6.00	D05	4442141	434166	LODGEPOLE	CC	2547	-39	18.3
GRAND	6.00	D06	4442631	428883	LODGEPOLE	CC	2556	-28	24.4
GRAND	50.00	D07	4428862	411455	LODGEPOLE	UN	2694	-31	12.2
GRAND	50.00	D08	4428754	411532	LODGEPOLE	UN	2705	-20	12.2
GRAND	85.00	D09	4429647	423649	ASPEN	CC	2779	-20	24.4
GRAND	30.00	D10	4410327	408965	LODGEPOLE	CC	2688	-3	30.5
GRAND	30.00	D11	4410218	408991	LODGEPOLE	UN	2691	-3	33.5
GRAND	30.00	D12	4409902	409079	LODGEPOLE	UN	2688	-4	42.7
GRAND	555.00	D13	4433660	411658	ASPEN	CC	2747	-36	12.2
GRAND	55.00	D14	4433890	412048	ASPEN	CC	2719	-14	42.7
GRAND	50.00	D15	4429334	411010	LODGEPOLE	CC	2675	-4	12.2
GRAND	50.00	D16	4428630	411645	ASPEN	CC	2721	-15	12.2
LARIMER	162.23	D01	4510174	449260	SUBALPINE FIR	CC	2675	-12	30.5
LARIMER	162.23	D02	4511105	448326	LODGEPOLE	UN	2666	-11	35.1
LARIMER	162.23	D03	4511630	448086	LODGEPOLE	CC	2649	-13	54.9
LARIMER	162.23	D04	4511292	448184	LODGEPOLE	CC	2672	-8	48.8
LARIMER	162.23	D05	4511685	448119	LODGEPOLE	CC	2655	-9	91.4
LARIMER	63.03	D07	4503753	458257	ASPEN	CC	2204	-17	12.2
LARIMER	63.029.1	D07.1	4503753	458257	ASPEN	CC	2204	-17	12.2
LARIMER	139.00	D08	4501875	448553	LODGEPOLE	UN	2716	-43	12.2
LARIMER	139.00	D09	4510868	448544	LODGEPOLE	LL	2717	-15	12.2
LARIMER	139.00	D10	4500549	447106	LODGEPOLE	CC	2934	-17	12.2
LARIMER	139.00	D11	4499830	440245	ENGELMANN SPRUCE	CC	3187	-23	12.2
LARIMER	162.23	D15	4513038	448480	ASPEN	CC	2632	-7	10.7
LARIMER	162.23	D16	-	449538	ASPEN	CC	2615	-18	22.9
LARIMER	139.00	D17	4499488	442786	SUBALPINE FIR	CC	3181	-25	12.2
LARIMER	103.00	D18	4513176	425432	LODGEPOLE	CC	2566	-30	42.7
LARIMER	103.00	D19	4500790	427106	SUBALPINE FIR	CC	2654	-11	24.4
LARIMER	103.00	D20	4501355	427242	SUBALPINE FIR	CC	2644	-19	18.3
LARIMER	103.00	D21	4504268	427762	LODGEPOLE	CC	2609	-6	30.5
LARIMER	103.00	D22	4501496	427239	ASPEN	CC	2666	-23	18.3
LARIMER	103.00	D23	4495641	428028	SPRUCE/FIR	CC	2834	-11	30.5
LARIMER	73.00	D24	4519260	446514	ASPEN	CC	2585	-5	36.6
LARIMER	162.23	D25	4512876	448373	ASPEN	CC	2640	-7	30.5
LARIMER	37.02	D26	4527352	477053	SHRUBS	cc	1983	-12	24.4
LARIMER	37.02	D27	4528098	-	SHRUBS	UN	2018	-4	24.4
LARIMER	37.02	D28	4533879	478881	SHRUBS	CC	2243	-8	48.8
LARIMER	80.06	D29	4520558	483081	SHRUBS	CC	1855	-5	48.8
LARIMER	163.00	D30	4513129	447690	ASPEN	CC	2663	-4	12.2
LARIMER	163.00	D31	4513149	447939	ASPEN	CC	2645	-6	12.2
LARIMER	162.23	D32	4510893	448685	LODGEPOLE	CC	2704	-5	24.4
LARIMER	162.23	D33	4511552	448039	LODGEPOLE	CC	2670	-2	24.4

Table D2 (cont). Drainage vegetation health plots locations and stand characteristics.

COUNTY	ROAD	PLOT	NORTHING	EASTING	DOMINANT TREE	TOPOGRAPHY	ELEVATION (m)	SLOPE	LENGTH (m)
LARIMER	162.23	D34	4510716	448830	LODGEPOLE	CC	2664	-1	18.3
LARIMER	162.00	D35	4517104	444804	LODGEPOLE	CC	2742	-19	12.2
LARIMER	162.00	D36	4517048	445050	ASPEN	CC	2734	-11	12.2
LARIMER	162.23	D37	4511950	448183	LODGEPOLE	CC	2633	-4	67.1
LARIMER	63.03	D38	4491060	451958	LODGEPOLE	CC	2728	-11	12.2
LARIMER	63.03	D39	4491035	452180	LODGEPOLE	CC	2712	-22	24.4
LARIMER	63.03	D40	4491036	452046	ASPEN	CC	2720	-29	12.2
LARIMER	44.34	D41	4492315	454465	LODGEPOLE	CC	2611	-6	12.2
LARIMER	63.03	D42	4491040	451972	ASPEN	CC	2720	-8	12.2
LARIMER	63.03	D43	4490812	452369	LODGEPOLE	CC	2680	-11	12.2
LARIMER	103.00	D44	4495548	428086	SPRUCE/FIR	CC	2843	-9	24.4
LARIMER	103.00	D45	4495771	428063	SPRUCE/FIR	CC	2861	-16	27.4
LARIMER	103.00	D46	4497814	427652	ASPEN	CC	2724	-8	24.4
LARIMER	103.00	D47	4496810	427414	SPRUCE/FIR	CC	2810	-8	21.3
LARIMER	103.00	D48	4496705	427406	SPRUCE/FIR	CC	2819	-8	45.7
LARIMER	162.00	D49	4520333	427922	SPRUCE/FIR	CC	2980	-7	12.2
LARIMER	162.00	D50	4519521	429180	SPRUCE/FIR	CC	3133	-22	12.2
LARIMER	103.00	D51	4496706	427431	ENGELMANN SPRUCE	CC	2897	-7	18.3
LARIMER	80.00	D52	4258215	431169	ASPEN	CC	2684	-2	12.2
LARIMER	162.00	D53	4517498	434590	SPRUCE/FIR	CC	3145	-9	12.2
LARIMER	162.00	D54	4517553	435053	SPRUCE/FIR	CC	3120	-4	12.2
LARIMER	103.00	D55	4495386	428189	SPRUCE/FIR	CC	2825	-6	18.3
LARIMER	162.00	D56	4516925	436313	SPRUCE/FIR	CC	3031	-4	12.2
LARIMER	162.23	D57	4513977	448966	ASPEN	CC	2609	-8	48.8
LARIMER	162.23	D58	4509335	449425	ASPEN	CC	2641	-11	36.6
LARIMER	162.23	D59	4512878	448403	ASPEN	CC	2655	-4	24.4
LARIMER	162.23	D60	4511044	448372	ASPEN	CC	2691	-8	24.4
LARIMER	162.23	D61	4510383	449275	ASPEN	CC	2690	-22	97.5
LARIMER	162.23	D62	4511334	447953	ASPEN	CC	2661	-7	36.6
LARIMER	73.00	D63	4518126	448451	ASPEN	UN	2614	-6	42.7
LARIMER	80.44	D64	4521414	471850	SHRUBS	CC	1942	-6	30.5
LARIMER	80.44	D65	4521044	473087	SHRUBS	CC	1989	-12	48.8
LARIMER	80.44	D66	4520251	473862	SHRUBS	CC	1951	-18	79.2

Appendix E: Study road and $MgCl_2$ application information

Table E1. County road $MgCl_2$ application rates through 2004.

				$MgCl_2$ SOLUTION APPLIED THROUGH 2004		$MgCl_2$ SOLUTION APPLIED THROUGH 2004		ANHYDROUS $MgCl_2$ WEIGHT APPLIED THROUGH 2004		ANHYDROUS $MgCl_2$ WEIGHT APPLIED THROUGH 2004	
COUNTY	ROAD NO.	ROAD NAME	FIRST TRT YEAR	TOTAL APPL.(gal mi^{-1})	AVERAGE APPL. (gal $mile^{-1} yr^{-1}$)	TOTAL APP. (gal sq.yd^{-1})	AVERAGE APPL. (gal·sq $yd^{-1}yr^{-1}$)	TOTAL APPL. (lbs mi^{-1})	AVERAGE APPL. (lbs $mi^{-1}yr^{-1}$)	TOTAL APPL. (kg km^{-1})	AVERAGE APPL. (kg $km^{-1}yr^{-1}$)
Larimer	190	Stub Creek	1996	2402	267	0.16	0.02	7388	821	2082	231
Larimer	103	Laramie River	1995	20668	2067	1.35	0.14	63574	6357	17918	1792
Larimer	73C	Creedmore Lk	1993	60441	5037	3.96	0.33	185918	15493	52401	4367
Larimer	162.234	Bellaire Lakes	1994	53029	4821	3.48	0.32	163116	14829	45974	4179
Larimer	80.435	Cherokee Park	2001	76765	19191	5.03	1.26	236129	59032	66553	16638
Larimer	37.023	Red Granite Mt.	2001	62840	15710	4.12	1.03	193295	48324	54480	13620
Larimer	80.062		1995	31941	3194	2.09	0.21	98250	9825	27692	2769
Larimer	80.030		1997	62284	7786	4.08	0.51	191586	23948	53998	6750
Larimer	89	80C to WY line	-	0	0	0	0	0	0	0	0
Larimer	163	Bellaire Lk CG	2004	10008	10008	0.66	0.66	30785	30785	8677	8677
Larimer	63.029	Pingree Park	2006	0	0	0	0	0	0	0	0
Larimer	44.340	Pennock Pass	-	0	0	0	0	0	0	0	0
Larimer	162D	Deadman	-	0	0	0	0	0	0	0	0
Larimer	139	Crown Point	-	0	0	0	0	0	0	0	0
Grand	1	Trough	1993	74489	6207	4.88	0.41	229128	19094	64579	5382
Grand	6	Monarch	1985	82362	4118	5.40	0.27	253344	12667	71405	3570
Grand	83	Devils Thumb	1992	58399	4492	3.83	0.29	179636	13818	50630	3895
Grand	55	Cottonwood Pass	1997	29327	3666	1.92	0.24	90211	11276	25426	3178
Grand	30	Upper Williams	1998	42694	6099	2.80	0.40	131326	18761	37014	5288
Grand	3	Williams Fork	1995	68129	6813	4.47	0.45	209564	20956	59065	5907
Grand	85	Lions Lane	1996	65137	7237	4.27	0.47	200360	22262	56471	6275
Grand	4	Idle Glen Road	2002	8000	2667	0.52	0.17	24608	8203	6936	2312
Grand	41	Stillwater	1997	31880	3985	2.09	0.26	98063	12258	27639	3455
Grand	8	Frasier to Ranch	1989	43604	2725	2.86	0.18	134125	8383	37803	2363
Grand	555.000	FS Rd 253	-	0	0	0	0	0	0	0	0
Grand	50.000	Beaver Creek	-	0	0	0	0	0	0	0	0

Table E2. County road $MgCl_2$ application rates through 2005.

			$MgCl_2$ SOLUTION APPLIED THROUGH 2005		$MgCl_2$ SOLUTION APPLIED THROUGH 2005		ANHYDROUS $MgCl_2$ WEIGHT APPLIED THROUGH 2005		ANHYDROUS $MgCl_2$ WEIGHT APPLIED THROUGH 2005	
ROAD NO.	ROAD NAME	FIRST TRT YEAR	TOTAL APPL.(gal mi^{-1})	AVERAGE APPL. (gal $mile^{-1}$ yr^{-1})	TOTAL APP. (gal sq.yd^{-1})	AVERAGE APPL. (gal·sq $yd^{-1}yr^{-1}$)	TOTAL APPL. (lbs mi^{-1})	AVERAGE APPL. (lbs $mi^{-1}yr^{-1}$)	TOTAL APPL. (kg km^{-1})	AVERAGE APPL. (kg $km^{-1}yr^{-1}$)
190	Stub Creek	1996	2816	282	0.18	0.02	8661	866	2441	244
103	Laramie River	1995	23154	2105	1.52	0.14	71221	6475	20074	1825
73C	Creedmore Lk	1993	71285	5483	4.67	0.36	219272	16867	61802	4754
162.234	Bellaire Lakes	1994	59860	4988	3.92	0.33	184129	15344	51897	4325
80.435	Cherokee Park	2001	89709	17942	5.88	1.18	275945	55189	77775	15555
37.023	Red Granite Mt.	2001	72616	14523	4.76	0.95	223365	44673	62955	12591
80.062		1995	37912	3447	2.49	0.23	116616	10601	32868	2988
80.030		1997	66276	7364	4.34	0.48	203864	22652	57459	6384
89	80C to WY line	-	0	0	0	0	0	0	0	0
163	Bellaire Lk CG	2004	10008	5004	0.66	0.33	30785	15392	8677	4338
63.029	Pingree Park	2006	0	0	0	0	0	0	0	0
44.340	Pennock Pass	-	0	0	0	0	0	0	0	0
162D	Deadman	-	0	0	0	0	0	0	0	0
139	Crown Point	-	0	0	0	0	0	0	0	0
1	Trough	1993	81389	6261	5.34	0.41	250352	19258	70562	5428
6	Monarch	1985	87612	4172	5.74	0.27	269493	12833	75956	3617
83	Devils Thumb	1992	61899	4421	4.06	0.29	190402	13600	53665	3833
55	Cottonwood Pass	1997	33358	3706	2.19	0.24	102608	11401	28920	3213
30	Upper Williams	1998	49566	6196	3.25	0.41	152466	19058	42972	5372
3	Williams Fork	1995	75129	6830	4.93	0.45	231096	21009	65134	5921
85	Lions Lane	1996	68637	6864	4.50	0.45	211126	21113	59506	5951
4	Idle Glen Road	2002	10667	2667	0.70	0.17	32811	8203	9248	2312
41	Stillwater	1997	35380	3931	2.32	0.26	108829	12092	30673	3408
8	Frasier to Ranch	1989	43604	2565	2.86	0.17	134125	7890	37803	2224
555.000	FS Rd 253	-	0	0	0	0	0	0	0	0
50.000	Beaver Creek	-	0	0	0	0	0	0	0	0

APPENDIX F. Ponderosa pine foliar sampling along three Larimer County roads in Summer 2007

Introduction

Ponderosa pine (*Pinus ponderosa*) trees with needle tip burn and defoliation were noted along several Larimer County non-paved roads treated with $MgCl_2$-based dust suppression products in 2007. Ponderosa pine occurred frequently along non-paved roads in Larimer County, but was not selected as a focus species in roadside vegetation health plots (Section 2) because of the tendency for ponderosa pines to grow as scattered individuals in roadside environments. The plot design used for other species was not sufficient to sample enough ponderosa pine trees from roadside habitats so this species was not used.

Objectives

In order to determine if the observed damage on ponderosa pines along county roads was related to $MgCl_2$ dust suppression application, a different survey and sampling of ponderosa pine health and foliar chloride content along three county roads was completed in June 2007.

Methods

Thirty-five roadside ponderosa pine trees were sampled along three county roads (Table F1). The survey began at a major intersection of each road, and all roadside ponderosa pines within 12 m up or downslope from the road were included in this study until 12 study trees were sampled. Two year-old needles were collected from at least two branches from the lower to mid-crown of all study trees and were washed with distilled water, dried, processed (ground) and analyzed for chemical content in the same way as foliar samples in Section 2. Total percent crown (percent of tree with live or dead foliage), mean incidence (of crown) and mean severity (of needles) of damage were recorded for each tree. Incidence refers to the percent of the tree crown (total foliage) with damage symptoms. Severity refers to the average percent of needle surface area with damage symptoms.

Results

Foliar chloride and damage severity in ponderosa pines

Ponderosa pines adjacent to the road had more foliar chloride (12,000 ppm) than trees further away from the road (1,000 ppm) (Figures F1a). More chloride occurred in trees downslope from the road through 9 m from the road. Trees in the 9 to 12 m distance interval had typical background concentrations of foliar chloride (Figure F1a). Foliar magnesium was also higher in trees closest to the road compared to trees in the 9 to 12 m interval (Figure F1b).

Ponderosa pines along the sampled county roads ranged in incidence and severity of foliar damage, exhibited as a tip necrosis of needles. Trees with more of the crown with damage had higher incidence ratings and needles with more necrotic surface area had higher severity ratings. Figures F2a-b illustrate needle severity ratings of sampled ponderosa pines on a scale from 0 to 100% of the needle surface area affected. High chloride concentrations in ponderosa pine foliage were positively related to the severity of damage on ponderosa pines along the three study roads (R^2 = 0.84) (Figure F2a) and not as well correlated with magnesium concentrations (R^2 = 0.66) (Figure F2b).

Testing the $MgCl_2$ application rate / foliar chloride model on sampled ponderosa pines

In Section 2 of this report, we found positive relationships between lodgepole pine and aspen foliar chloride and the average rate of $MgCl_2$ applied per year ($kg \cdot km^{-1} \cdot yr^{-1}$). However, both species only occurred along non-paved county roads treated with up to 6,000 $kg \cdot km^{-1} \cdot yr^{-1}$ while the county roads ponderosa pines were sampled along had much higher application rates (Table F1). In order to determine if relationships between foliar chloride and $MgCl_2$ application rates were applicable along roads treated with higher rates of $MgCl_2$, we extended the model through the average application rate of 16,000 $kg \cdot km^{-1} \cdot yr^{-1}$ and compared the study road mean of ponderosa pine foliage at 0 to 3 m downslope from the road to lodgepole pine study road means at 0 to 3m from the road (Figure F3). The study road means of ponderosa pine foliar chloride fell fairly close to the prediction model line (Figure F3); thus, the model estimations are still valid when predicting foliar chloride close to the road through 16,000 kg $MgCl_2 \cdot km^{-1} \cdot year^{-1}$.

Appendix F (cont.) Figures and Tables

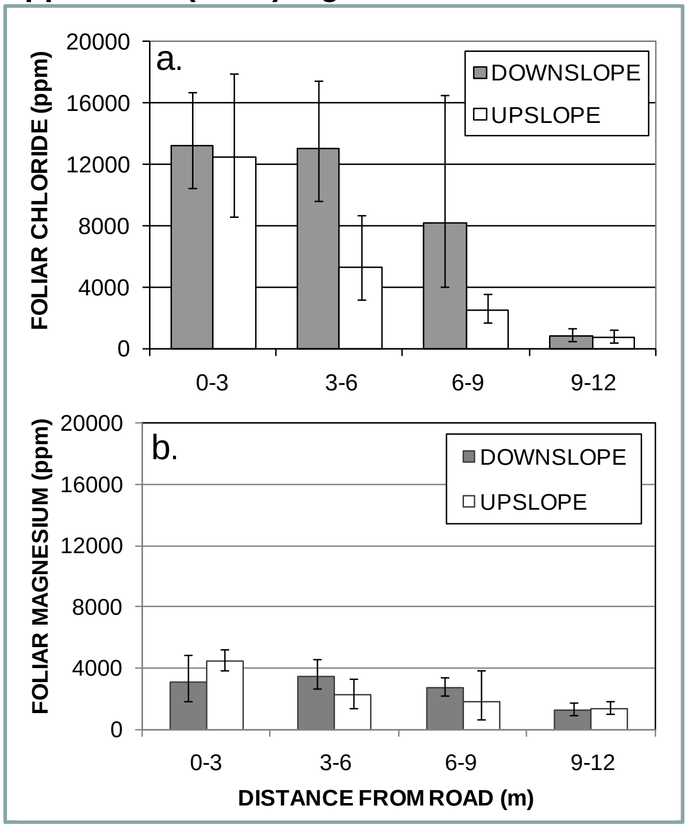


Figure F1a-b. Ponderosa pine foliar chloride adjusted means upslope and downslope from three non-paved roads treated with $MgCl_2$ dust suppression products in Larimer County, Colorado (*n* = 35 trees).

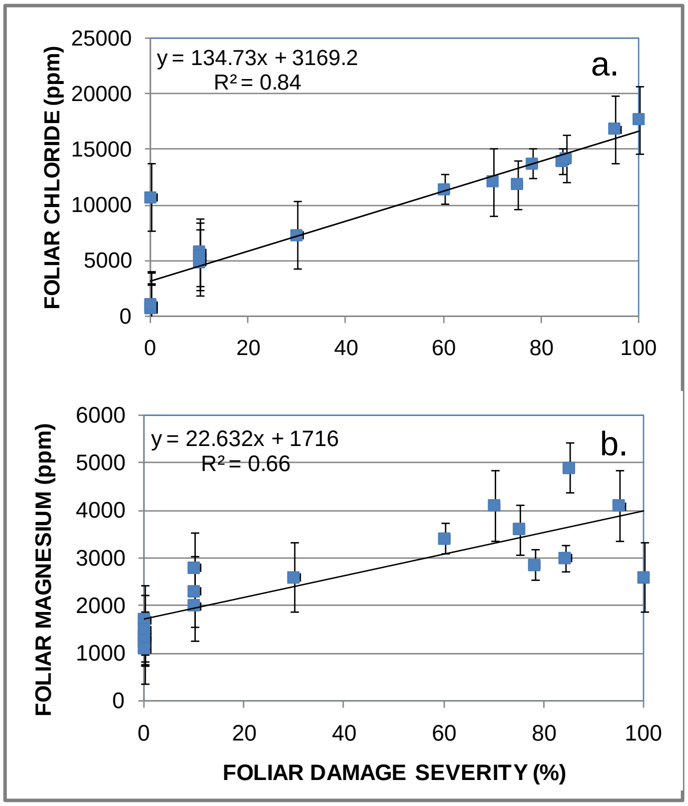


Figure F2a-b. Relationships between (a) foliar chloride and damage severity and (b) foliar magnesium and damage severity in roadside ponderosa pine trees along three $MgCl_2$ treated roads in Larimer County, Colorado (*n* = 35).

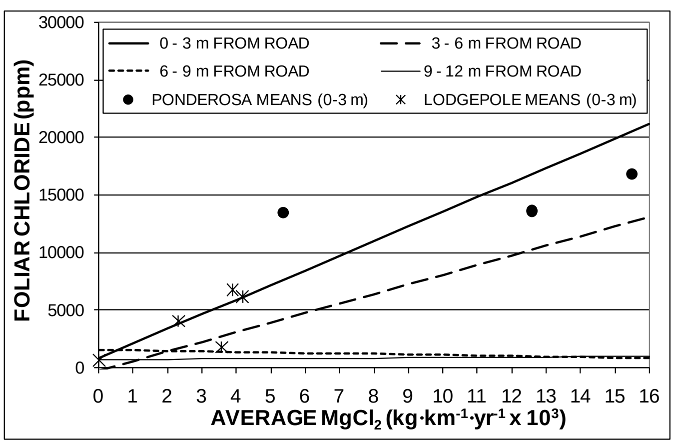


Figure F3. Lodgepole pine foliar chloride increase with average $MgCl_2$ application rate, modeled from data collected along study roads ranging from 0 to 6,000 kg·km^{-1}·yr^{-1} in Larimer and Grand Counties, Colorado in 2004 and 2005 field study (*n* = 615 foliar lodgepole foliar samples) using the Solution Function (The Mixed Procedure, SAS 2001). Model "extended" to 16,000 kg $MgCl_2$·km^{-1}·yr^{-1}. Study road lodgepole and ponderosa pine foliar chloride lsmeans (0 to 3 m downslope from the road [n = 5 roads for lodgepole pine and 3 roads for ponderosa pines]) included to test field measurements with model extension.

Table F1. Ponderosa pine sampling study roads, mileage and study trees per road.

County Roads		**Number of Trees**	**Average $MgCl_2$ Application Rate ($kg \cdot km^{-1} \cdot yr^{-1}$)**
CR 37.023	Red Mountain Granite Canyon Road	12	12,600
CR 68C	Boy Scout Road	12	5,370
CR 80	Cherokee Park Road	11	15,555

Section 3. Monitoring surface water chemistry near magnesium chloride dust suppressant treated roads in Colorado

Abstract

Magnesium chloride-based dust suppression products are commonly used throughout western United States on non-paved roads for dust suppression and road stabilization by federal, state and county transportation agencies. The environmental implications of annually applying these products throughout spring and summer months on adjacent stream chemistry are not known. Sixteen streams were monitored bi-weekly for one to two years in two Colorado counties for a suite of water quality variables up and downstream of non-paved roads treated with $MgCl_2$-based dust suppression products. Nine of sixteen streams had significantly higher downstream than upstream concentrations of chloride or magnesium over the entire monitoring period ($p \leq 0.10$). Mean downstream chloride concentrations ranged from 0.17 to 36.2 mg/L and magnesium concentrations ranged from 1.06 to 12.8 mg/L. Several other ions and compounds, including those commonly found in dust suppression products such as sodium, calcium and sulfate, were also significantly higher downstream at some sites. Downstream electrical conductivity, chloride and magnesium concentrations were positively correlated with road surface area draining water towards the stream and yearly amount of $MgCl_2$ applied (R^2 = 0.75, 0.51 and 0.49, respectively), indicating that road managers can limit the amount of product entering roadside streams by assessing drainage characteristics and application rates in best management practices. Although $MgCl_2$-based dust suppressants did move into some roadside streams, the concentrations detected were below those reported to adversely affect fresh water aquatic organisms, but the ultimate fate of these ions in Colorado waterbodies are not known.

3.1. Study objectives

The effects of summer applied chloride-based dust suppression and road stabilization products on surface water chloride concentrations are not currently known. This study was initiated to determine if $MgCl_2$-based dust suppressant products affected the chemistry of surface waters adjacent to treated non-paved roads in two Colorado counties.

3.2. Methods and Materials

Study sites. Stream sampling sites were established in May and June 2004 with seven and nine sites at 2,200 to 2,730 m elevation in Grand and Larimer Counties, Colorado, respectively (see study map). Streams were selected if they crossed under, or were adjacent to, a non-paved road treated with $MgCl_2$-based dust suppressant and there were roadside ditches that discharged road surface water directly into or to within 10 m of the stream. We hypothesized that the surrounding area and road topography would influence $MgCl_2$ runoff into the streams directly from the road and roadside ditches, so the amount of surface area that potentially diverted water into a stream (surface area index) was measured (Figure 3.1). The surface area of all road sections, the length and slope of all roadside ditches, and the area of all embankments (surface area directly off the road shoulder) that would divert road water run-off towards the stream were combined to calculate the surface area index (Figure 3.1). If a roadside ditch discharged onto the embankment before the stream, the ditch length was reduced by the distance from the stream. Surface area index values lack units as they combine percentage, length and surface area values (Appendix G: Table G1). The average monthly precipitation at each site was obtained for 1971 to 2000 from spatially gridded 800 m data (PRISM) (PRISM 2006) and seasonal precipitation was totaled for the months streams were sampled: May through October (Appendix G: Table G1).

Average anhydrous $MgCl_2$ application amounts ($kg \cdot km^{-1} \cdot yr^{-1}$) for each road were calculated from dust suppression application records ($gal \cdot mi^{-1}$ of $MgCl_2$ solution applied), using 369 g anhydrous $MgCl_2$ per liter of dust suppression solution applied as the active ingredient weight/solution ratio (personal communication Dale L. Miller, Larimer County Road and Bridge Department, Fort Collins, Colorado and Alan Green, Grand County Department of Road and Bridge, Granby, Colorado, 2006) (Appendix G: Table G1). Various formulations of dust suppressants have been applied to some roads, specifically 1:1 mixtures of $MgCl_2$ and lignin sulfonate products (see Section 2, Table 2.1). The volume of lignin was not including in application rate calculations. Dust suppression products are initially applied to non-paved roads after snow melts in the spring and are typically applied only 1 to 3 times per road each season (Appendix G: Table G1). Stream sampling was conducted every other week at each site, with no previous knowledge of the timing or frequency of $MgCl_2$ application on non-paved roads adjacent to each stream sampling site. Both $MgCl_2$ and lignin based products were sampled directly from application trucks or tanks and analyzed for chemical content (see Section 2, Table 2.1).

Bi-Weekly stream water sampling. Two permanently marked water sampling locations were established at each stream, one 20 to 50 m upstream and another 20 to 50 m downstream from the road. Upstream collection locations were above any possible area where road drainage water could enter the stream, except for 2 sites as noted in the discussion (Figure 3.1). Downstream collection locations were below the output of all ditches, embankments, and road sections that could divert water towards the stream (Figure 3.1). Both sides of the stream were marked with wooden stakes and measurements of stream width, average depth and velocity were collected twice in May and twice in October to quantify the range of stream characteristics in the spring, when water sampling began, to fall, when water sampling was ending (Appendix G: Table G1). Stream width was measured from edge to edge of the current water channel, and two to eight depth measurements were averaged across each cross section depending on stream width. Velocity was determined using a hand-held flow probe equipped with a water velocity meter (Global Water Instrumentation, Inc., Gold River, CA.), averaged across the width of each stream, measured at approximately half the vertical distance between the stream bottom and surface of the stream. Velocity measurements were taken at each point until three consistent readings were obtained in a row. Two measurements each in May and October of stream area (m^2 = depth x width) and velocity (ft/sec converted to m/sec) were averaged to obtain average spring and fall stream flow (m^3/sec) (Appendix G: Table G1). Water samples were collected upstream and downstream at each stream site once every two weeks from May 12 to October 16, 2004 in Grand County (n = 4 to 11 per site) and from May 7 to October 8, 2004, and May 18 to November 2, 2005 in Larimer County (n = 22 per site). Water was collected in 125-mL Nalgene® containers that were triple-rinsed with stream water just before collections.

Chemical analyses. Each stream water sample and three replicates of both dust suppression products were analyzed for: alkalinity ($CaCO_3$), ammonia (NH_3), boron (B^-), calcium (Ca^{+2}), iron (Fe^{+2}), magnesium (Mg^{+2}), manganese (Mn^+), nitrate (NO_3^-), phosphorus (P), potassium (K^+), sodium (Na^+), sulfate (SO_4^{-2}), bicarbonate (HCO_3^-), carbonate (CO_3^{-2}), electrical conductivity (EC), pH and chloride (Cl^-). Alkalinity was determined via acid titration. Boron, calcium, iron, magnesium, manganese, phosphorus, potassium, sodium, and sulfate concentrations were determined using Inductively Coupled Plasma (ICP) spectrometry. Nitrate was determined using the cadmium reduction colorimetric method (USEPA 1984). An acid titration method was used to determine bicarbonates and carbonates. Electrical conductivity was determined using a Duraprobe Model 152A (Thermo Scientific, Waltham, Massachusetts). Chloride was determined using the cadmium reduction colorimetric method. All methods were approved based on the Association of Official Agricultural Chemists (AOAC 1995, Kevin Klink, personal communication, AgSource Harris Laboratories, Lincoln, NE., 2007). Quality control measures for AgSource Harris Laboratories are defined and measured with a Standard Operating Procedure and are available online (http://ag.agsource.com/lab_accuracy/quality_control.asp). For additional QA/QC purposes, duplicate water samples were sent in for one stream sample and all major ions were within < 1.0 ppm of the duplicate.

Statistical Analyses. The GLIMMIX Procedure, which fits generalized linear mixed models, was used to fit fixed and random effects in statistical analyses (Version 9.1 of the SAS® System for UNIX [SAS Institute Inc., Cary, North Carolina]). Fixed effects included stream site (each stream site was treated as a group of samples so variance was pooled over sites [$n = 4$ to 22 collections per site]) and position from road (upstream or downstream). Random effects in the model were date of sample collection and the date by site interactions. This model compared upstream and downstream ion concentrations (in milligrams/liter [mg/L]) for each stream site averaged over all sampling dates using $p \leq 0.10$ as statistical significance. Ion concentrations were logarithmically transformed to equalize variability in the data and back-transformed to present means in a biologically relevant manner. Pearson Correlation Coefficients (r) were used to compare simple linear regressions of site parameters with mean downslope ion concentrations. An analysis of covariance (ANCOVA) model was used in the Regression Procedure to determine if the upstream concentration, surface area index, total precipitation, average rate of $MgCl_2$ application, and month of collection could explain mean downstream EC and concentrations of chloride and magnesium by using the coefficient of determination (R^2) for each model.

3.3. Results

Water chemistry. Mean upstream concentrations of chloride ranged from 0.15 to 31.5 mg/L while downstream concentrations ranged from 0.17 to 36.2 mg/L over all 16 streams monitored in both counties (Table 3.2). Upstream concentrations of magnesium ranged from 1.15 to 12.8 mg/L and downstream concentrations were 1.06 to 12.8 mg/L. Over all sampling dates, significantly higher downstream concentrations of chloride ($p \leq 0.10$) occurred in 7 out of 16 streams and higher downstream magnesium occurred in 8 out of 16 streams (Table 2). Electrical conductivity (EC) was higher downstream from the road in 5 of 16 streams and ranged from 0.04 to 0.84 dS/m in downstream samples (Table 3.2). Stream flow was variable across the 16 stream sites, ranged from 0.0003 to 0.38 m^3/sec, and was higher at all sites in May compared to October, with the exception of 2 sites in Grand County (Appendix G: Table G1).

In Grand County, no significant differences occurred between upstream and downstream measurements of ammonia, copper, iron, manganese, nitrate, pH, or zinc. At a few Grand County sites significant differences occurred between upstream and downstream water samples for alkalinity, aluminum, boron, calcium, potassium, sulfate, and sodium (Appendix G: Tables G2 and G3). Several streams in Grand County (Sites 3, 4, 6 and 7) had high concentrations of sodium, sulfate and alkalinity in both up and downstream samples (Appendix G: Tables G3 and G3). Significant differences between up and downstream measurements of alkalinity, aluminum, boron, calcium, pH, potassium, sodium, and sulfate occurred at some sites in Larimer County (Appendix G: Tables G2 and G3).

Relationships between site factors and downstream EC, chloride and magnesium. After accounting for ion concentrations in upstream waters, the site factors measured at each stream site explained the variability of downstream EC, chloride and magnesium concentrations fairly well (R^2 = 0.49 to 0.75) (Table 3.3). The $MgCl_2$ application rate, surface area index, precipitation and month of water collection were all significant factors in ANCOVA models to predict downstream ion concentrations with the upstream equivalent used as a covariate (Table 3.3).

As the average $MgCl_2$ application rate increased along study roads, downstream EC, chloride and magnesium concentrations increased (Table 3.3). The average $MgCl_2$ application rate on study roads ranged from 1,790 to 5,910 kg $MgCl_2$ per km per year and mean average application rate was 4,280 $kg{\cdot}km^{-1}{\cdot}yr^{-1}$ (SD = 982 $kg{\cdot}km^{-1}yr^{-1}$) . When compared using simple linear correlations, average $MgCl_2$ application rate was positively correlated with downstream chloride ($r = 0.42$, $p < 0.001$) and magnesium ($r = 0.41$, $p < 0.001$) concentrations (Table 3.4).

In addition to $MgCl_2$ application rate, increases in downstream values of all variables were significantly related to increases in the surface area draining water into each stream site (Table 3.3). Surface area indices (no units) ranged from 18,600 to 634,000 across stream sampling sites and were as dramatically different in the field as these numbers indicate (Appendix G, Table G1, Figure 3.1). In simple linear regression, surface area index alone was positively related to chloride concentrations ($r = 0.45$, $p < 0.0001$) and had significant but weaker correlations with all other values (Table 3.4).

Based on PRISM data (PRISM 2006), total May through October 30-year average precipitation ranged from 19.8 to 27.2 cm at stream sampling sites over both study counties, with an average of 23.0 and 26.2 cm for Grand and Larimer Counties, respectively (Appendix G: Table G1). Precipitation was significantly negatively correlated with EC ($r = -0.58$, $p < 0.0001$)), but not with chloride or magnesium concentrations ($r = 0.06$ and 0.04, not significant) (Table 3.4). The thirty-year average precipitation was also significant variable in modeling EC and Mg^{+2} concentrations with ANCOVA models (Table 3.3).

The month stream water was collected (May through October) was a significant variable in all models (Table 3.3). The highest EC, chloride and magnesium concentrations were measured in October and were lower in spring months (negative coefficients for May and June in these models) (Table 3.3). In simple linear regressions, an increase in stream flow decreased all concentrations data while increasing the total load of chloride and magnesium (Table 3.4).

3.4. Discussion

Ion concentrations in roadside streams and relevance to other Colorado waterbodies. We did not find a consistent regional stream water response associated with the application of $MgCl_2$-based dust suppression products to non-paved roads throughout northern Colorado. However, $MgCl_2$ products did move into some streams and the ions occurred in measurable concentrations in flowing streams throughout spring, summer and fall. Chloride concentrations measured in northern Colorado streams (0.15 to 36.2 mg/L) were similar to those in the Roaring Fork (1.0 to 43.0 mg/L) and the Big Thompson (0.16 to 22.0 mg/L) rivers in Colorado, both in drainages where deicing chloride compounds are used on adjacent paved roads (Fischel 2001, Jassby and Goldman 2003). Concentrations were at the low end of the range measured in Turkey Creek, CO (5.41 to 390 mg/L), where chloride inputs had presumably occurred from deicing compounds (Bossong et al. 2003). Magnesium concentrations in northern Colorado streams (1.06 to 12.8 mg/L) were also on the low end of the 1.83 to 70.9 mg/L range measured in Turkey Creek (Bossong et al. 2003) and similar to those measured in the Guanella Pass, CO. watershed (Stevens 2001) (Table 3.1). Compared to surface water concentrations of streams impacted by winter deicing practices, concentrations measured in northern Colorado streams adjacent to non-paved roads are low (Environment Canada 2001, Kaushal et al. 2005) (Table 3.1). Chloride concentrations have been measured above 1,000 mg/L during winter months in watersheds impacted by chloride salts used for snow and ice control (Environment Canada 2001, Kaushal et al. 2005), and the effects of NaCl deicing agents can also persist past winter months. Ponds within 60 m of secondary roads or highways have been measured with over 500 mg/L chloride in spring and over 400 mg/L in late summer months (Collins and Russell 2009). In contrast, other studies have shown that although high sodium and chloride concentrations can be measured downstream from NaCl treated roads in winter months, this may not translate into increased concentrations during summer months (Hoffman et al. 1981, Environment Canada 2001).

Other sources and elements of surface water concentrations. In our modeling efforts we assumed that any increases in ion concentrations from upstream to downstream surface waters would be an effect of the $MgCl_2$ treated road that separated them, hence the reason for sampling upstream as a control for the downstream section for each stream site. We assumed that dust movement off roads that may contain $MgCl_2$ was negligible since we did not measure significantly higher soil concentrations of these ions upslope from roads past the road shoulders in previous sampling (Goodrich et al. 2009). Background, or natural, concentrations of chloride in surface water are generally low (Jassby and Goldman 2003, Godwin et al. 2003, Panno et al. 2006, Collins and Russell 2009), and high upstream concentrations at three of our stream sites indicate chloride was introduced into the surface water above the adjacent study road. Other human inputs besides road treatment products can be measurable in adjacent roadside water bodies and include agricultural chemicals, effluent from septic systems, animal waste, and municipal landfills (Panno et al. 2006). Grand County Site 7 was located approximately 1 km downstream of a large mine spoils pile that might have caused relatively high upstream and downstream concentrations of several ions, including chloride (6.14 and 10.8 mg/L, respectively). This site also had higher up and downstream sulfate (30.8 to 35.7 mg/L), sodium (9.33 to 12.7 mg/L), and alkalinity (48.7 to 70.6 mg/L $CaCO_3$) than any stream sites in either county (Appendix G: Tables G2 and G3). Grand County Site 6 also had high concentration of sodium and sulfate in the upstream surface waters, which may have been due to extensive cattle grazing in the area (i.e. Panno et al. 2006). Larimer County Site 6, which had a mean upstream chloride concentration of 9.66 mg/L, had approximately 1 km of non-paved road area draining into the stream above the upstream collection site as the stream ran parallel with the road. Larimer County Site 7, with an upstream mean chloride concentration of 31.5 mg/L, was further downstream from Site 2, which had 24.5 mg/L chloride downstream from the road. Grand County Site 3 had higher than average concentrations of magnesium (both 12.8 mg/L) both up and downstream from the road, of which we do not know the source. The remaining 12 sites did not have additional chloride or magnesium inputs into the upstream sampling sites and represent background concentrations of chloride (0.15 to 2.83 mg/L) and magnesium (1.15 to 4.62 mg/L) in these areas of Colorado.

Larimer County Sites 2 to 4 had higher calcium, sodium, and sulfate concentrations downstream compared to upstream waters (Appendix G: Tables G2 and G3). These chemicals occur in small quantities in $MgCl_2$-based dust suppression products (see Section 2: Table 2.1) and were higher in streams where magnesium and chloride inputs were detectable (Appendix G: Tables G2 and G3). Boron, which occurs naturally in the brine of salt lakes and oceans where $MgCl_2$ is extracted, was not detected above 0.40 mg/L in stream water. These small chemical inputs, in addition to increased magnesium and chloride, did not have a major effect on water characteristics such as pH or alkalinity. pH was significantly different between up and downstream samples in three Larimer County streams but differed by less than 0.10, and the mean pH ranged from 7.47 to 8.44 for all streams (Appendix G: Table G3). Alkalinity was higher downstream, when compared to upstream, in several Larimer County streams affected by $MgCl_2$ inputs, but significantly lower in downstream samples from several Grand County streams (Appendix G: Table G3). Aside from these noted changes, $MgCl_2$ inputs did not drastically alter water chemistry in northern Colorado streams.

Ion concentrations relevant to aquatic life. Chloride concentration estimates of acute and chronic lethality of aquatic organisms are not always consistent between reports, but are generally fairly high. Predictive lethality models estimate 5 to 10% changes in aquatic organisms approximately at the EPA SMCL of 250 mg/L chloride (Environment Canada 2001). The ranges of short term LC_{50}, summarized by Environment Canada for the Canadian Environmental Protection Act) included 6,060 to 30,300 mg/L chloride for fish and benthic organism in less than 24 hours; 4,990 to 8,550 mg/L chloride for 24 hour tests, 1,400 to 13,100 mg/L chloride for 3 to 4 day tests; and 874 to 3,660 mg/L for 7 to 10 day tests (Evans and Frick 2001, Environment Canada 2001). In a 1988 EPA assessment of various chloride salt toxicities, raw acute (24 to 96 hours) LC_{50} or EC_{50} values ranged from 86.0 mg/L chloride for the most sensitive genus, *Daphnia* spp. to 13,100 mg/L chloride for *Anguilla rostrata* (America eel) (USEPA 1998). Mean concentrations of chloride and magnesium ions found in surface water samples in northern Colorado streams over the summers of 2004 and 2005 are well below the ranges considered to be deleterious to aquatic life, based on previous research and standards set by Environment Canada (2001) and USEPA (1988), but there is limited research on acute, chronic or seasonal impacts of chloride-based salts on population levels or mortality thresholds of aquatic life in Rocky Mountain watersheds.

Ion concentrations relevant to road and stream site factors. We assumed that the water quality of roadside streams adjacent to $MgCl_2$ treated roads would be related to several interacting factors. The amount of $MgCl_2$ that moves off treated roads and into roadside streams should be a function of the annual or total $MgCl_2$ application rates, composition and type of roadside or streambank soils, the type, intensity and amount of precipitation and the drainage of the road system (Addo et al. 2004). Stream characteristics, such as depth, width and stream flow will also influence the measurable amount of these ions in moving water, as the slower the water moves the higher the ion concentrations will occur. Out of these factors, we chose to measure several that our ANCOVA models illustrate do interact with one another and influence downstream chloride and magnesium concentrations in roadside streams (Table 3.3). Delineating easily measurable site factors at streams adjacent to or crossing under treated roads can help road managers focus on areas with a high risk of $MgCl_2$ inputs. These high risk streams can be monitored for environmental impacts or transportation officials can utilize better management practices to reduce runoff from roads at those road sections with the application of these regression equations (Table 3.3). Equations can be used to calculate how much surface area, $MgCl_2$ application rate, and month of sampling will affect downstream concentrations by inputing some background concentration (0.15 to 2.73 mg/L for chloride and 1.15 to 4.62 mg/L for magnesium) for the upstream coefficient. Our ANCOVA model illustrates that increased annual $MgCl_2$ application rate along non-paved roads will increase the downstream concentration of both chloride and magnesium in roadside streams. In addition, the higher surface area a stream site was associated with (longer or steeper ditches channeling water towards the stream or more road surface area angled towards the stream) the more chloride and magnesium was measured downstream. We speculate that these factors need to occur together for $MgCl_2$ ions to move into roadside streams and the effects of runoff may be limited by reducing $MgCl_2$ application in areas with a high surface index. By measuring these site factors, road managers can, with some confidence (R^2 = 0.49 to 0.75), determine if a stream adjacent to a treated road will increase in EC, chloride or magnesium concentrations when $MgCl_2$ is applied.

Thirty-year average precipitation data from PRISM models were a significant variable in most ANCOVA models, but is not the most accurate measurement of how precipitation may affect $MgCl_2$ movement into streams. Precipitation can cause runoff from fairly impenetrable surfaces such as paved or well stabilized non-paved roads and move into roadside environments (Mason et al. 1999, Addo et al. 2004). Using daily site specific precipitation data and sampling streams during or directly after rainfall would be useful in determining if ions move into streams and peak during or directly after precipitation events, neither of which were measured in this study. The twice-monthly sampling design for each stream in this study was meant to measure the mean concentrations over a 6 month period each year, and do not necessarily indicate the maximum fluxes that may occur in downstream areas. We speculate that during precipitation events, streams with higher surface area indices (i.e. longer, steeper ditches or more road surface angled towards the downstream site) would have greater road water runoff moving more chloride and magnesium ions into the stream; however more water in the stream (higher stream flow) from upstream precipitation and snowmelt may dilute the ions, making concentrations lower. Based on our monthly sampling data, it is clear that chloride concentrations are lower in spring months and higher in the fall in most streams sampled (Appendix G: Table G4), while stream flow is lowest in fall months (Appendix G: Table G1). Generally, higher precipitation (PRISM 2006) and more snowmelt occur during spring months and increased stream flow. While consistent amounts of $MgCl_2$ ions may be moving off treated roads throughout the 6 month sampling period, the lower concentrations measured during the spring months were most likely due to higher rates of stream flow (Appendix G: Tables G1 and G4). Using machines to monitor hourly or daily measurements of EC, chloride, magnesium and precipitation at each stream site throughout the 6 month period could have helped better explain the daily and seasonal changes in $MgCl_2$ movement into roadside streams, but were not feasible in this study. Knowing this information may be critical, as the total ion loads, or yields (e.g. mg chloride/sec, kg chloride/day), increase with higher stream flow, and ions may be carried downstream to standing lakes or ponds and intensify - affecting both water quality and aquatic life (Environment Canada 2001, Collins and Russell 2009). The ultimate fate of $MgCl_2$ ions in northern Colorado waterbodies was not determined in this study.

The exact physical processes of ion movement from $MgCl_2$ treated roads was not quantified in this study, although through personal observation we speculate that during large precipitation events the majority of ions are washed from the crown of the upper road surface towards the road edges and into roadside ditches, where they are carried downslope with water towards roadside culvert or stream systems. The physical and chemical properties of magnesium and chloride ions most likely affect the amount that are washed from the road base and enter streams below treated roads. Chloride ions do not readily precipitate and move fairly easily through soil solutions, while magnesium may remain in the soil matrix as it interacts and potentially exchanges with other cations on exchange complexes (Mason 1999, White and Broadley 2001). These different properties may affect the percentage of ions which leave the road base where they are applied and also move through roadside soils and ditches to reach surface waters. Chloride, in general, was in higher concentrations than magnesium in downstream surface waters (Table 3.2) but does not occur in higher amounts in natural systems (White and Broadley 2001). There are also twice the amount chloride ions as there are magnesium ions in the application solution, and more chloride is introduced to the environment with $MgCl_2$-based dust suppressant application relative to magnesium (see Section 2: Table 2.1). Other factors, including unaccounted variations in $MgCl_2$ application rates from one section of road to another, pulses of rain, and the ability of chloride and magnesium ions to move vertically and horizontally in different soil types, may help to explain some of the unexplained variation in our prediction models.

3.5. Conclusions

Chloride and magnesium ions from $MgCl_2$-based dust suppression products did move into several streams passing under or adjacent to treated non-paved roads, but downstream concentrations were not dramatically different than those measured upstream. We did not find a strong water quality response to the application of $MgCl_2$-based dust suppression products to adjacent non-paved roads throughout two northern Colorado counties. The input from $MgCl_2$ ions did not alter many other elements in or characteristics of surface waters to a significant degree, although several additional ions and compounds found in $MgCl_2$-based dust suppression products were measured in downstream surface waters affected by road runoff. Surface area potentially draining water into the stream, average yearly amount of $MgCl_2$ applied, month of sampling, and total May through October total precipitation can partially explain the variation in EC, chloride and magnesium concentrations found downstream of treated roads. The mean concentrations of chloride and magnesium ions found in stream water samples collected over the six-month periods in 2004 and 2005 are well below the ranges considered to be deleterious to aquatic life based on previous research and standards set by Environment Canada (2001) and USEPA (1988), although the lack of continuous water quality monitoring in this study may not accurately represent the pulses of maximum concentrations which could occur during, or directly following, precipitation events.

3.6. Section 3 Figures and Tables

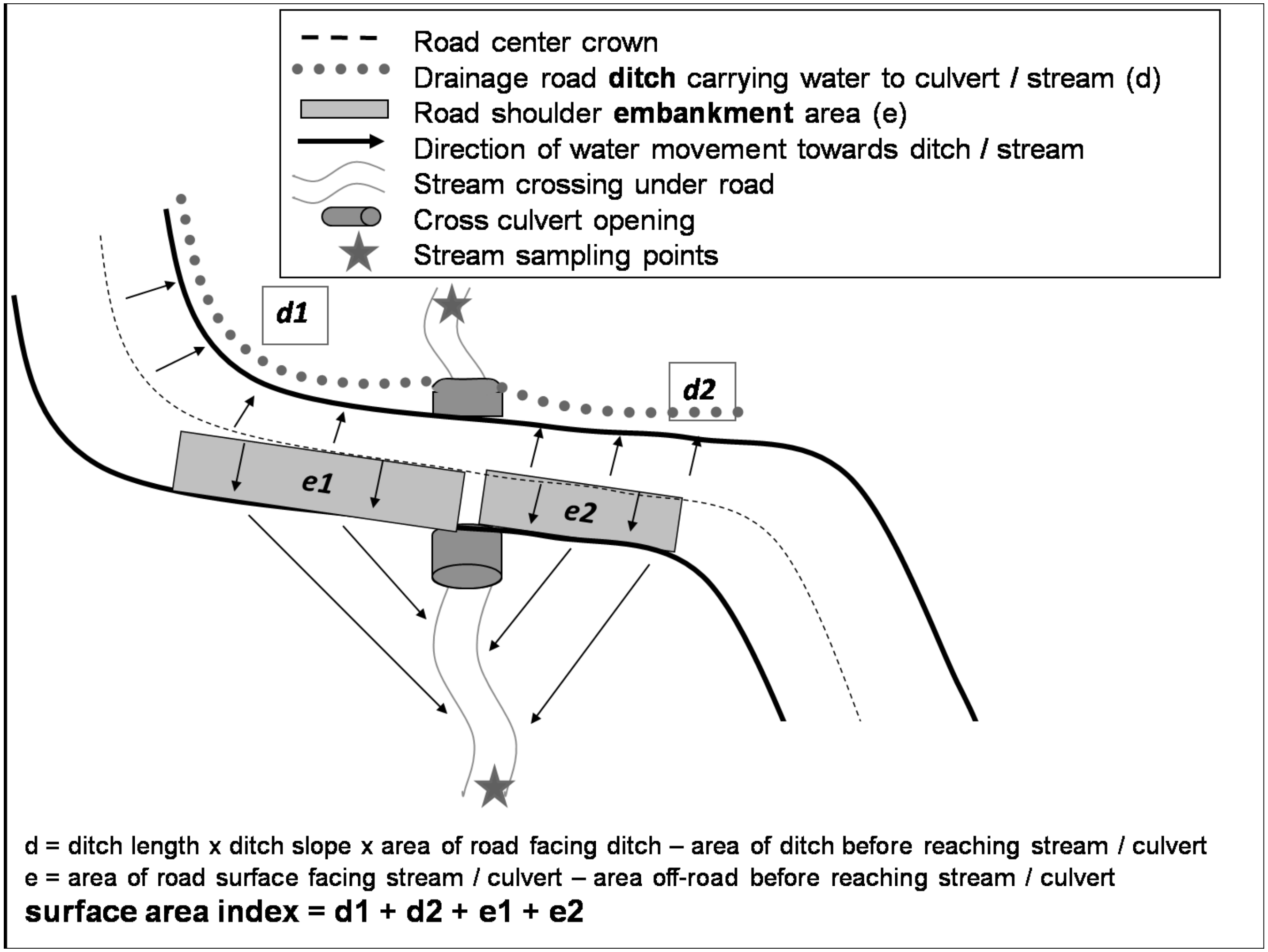


Figure 3.1 Measurements and equations used to calculate surface area index values for use in statistical models to predict downstream electrical conductivity (EC), chloride and magnesium concentrations of 16 stream sampling sites in Larimer and Grand Counties, Colorado sampled for surface water chemistry up and downstream of $MgCl_2$ treated roads in 2004 and 2005.

Table 3.1. Background (natural inputs) and elevated (human activity inputs) chloride and magnesium concentrations in Colorado watersheds and select watersheds from other parts of North America

		Chloride concentrations (mg/L)		Magnesium concentrations (mg/L)		
Watershed	**Area/State**	**Background**	**Elevated**	**Background**	**Elevated**	**Source**
High elevation lakes and streams	CO	0 – 2.0	-	-	-	Musselmann et al. 1996
Guanella Pass	Clear Creek County, CO	< 1.0	0.10 – 36.0	-	0.6 – 12.0	Stevens 2001
Snake River	Summit County, CO	< 5.0	-	-	-	Lewis 2001
Roaring Fork	Pitkin and Garfield Counties, CO	-	1.0 – 43.0	-	-	Fischel 2001
Upper Big Thompson	Larimer County, CO	-	1.6 – 22.0	-	0.01 - 3.2	Jassby and Goldman 2003
Coal Creek	Gunnison County, CO	0 - 2.7	-	0.9 - 4.8	-	Coal Creek Watershed Coalition 2007
Turkey Creek	Jefferson County, CO	-	5.4 - 390.0	-	1.8 to 70.9	Bossong et al. 2003
Turkey Creek[1]	Jefferson County, CO	9.3 (1970)	78.9 (1999)	-	-	Bossong et al. 2003
various watersheds	eastern Canada	0.3 - 4.5	189 – 4,300	-	-	Environment Canada 2001
various watersheds in rural and urban areas	Baltimore, MD	3.0 - 8.0	24.0 - 4,630	-	-	Kaushal et al. 2005

1. Water sampling conducted in 1970 and repeated in 1999.

Table 3.2. Mean chloride and magnesium concentrations (mg/L) and electrical conductivity (EC, dS/m) from 16 streams adjacent to $MgCl_2$-treated non-paved roads in Grand (2004) and Larimer (2004 and 2005) Counties, Colorado

County	Site	Upstream chloride (mg/L)	Downstream chloride (mg/L)	Pr > |t|[1]	Upstream magnesium (mg/L)	Downstream magnesium (mg/L)	Pr > |t|[1]	Mean Upstream EC (dS/m)	Mean Downstream EC (dS/m)	Pr > |t|[1]	*n*[2]
Grand	1	0.85	0.66	0.544	[e]**1.38**	**1.06**	**0.006**	0.05	0.04	0.932	11
Grand	2	0.87	1.30	0.293	**2.07**	**2.50**	**0.023**	0.21	0.24	0.334	9
Grand	3	2.63	2.90	0.815	12.83	12.83	1.000	0.42	0.42	0.999	4
Grand	4	2.01	2.63	0.305	**4.62**	**5.23**	**0.051**	0.33	0.37	0.150	11
Grand	5	0.15	0.35	0.368	1.86	1.86	0.963	0.08	0.08	0.996	12
Grand	6	2.83	3.11	0.713	1.50	1.50	1.000	0.84	0.84	0.861	10
Grand	7	**6.14**	**10.80**	**0.006**	**4.00**	**5.76**	**<.0001**	0.26	0.26	0.863	11
Larimer	1	2.06	2.07	0.984	2.42	2.24	0.512	0.07	0.07	1.000	22
Larimer	2	**0.89**	**24.47**	**<.0001**	**2.77**	**5.72**	**<.0001**	**0.09**	**0.19**	**<.0001**	22
Larimer	3	**0.51**	**10.09**	**<.0001**	**2.38**	**4.63**	**<.0001**	**0.08**	**0.15**	**<.0001**	23
Larimer	4	**2.37**	**19.81**	**<.0001**	**2.64**	**8.02**	**<.0001**	**0.09**	**0.24**	**<.0001**	22
Larimer	5	**1.06**	**3.89**	**<.0001**	**2.46**	**3.04**	**0.064**	**0.08**	**0.11**	**0.044**	22
Larimer	6	**9.66**	**13.79**	**0.016**	**4.15**	**5.03**	**0.063**	**0.17**	**0.21**	**0.073**	22
Larimer	7	31.52	36.24	0.317	6.92	7.98	0.133	0.22	0.25	0.224	22
Larimer	8	**2.34**	**3.67**	**0.014**	2.21	2.57	0.211	0.07	0.09	0.304	22
Larimer	9	0.30	0.17	0.460	1.15	1.19	0.825	0.04	0.04	0.977	22

1. Pr < |t| = differences significant between upstream and downstream means at $p \leq 0.10$ appear in **BOLD** text.
2. *n* = number of collection days at each site

NOTE: Concentrations shown are back-transformed $\log_{10}$ mean concentration data. Concentrations were averaged over all months.

Table 3.3. Best regression equations (highest R^2) for downstream electrical conductivity, chloride and magnesium concentrations values using upstream values and site variables as covariates in Grand and Larimer Counties, Colorado, 2004 and 2005 (*n* = 15 streams[1], 504 observations)

							Month[5]					
Downstream Variable (Log_{10})	**R^2**	**Intercept**	**Log_{10} Upstream Variable**	**Log_{10} Surface Area**[2]	**$MgCl_2$ Application Rate**[3]	**Precipitation**[4]	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**
Electrical conductivity (mmhos/cm)	0.75	0.4179	0.6977	0.0454	2.61×10^{-5}	-0.0389	-0.0993	-0.1353	-0.0699	*-0.0427*	*-0.0297*	0
Chloride concentration (mg/L)	0.51	-1.8634	0.5658	0.4722	12.59×10^{-5}	*-0.0295(N.S.)*	*-0.1249*	-0.3246	-0.0620	*-0.1640*	*-0.1507*	0
Magnesium concentration (mg/L)	0.49	-0.0044	0.5831	0.1031	4.40×10^{-5}	-0.0178	-0.1117	-0.1661	-0.0833	*-0.0433*	*-0.0552*	0

1. *n* = 15 stream sites used to calculate regression equations. County 1: Site 3 dropped due to disrupted sampling at stream mid-season.
2. Surface area = measured for each stream site through road width, drainage length and slopes, and embankment width and lengths (Figure 3.1).
3. $MgCl_2$ application rate = $kg \cdot km^{-1}\ year^{-1}$ based on 3.076 pounds of anhydrous $MgCl_2$ in every gallon of $MgCl_2$ / water solution applied.
4. Precipitation = 30-year total precipitation during stream sampling (May through October, in cm) (Table 1).
5. Month = month when stream was sampled for water.

Log_{10}Downstream Variable = $\beta_{\alpha} + \beta_{upstream}$($Log_{10}$Upstream Variable) + $\beta_{surface}$(Log_{10}Surface Area) + $\beta_{application}$(Average $MgCl_2$ Application) + β_{precip}(Seasonal Precipitation) + β_{month}

NOTE: all parameters except months are significant covariate effects (using Type III SS) at $p < 0.05$ unless denoted not significant by *N.S.*

NOTE: monthly *italic* numbers indicate value is not significantly different from the baseline October [zero] when used in the equation.

Table 3.4. Pearson correlation coefficients for stream water electrical conductivity, chloride and magnesium concentrations versus site variables in Grand And Larimer Counties, Colorado, 2004and 2005 (n = 15 streams[1], 521 observations).

Downstream Variable	**Upstream Equivalent Variable**[2]	**Stream Flow**[3]	**Surface Area**[4]	**$MgCl_2$ Application Rate**[5]	**Precipitation**[6]
EC	0.82	-0.12	0.09	0.18	-0.58
Chloride concentration	0.64	-0.21	0.45	0.42	*0.06 (N.S.)*
Magnesium concentration	0.65	-0.16	0.39	0.41	*0.04 (N.S.)*

1. n = 15 stream sites used to calculate regression equations. County 1: Site 3 dropped due to disrupted sampling at stream mid-season.
2. All downstream variables significantly correlated to upstream equivalent variable at $p < 0.0001$.
3. Stream flow (ft^3/sec) = stream velocity (ft/sec) x stream area (ft^2). All downstream variables significantly correlated to stream flow at $p < 0.05$.
4. Surface area = measured for each stream site through road width, drainage length and slopes, and embankment width and lengths. All downstream variables significantly correlated to surface area at $p < 0.05$.
5. $MgCl_2$ application rate = $kg \cdot km^{-1}$ $year^{-1}$ based on 3.076 pounds of anhydrous $MgCl_2$ in every gallon of $MgCl_2$ / water solution applied. All downstream variables significantly correlated to average application rate at $p < 0.001$.
6. Precipitation = 30-year average total precipitation during stream sampling (May through October, in cm). All downstream variables significantly correlated to seasonal precipitation at $p < 0.05$ except Cl^- and Mg^{+2} concentrations (p =0.19 and p = 0.32, respectively).

3.7. Section 3 Appendices

Appendix G. Supplemental site factor and surface water chemistry results.

Table G1. Stream sites and $MgCl_2$ application history for 16 stream sites adjacent to non-paved roads treated with $MgCl_2$-based dust suppression products in Grand and Larimer Counties, Colorado.

County	Site Number	Road Number	Stream Name	Elevation (m)	Average May Stream Width[1] (m)	Average October Stream Width[1] (m)	Average May Stream Depth[1] (cm)	Average October Stream Depth[1] (cm)	Average May Stream flow[1] (m^3/sec)	Avgerage October Stream flow[1] (m^3/sec)	Surface Area Index Value	Average Annual Precipitation[2] (cm)	Average May – October Precipitation[2] (cm)	Avg $MgCl_2$ Application[3] ($kg \cdot km^{-1} yr^{-1}$ $MgCl_2$)	Avg. Number of App / year[3]	Years of $MgCl_2$ Application[4]
Grand	1	6	Strawberry Creek	2450	5.38	5.15	0.52	0.45	0.04	0.03	28,000	53.6	25.9	3570	1	21
Grand	2	40	-	2480	2.83	2.55	0.37	0.14	0.04	0.005	16,200	36.1	20.6	3760	1	9
Grand	3*	1	-	2200	1.30	-*	0.12	-*	0.003	-*	391,000	33.3	19.8	5380	1	13
Grand	4	33	Reeder	2310	6.48	7.20	0.46	0.93	0.12	0.38	43,800	33.5	20.3	3380	1	5
Grand	5	30	-	2730	4.08	2.90	0.29	0.23	0.05	0.02	25,500	55.9	25.7	5290	1	8
Grand	6	22	Seep	2340	5.40	5.75	0.24	0.22	0.02	0.04	32,100	33.3	20.1	3280	1	17
Grand	7	3	Ute	2600	7.40	2.63	0.62	0.10	0.10	0.004	18,600	45.0	24.4	5910	1	8
Larimer	1	162	Swamp	2670	3.75	3.02	0.43	0.21	0.05	0.01	107,000	47.5	27.2	4180	1.5	12
Larimer	2	162	Manhattan	2540	2.48	1.37	0.32	0.15	0.03	0.00	196,000	44.2	26.7	4180	1.5	12
Larimer	3	69	Sevenmile	2230	6.51	4.07	0.53	0.22	0.14	0.01	634,000	40.9	24.9	5040	1.8	14
Larimer	4	73C	North Columbine	2620	2.31	1.32	0.16	0.08	0.004	0.0003	83,700	48.0	26.2	4370	2.4	13
Larimer	5	73C	North Lone Pine	2600	7.74	5.58	1.06	0.46	0.26	0.08	67,800	48.0	26.2	4370	2.4	13
Larimer	6	73C	Bear Trap	2550	3.25	2.67	0.50	0.28	0.06	0.01	420,000	47.0	26.4	4370	2.4	13
Larimer	7	162/68C/69	Manhattan	2500	2.88	2.03	0.41	0.22	0.03	0.004	499,000	43.7	26.4	5180	1.9	15
Larimer	8	68C	Elkhorn	2360	10.4	7.72	0.83	0.43	0.44	0.05	170,000	42.4	26.2	5180	1.9	15
Larimer	9	103	Laramie River	2680	6.82	6.02	0.41	0.30	0.15	0.05	41,700	56.4	26.4	1790	1.2	11

1. Average of upstream and downstream sites.
2. Average Annual and Monthly May to October Precipitation (cm) = Based on PRISM models (OSU PRISM Group 2006).
3. Average $MgCl_2$ Application Rate and average number of application per year = kg of anhydrous $MgCl_2$ applied per km through 2004 (personal communication, Dale L. Miller, Larimer County Road and Bridge Department and Alan Green, Grand County Department of Road and Bridge, 2006).

4. Years of $MgCl_2$ Application = Number of years $MgCl_2$ products have been applied for dust suppression through 2005 (personal communication, Dale L. Miller, Larimer County Road and Bridge Department and Alan Green, Grand County Department of Road and Bridge, 2006).
* Water stopped flowing at this stream site in July 2004.

Table G2. Mean aluminum, boron, sodium, and sulfate concentrations from 16 streams adjacent to $MgCl_2$ treated non-paved roads in Grand (2004) and Larimer (2004 and 2005) Counties, Colorado.

County	**Site**	**Upstream Aluminum (mg/L)**	**Downstream Aluminum (mg/L)**	Pr > |t|[1]	**Upstream Boron (mg/L)**	**Upstream Boron (mg/L)**	Pr > |t|[1]	**Upstream Sodium (mg/L)**	**Downstream Sodium (mg/L)**	Pr > |t|[1]	**Upstream Sulfate (mg/L)**	**Downstream Sulfate (mg/L)**	Pr > |t|[1]	***n***[2]
Grand	**1**	0.05	0.04	0.511	0.008	0.008	1.000	**4.47**	**3.27**	**0.018**	**1.74**	**1.24**	**0.078**	11
Grand	**2**	**0.08**	**0.03**	**<.0001**	0.008	0.008	1.000	6.05	6.29	0.776	7.86	8.82	0.397	9
Grand	**3**	**0.02**	**0.24**	**<.0001**	0.008	0.008	1.000	10.88	10.88	1.000	11.82	12.08	0.914	4
Grand	**4**	0.07	0.08	0.528	0.008	0.008	1.000	14.65	15.36	0.706	14.93	15.18	0.887	11
Grand	**5**	0.01	0.01	0.378	0.008	0.008	1.000	2.16	1.90	0.320	4.11	3.73	0.494	11
Grand	**6**	0.15	0.17	0.520	0.078	0.083	0.454	138.38	140.05	0.929	92.43	94.68	0.840	10
Grand	**7**	**0.02**	**0.03**	**0.017**	**0.010**	**0.008**	**0.021**	**12.74**	**9.33**	**0.014**	30.79	35.72	0.194	11
Larimer	**1**	0.87	0.88	0.885	0.009	0.008	0.437	**4.68**	**3.92**	**<.0001**	3.47	3.33	0.679	22
Larimer	**2**	**0.51**	**0.22**	**<.0001**	0.008	0.009	0.437	**4.48**	**6.08**	**<.0001**	**3.66**	**6.31**	**<.0001**	22
Larimer	**3**	0.13	0.13	0.890	0.008	0.009	0.444	**3.62**	**4.79**	**<.0001**	**4.30**	**5.82**	**0.001**	23
Larimer	**4**	0.23	0.26	0.352	**0.009**	**0.021**	**<.0001**	**3.85**	**5.34**	**<.0001**	**3.13**	**6.04**	**<.0001**	22
Larimer	**5**	0.10	0.10	0.672	0.008	0.009	0.437	2.91	3.09	0.117	3.34	3.72	0.271	22
Larimer	**6**	**0.13**	**0.17**	**0.011**	0.009	0.010	0.313	**4.69**	**4.99**	**0.096**	3.84	4.30	0.245	22
Larimer	**7**	0.14	0.15	0.234	0.010	0.011	0.437	6.53	6.76	0.354	7.17	7.04	0.832	22
Larimer	**8**	0.27	0.26	0.797	0.008	0.009	0.437	3.72	3.84	0.422	2.42	2.75	0.243	22
Larimer	**9**	0.02	0.02	0.506	0.008	0.008	1.000	**1.40**	**1.31**	**0.078**	1.25	1.37	0.501	22

1. Pr > |t| = significant upstream and downstream differences indicated in **BOLD** at $p \leq 0.10$.
2. *n* = number of collection days at each stream sampling site.
NOTE: Numbers shown are back-transformed $\log_{10}$ mean concentration data. Concentrations were averaged over all months.

Table G3. Mean pH, alkalinity, potassium and calcium of 16 streams adjacent to $MgCl_2$ treated non-paved roads in Grand (2004) and Larimer (2004 and 2005) Counties, Colorado.

County	**Site**	**Upstream pH**	**Downstream pH**	Pr > $\lvert t \rvert$[1]	**Upstream Alkalinity (mg/L)**	**Downstream Alkalinity (mg/L)**	Pr > $\lvert t \rvert$[1]	**Upstream Potassium (mg/L)**	**Downstream Potassium (mg/L)**	Pr > $\lvert t \rvert$[1]	**Upstream Calcium (mg/L)**	**Upstream Calcium (mg/L)**	Pr > $\lvert t \rvert$[1]	***n***[2]
Grand	**1**	7.70	7.71	0.810	23.70	23.21	0.876	**0.65**	**0.24**	**0.0002**	2.93	2.78	0.5110	11
Grand	**2**	7.95	8.01	0.442	**72.78**	**108.54**	**0.007**	0.76	0.89	0.509	**31.52**	**35.48**	**0.0875**	9
Grand	**3**	8.29	8.29	1.000	185.14	204.79	0.654	1.50	1.86	0.544	54.34	55.09	0.8947	4
Grand	**4**	8.43	8.44	0.904	166.65	168.58	0.931	3.29	3.45	0.818	**43.99**	**48.96**	**0.0930**	11
Grand	**5**	7.93	7.97	0.630	**43.48**	**32.68**	**0.035**	0.32	0.32	0.994	9.45	9.21	0.6958	11
Grand	**6**	8.29	8.39	0.209	304.02	297.30	0.874	1.06	1.10	0.892	40.50	40.48	0.9946	10
Grand	**7**	7.81	7.77	0.557	**70.63**	**48.74**	**0.007**	0.92	1.05	0.561	23.38	24.19	0.5898	11
Larimer	**1**	7.47	7.51	0.292	**30.19**	**26.47**	**0.015**	0.91	0.69	0.211	6.38	6.24	0.6926	22
Larimer	**2**	7.70	7.65	0.148	34.17	35.21	0.577	0.71	0.84	0.437	**7.81**	**15.76**	**<.0001**	22
Larimer	**3**	7.86	7.85	0.741	**32.00**	**40.11**	**<.0001**	**0.52**	**0.88**	**0.024**	**5.78**	**11.56**	**<.0001**	23
Larimer	**4**	**7.53**	**7.41**	**0.001**	**30.74**	**35.98**	**0.004**	**0.49**	**0.79**	**0.037**	**8.12**	**11.38**	**<.0001**	22
Larimer	**5**	7.73	7.74	0.895	27.24	29.40	0.157	0.38	0.50	0.227	**6.51**	**7.62**	**0.0077**	22
Larimer	**6**	7.63	7.67	0.236	**32.34**	**35.93**	**0.052**	0.53	0.38	0.157	13.89	14.96	0.1792	22
Larimer	**7**	**7.72**	**7.64**	**0.026**	**39.50**	**43.19**	**0.098**	0.70	0.73	0.874	18.79	20.52	0.1033	22
Larimer	**8**	**7.69**	**7.61**	**0.026**	26.77	25.83	0.508	0.43	0.43	0.959	**5.32**	**6.06**	**0.0327**	22
Larimer	**9**	7.78	7.79	0.792	20.66	20.30	0.740	0.27	0.20	0.263	3.28	3.51	0.3082	22

1. Pr > |t| = significant upstream and downstream differences indicated in **BOLD** at $p \leq 0.10$.
2. *n* = number of collection days at each stream sampling site.

NOTE: Numbers shown are back-transformed $\log_{10}$ mean concentration data. Concentrations were averaged over all months.

Table G4. Mean monthly chloride concentrations (mg/L) for 16 study streams adjacent to $MgCl_2$ treated non-paved roads in Grand and Larimer Counties, Colorado.

County	Site	May		June		July		August		September		October	
		Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
Grand	**1**	0.78	0.54	2.56	0.95	0.20	0.18	0.05	1.32	0.37	0.34	1.94	0.94
Grand	**2**	1.04	1.50	1.15	1.37	0.62	1.04	-	0.78	0.74	1.47	0.93	1.58
Grand	***3**	2.49	2.67	2.59	2.93	-	-	-	-	-	-	-	-
Grand	**4**	1.89	2.23	2.06	1.82	1.67	1.61	2.15	9.32	2.58	2.00	1.47	1.32
Grand	**5**	0.23	0.16	0.07	0.26	0.04	0.04	0.01	0.17	0.08	0.19	0.45	0.32
Grand	**6**	1.30	1.49	1.05	0.96	2.80	2.86	4.70	6.70	4.90	5.01	3.50	3.82
Grand	**7**	2.23	3.62	5.00	5.86	6.52	11.67	8.51	6.05	9.54	32.50	9.39	54.50
Larimer	**1**	1.13	1.25	1.34	1.14	1.95	2.07	1.96	2.25	3.72	3.22	3.59	4.19
Larimer	**2**	0.28	14.01	0.84	19.94	0.76	29.08	0.78	28.43	1.04	26.95	1.37	38.02
Larimer	**3**	0.67	4.84	0.43	9.37	0.37	8.25	0.32	11.92	0.63	16.48	0.99	13.46
Larimer	**4**	2.60	14.68	1.92	6.62	2.11	9.98	2.36	24.69	2.72	72.74	3.46	51.53
Larimer	**5**	1.42	3.55	0.70	2.65	0.77	2.30	0.64	2.43	1.19	5.33	3.27	20.99
Larimer	**6**	2.31	4.04	3.22	5.23	6.32	9.22	19.67	25.77	30.80	37.23	24.14	43.59
Larimer	**7**	18.20	19.28	27.07	29.10	33.70	36.84	35.30	41.68	36.58	46.78	55.61	71.80
Larimer	**8**	3.26	3.19	1.54	1.72	2.25	3.08	2.22	2.66	2.64	7.43	3.35	9.56
Larimer	**9**	0.25	0.30	0.09	0.12	0.12	0.05	0.03	0.04	0.27	0.37	0.51	0.35

* Water stopped flowing at this stream site in July 2004.

Section 4. Leaching potential from intact solid asphalt and recycled asphalt pavement by magnesium chloride, lignin and water

Abstract

A study was conducted in 2006 to determine the leaching capabilities of lignin and $MgCl_2$ solutions versus distilled water on solid and recycled asphalt pavement (RAP). No solution extracted more carbon from the solid asphalt than was already present in the solutions during the 14 day leaching tests. Distilled water extracted more carbon out of two RAP sources than was already present in the control solutions, while $MgCl_2$ and lignin solutions did not. There were no significant differences in the leachate concentrations of the majority of other ions tested between the water, $MgCl_2$ and lignin solutions. Distilled water extracted calcium out of all the solid asphalt sources while $MgCl_2$ and lignin solutions did not. Several ions were extracted from the RAP by all three solutions. Lignin solutions extracted iron and manganese and $MgCl_2$ extracted manganese from all RAP sources tested, while distilled water extracted manganese from one RAP source. Copper and zinc were extracted from one RAP source by the lignin solution. Strontium was leached out of every RAP source by all three solutions and more was extracted by $MgCl_2$ than distilled water in every source tested.

4.1. Introduction

Reclaimed or recycled asphalt pavement (RAP) is often used on asphalt roads and sometimes on gravel roads as fill or surface material. This allows old asphalt pavement to be recycled rather than discarded in the landfill. The major concerns about using RAP are the unknown risks of pollutants leaching from these materials into the surrounding environment. It has been suggested that chemical compounds such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals might be present in RAP and therefore leach from RAP. Data regarding the composition of leachate from RAP is limited (Townsend 1998). Townsend (1998) did a study to address concerns associated with leaching of chemicals from RAP under simulated environmental conditions. This study also provided information regarding possible environmental impacts associated with the leaching of pollutants from RAP (Townsend 1998). RAP is used on roadways in Larimer County, Colorado. Community members in Larimer County expressed concern about the use of road maintenance products composed of $MgCl_2$ on roadways where RAP was also used. This study was conducted to determine what compounds and elements leach from intact asphalt pavement and from RAP when these are exposed to solutions of $MgCl_2$, lignin and distilled water.

4.2. Study objectives

Objectives of this study were to 1) determine if $MgCl_2$ leached more carbon or other ions from solid intact or recycled asphalt pavement (RAP) when compared to the leaching potential of distilled water, 2) determine if $MgCl_2$ solution leached carbon or other ions from solid intact or RAP compared to what was already in the $MgCl_2$ solution and 3) determine if lignin solution leached more carbon or other ions from RAP compared to what was already in the lignin solution.

4.3. Methods and materials

Three sources of intact solid asphalt cores were used in this study: 1) SX (75)(64-22), 2) S(75)(64-22) and 3) S(100)(64-28). Five cores of each type were supplied by Larimer County

Road and Bridge Department (Fort Collins, Colorado). Cores could not be cut into smaller pieces and were used as provided. Four sources of Recycled Asphalt Pavement (RAP) were utilized: 1) City of Fort Collins, 2) City of Loveland, 3) Coulson Excavating and 4) Lafarge, also supplied by Larimer County Road and Bridge Department. The three solvent treatments were: 1**)** glass distilled water (pH = 7.3), 2) lignin-based Lignosulfonate® Dust Control and Road Stabilization solution (pH = 3.7) and 3) $MgCl_2$-based RoadSaver® Dust Control and Road Stabilization solution (pH = 5.2).

Extraction methods: RAP. Bulk samples of four sources of recycled asphalt pavement were delivered to CSU in April 2006. Each bulk sample of RAP was broken up into smaller aggregates using a chisel and hammer because aggregates were stuck together. For each recycled asphalt pavement source, a 250 mL beaker was used to measure out twelve samples of similar volume; each sample was placed in an 800 ml beaker. Prior to adding the treatment solutions to asphalt samples, each sample was weighed (Table 4.1).

Four replicate 250 mL samples of each RAP source was used with each of the three treatments. Four hundred ml of distilled water, lignin solution, or $MgCl_2$ solution were poured into each of four beakers of each recycled asphalt pavement source, for a total of 12 beakers of each recycled asphalt pavement source. Filled beakers were then placed on a lab bench in a room kept at 19 to 21 ºC and the content of each beaker was stirred once each day for 14 days. After 14 days, each liquid sample was vacuum filtered three times through a 9 cm diameter Buchner funnel lined with No. 3 filter paper. Filtered samples were placed in 125 ml Nalgene Labware® bottles and sent to Colorado State University Soil, Water and Plant Testing Laboratory (Fort Collins, Colorado) for analysis.

Extraction methods: Solid asphalt samples. Five cores from each of the three solid asphalt sources were weighed and placed into a rectangular plastic container that had been triple rinsed with distilled water (Table 4.1). One thousand mL of the $MgCl_2$ solution were poured over three of the five cores for each of the three solid asphalt sources, and 1,000 mL of distilled water was poured over the remaining two cores from each of the three solid asphalt sources. Containers were kept at 19 to 21 ºC and agitated once each day for 14 days. After 14 days, each liquid sample was vacuum filtered three times through a 9 cm diameter Buchner funnel lined with No. 3 filter paper. Filtered samples were placed in 125 mL Nalgene® bottles and sent to Colorado State University Soil, Water and Plant Testing Laboratory for analysis.

Chemical Analyses. Leachate samples were analyzed for: aluminum (Al), barium (Ba), boron (B), cadmium (Cd), calcium (Ca), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), magnesium (Mg), manganese (Mn), molybdenum (Mo), nickel (Ni), potassium (K), phosphorus (P), silicon (Si), sodium (Na), strontium (Sr), titanium(Ti), vanadium (V), and zinc (Zn). Leachates were analyzed from an acidified sample by inductively coupled plasma-optical emission spectroscopy (ICP) using a Thermo Jarrell Ash Dual View High Resolution ICP (EPA method 0200.7 Trace Element [Metals] using ICP) (EPA Report # 600/R-94-111). Total percent carbon was analyzed by combustion using a Leco TruSpec C/N analyzer since carbon values were high. Samples were weighed using COM-AID® as an absorbent so that liquid would remain in the weighing tin (EPA method 0413.2 [Oil & Grease, Total Recoverable – Spectrophot] modified for total carbon [EPA

Report # 600/4-79-020]). All elements, except carbon (reported as % total carbon), were reported in milligrams per liter (mg/L).

4.4. Results

Total Percent Carbon. None of the solutions tested (distilled water, $MgCl_2$ or lignin solutions) extracted any more carbon from the solid asphalt cores than the control (Tables 4.2 and 4.3). When distilled water and $MgCl_2$ were compared within asphalt sources, distilled water appeared to leach out more carbon than $MgCl_2$ solution in one solid core sample (Sx(75)(64-22)), although neither was in significantly higher concentrations than their respective controls (Table 4.2). Distilled water extracted more carbon out of two RAP sources than was already present in the control solutions, while $MgCl_2$ and lignin did not (Table 4.3).One RAP sample source yielded less carbon than the lignin solution contained, suggesting that some lignin bound to the sample (Table 4.3).

Other Elements. There were no significant differences in concentrations of many of the other ions between the control samples of water, $MgCl_2$ or lignin solutions and what was present in the leachates. Significantly more calcium, magnesium, sodium, potassium, iron, manganese, zinc, molybdenum, strontium, boron, nickel, chromium and silicon were found in the $MgCl_2$ and lignin control solutions compared to distilled water (Tables 4.2 and 4.3). Therefore, these elements would be expected to be in higher concentrations in $MgCl_2$ and lignin leachates compared to leachate from distilled water (Tables 4.2 and 4.3). In the solid asphalt analyses, distilled water extracted calcium out of all the asphalt sources while $MgCl_2$ and lignin solvents did not. No other ions were extracted from the solid asphalt cores by any solution (Table 4.2).

In the RAP analyses, several ions were extracted from the recycled asphalt sources by distilled water, $MgCl_2$ and lignin solvents. All three solutions extracted calcium from RAP (Table 4.3). Distilled water extracted both magnesium and sodium from RAP, while $MgCl_2$ and lignin did not (Table 4.3). Aluminum was extracted by distilled water in one RAP source (Table 4.3). Lignin solutions extracted iron and manganese from all RAP sources tested, while distilled water extracted manganese from one RAP source and did not extract iron from any source (Table 4.3). Iron from $MgCl_2$ solutions appeared to be bound up in all RAP sources, and was significantly lower in the leachates, while $MgCl_2$ did extract manganese from RAP (Table 4.3). Copper and zinc were extracted from one RAP source by the lignin. A significant amount of chromium was extracted from one RAP source by lignin (Table 4.3). Strontium was leached out of every RAP source by all three solutions and more was extracted by $MgCl_2$ than distilled water in every source tested (Table 4.3). Boron was extracted out of 3 RAP sources by distilled water (Table 4.3). Lead was extracted out of two RAP sources by the $MgCl_2$ solution alone. Silicon was in higher concentrations than controls in distilled water and lignin leachates, but was not extracted by the $MgCl_2$ solution (Table 4.3).

4.4. Discussion and Conclusions

None of the solutions tested (distilled water, $MgCl_2$ or lignin solutions) extracted any more carbon from the solid asphalt cores than what was already present in the solution. In the RAP analyses, several ions were extracted from the recycled asphalt sources by distilled water, $MgCl_2$ and lignin solvents, and ions that were extracted by only lignin or $MgCl_2$ (not distilled water) include iron, copper, zinc, and lead. More strontium was leached by $MgCl_2$ than distilled water in every source tested, but even distilled water extracted approximately 10 times more strontium from RAP sources than what was present in the control (Table 4.3). Aluminum, boron and silicon were also extracted from RAP sources by distilled water, indicating that while the contents of RAP may have some environmental implications for introducing these ions into the environment, distilled water appears to extract as much, if not more, from these sources than $MgCl_2$ or lignin solutions.

4.6. Section 4 Tables

Table 4.1. Asphalt source ownership information, weights and sample sizes.

Asphalt Source Name	Asphalt Source Number	Asphalt Source Type	Average Weight of Asphalt Source Sample (grams)[1]	Range of Weight of Asphalt Source Sample (grams)		Standard Deviation of Weight of Asphalt Samples (grams)	Number of Samples
				Low	High		
Sx(75)(64-22)	1	Asphalt Core	1150.24	1142.42	1160.39	9.01	5
S(75)(64-22)	2	Asphalt Core	820.19	698.03	944.33	90.28	5
S(100)(64-28)	3	Asphalt Core	867.37	809.22	924.86	44.90	5
City of Fort Collins	4	Recycled Asphalt Pavement	452.93	428.75	471.61	14.34	12
City of Loveland	5	Recycled Asphalt Pavement	431.57	412.31	460.38	12.81	12
Coulson Excavating	6	Recycled Asphalt Pavement	337.75	326.18	357.62	9.69	12
Lafarge	7	Recycled Asphalt Pavement	370.10	348.55	385.35	11.56	12

1. Asphalt cores were approximately 10 cm in diameter and 4.5 cm thick; Recycled Asphalt Pavement samples were the amount that filled a 250 mL beaker.

Table 4.2. Mean Concentration of Elements in Leachates of Asphalt Core Samples.

Element[1]	Asphalt Core Leachate Analyses							
	Solution							
	Distilled Water				Magnesium Chloride Solution			
	Distilled Water Control	Asphalt Core Source[2]			Magnesium Chloride Control	Asphalt Core Source[3]		
		Sx(75)(64-22)	S(75)(64-22)	S(100)(64-28)		Sx(75)(64-22)	S(75)(64-22)	S(100)(64-28)
Ca	**0.296**	**3.044**	**4.211**	**6.066**	93.22	93.26	90.71	92.87
Mg	0.018	2.652	7.503	9.230	89400	88111	87606	88327
Na	1.733	2.058	4.231	5.448	2204	2153	2061	2122
K	0.100	0.100	0.563	2.441	1438	1409	1340	1365
P	0.100	0.082	0.441	0.252	0.264	0.798	0.630	0.298
Al	0.010	0.083	0.017	0.036	0.022	0.037	0.032	0.046
Fe	0.010	0.026	0.026	0.019	5.099	4.554	4.160	4.314
Mn	0.010	0.008	0.008	0.010	1.038	1.016	1.045	1.070
Ti	0.163	0.101	0.146	0.258	0.010	0.010	0.010	0.113
Cu	0.010	0.020	0.009	0.010	0.010	0.010	0.010	0.010
Zn	0.010	0.008	0.011	0.015	0.041	0.055	0.042	0.042
Ni	0.042	0.044	0.044	0.072	0.156	0.131	0.162	0.172
Mo	0.010	0.008	0.010	0.010	5.650	5.676	5.681	5.851
Cd	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Cr	0.010	0.010	0.010	0.010	0.062	0.038	0.049	0.052
Sr	0.010	0.010	0.010	0.010	0.057	0.071	0.062	0.060
B	0.030	0.438	0.724	0.818	221.8	219.1	221.5	223.9
Ba	0.034	0.045	0.068	0.029	0.042	0.029	0.070	0.039
Pb	0.005	0.043	0.022	0.017	0.005	0.019	0.005	0.013
Si	0.010	0.010	0.113	0.182	0.735	0.576	0.540	0.616
V	0.024	0.036	0.035	0.033	0.027	0.019	0.014	0.027
Total % C	0.246	0.307	0.287	0.303	0.231	0.234	0.264	0.259

1. For all elements except carbon, median concentrations reported in mg/L; carbon concentrations are reported as total % carbon.
2. Two of five cores for each of three core asphalt sources (*n*=2).
3. Three of five cores for each of three core asphalt sources (*n*=3).
4. Grey shaded areas indicate significant differences ($p < 0.05$) between ion concentrations in distilled water and $MgCl_2$ control. (higher concentrations in $MgCl_2$ control, hence higher concentrations in $MgCl_2$ leachates).
5. Bold numbers/blue shading indicate significant differences ($p < 0.05$) between control and leachate concentrations (indicates leaching of ions due to specific solution).

Table 4.3. Mean Concentration of Elements in Leachates of Recycled Asphalt Pavement Samples.

Ion[1]	Solution													
	Distilled Water					Magnesium Chloride Solution					Lignin			
	Distilled Water Control	Recycled Asphalt Pavement Source[2]				$MgCl_2$ Control	Recycled Asphalt Pavement Source[2]				Lignin Control	Recycled Asphalt Pavement Source[2]		
		Fort Collins	Loveland	Coulson	Lafarge		Fort Collins	Loveland	Coulson	Lafarge		Fort Collins	Loveland	Coulson	Lafarge
Ca	0.296	**85.07**	**48.06**	**61.38**	**124.09**	93.22	**127.7**	**134.1**	**124.8**	**122.2**	496.7	**993**	**992.5**	**1087.2**	**919.7**
Mg	0.018	**15.99**	**6.54**	**11.01**	**28.80**	89400	88690	87903	88830	88825	4787	4820	4794	4842.4	4843.9
Na	1.733	**26.80**	**14.26**	**24.13**	**25.56**	2204	2005	2084	2052	2035	359.8	400.0	390.4	387.2	386.5
K	0.100	1.590	0.184	0.669	2.137	1438	1231	1274	1274	1257	482.1	479.1	500.8	470.7	481.7
P	0.100	0.315	0.706	0.279	0.178	0.264	0.597	0.884	0.838	0.739	21.53	**9.22**	**11.19**	**8.22**	**9.89**
Al	0.010	0.037	0.075	0.024	**0.085**	0.022	0.074	0.072	0.062	0.050	0.120	0.075	0.100	0.059	0.057
Fe	0.010	0.008	0.011	0.011	0.016	5.099	**2.625**	**2.962**	**3.699**	**3.32**	92.01	**135.7**	**151.5**	**145.96**	**139.4**
Mn	0.010	0.009	0.010	0.015	**0.256**	1.038	**4.226**	**5.370**	**2.995**	**3.38**	8.28	**22.98**	**24.54**	**23.33**	**19.99**
Ti	0.163	0.057	0.219	0.363	0.110	0.010	0.045	0.010	0.163	0.083	4.696	5.444	5.749	5.535	5.412
Cu	0.010	0.020	0.012	0.011	0.019	0.010	0.013	0.027	0.027	0.010	0.083	0.173	**0.260**	0.183	0.171
Zn	0.010	0.009	0.010	0.010	0.025	0.041	0.047	0.057	0.049	0.048	0.025	0.044	**0.074**	0.053	0.055
Ni	0.042	0.044	0.031	0.039	0.052	0.156	0.144	0.131	0.126	0.131	0.166	0.227	0.229	0.230	0.182
Mo	0.010	0.012	0.010	0.012	0.011	5.650	5.434	5.109	5.305	5.19	0.080	0.112	0.107	0.106	0.102
Cd	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Cr	0.010	0.011	0.009	0.010	0.010	0.062	0.058	0.038	0.049	0.051	0.048	0.043	0.024	0.060	0.030
Sr	0.010	**0.150a**	**0.057a**	**0.115a**	**0.309a**	0.057	**0.625b**	**1.090b**	**0.683b**	**0.655b**	2.950	**6.140**	**6.915**	**7.829**	**5.902**
B	0.030	**0.553**	0.287	**0.480**	**0.733**	221.800	209.613	191.179	200.493	190.4	21.76	23.026	23.495	22.030	21.89
Ba	0.034	0.052	0.072	0.043	0.043	0.042	0.057	0.040	0.039	0.042	0.071	0.125	0.112	0.094	0.063
Pb	0.005	0.035	0.068	0.063	0.012	0.005	0.138	**0.563**	**0.289**	0.120	0.051	0.097	0.155	0.183	0.150
Si	0.010	**4.554**	**3.482**	**6.916**	**4.478**	0.735	0.732	0.564	0.868	0.549	11.19	**27.51**	**28.60**	**25.63**	**24.26**
V	0.024	0.012	0.015	0.014	0.013	0.027	0.010	0.016	**0.009**	0.018	0.034	0.018	0.009	0.017	0.020
% C	0.246	**0.312**	0.259	0.281	**0.311**	0.231	0.233	0.252	0.256	0.225	10.41	10.60	11.13	**9.22**	10.33

1. For all elements except carbon, concentrations reported in units of mg/L; carbon concentrations are reported as total % carbon.
2. Four replications of each of four recycled asphalt pavement sources (*n*=4).
3. Grey shaded areas indicate significant differences ($p < 0.05$) between ion concentrations in $MgCl_2$ and distilled water control solutions. Grey shaded areas in lignin column indicate significant differences ($p < 0.05$) between leachate concentrations by source in lignin.
   analyses (different concentrations by different sources, regardless of whether these concentrations were different than the control).
4. Bold numbers/blue shading indicate significant differences ($p < 0.05$) between control and leachate concentrations for distilled water, $MgCl_2$ and lignin solutions (indicates leaching of ion due to specific solvent).
5. Numbers followed by different letters (ab) are significantly different ($p < 0.05$) between solutions (distilled water or$MgCl_2$) within the same asphalt source.

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Section 6: Research and Study Site Photos

Roadside vegetation health plots

Figure 6.1. Downslope lodgepole pine-dominated roadside vegetation health plot.

Figure 6.2. Upslope lodgepole pine-dominated roadside vegetation health plot.

Figure 6.3. Downslope Engelmann spruce and subalpine fir-dominated roadside vegetation health plot.

Figure 6.4. Upslope Engelmann spruce and subalpine fir-dominated roadside vegetation health plot.

Figure 6.5. Downslope Engelmann spruce / subalpine fir roadside vegetation health plot with visible foliar damage.


Figure 6.6. Upslope trembling aspen-dominated roadside vegetation health plot.


Figure 6.7. Downslope trembling aspen-dominated roadside vegetation health plot.


Figure 6.8. Downslope roadside vegetation health plot in non-forested, shrubland habitat.

Drainage vegetation health plots

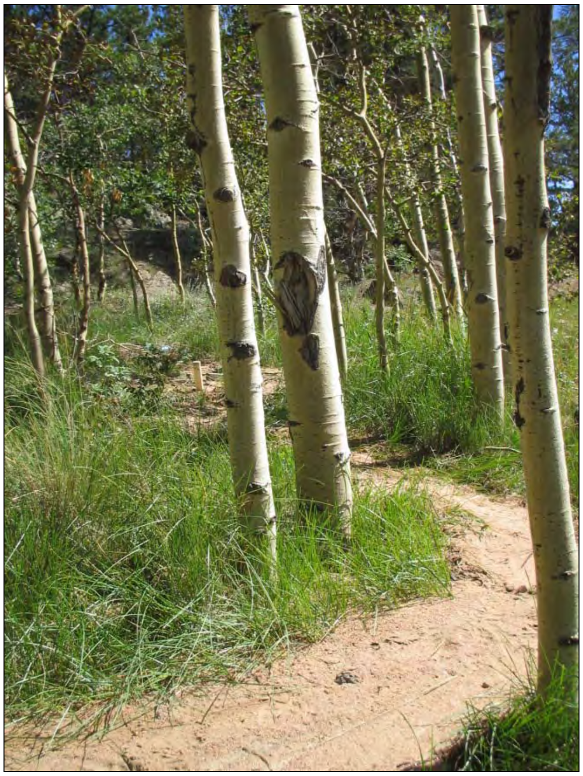

Figure 6.9. Trembling aspen drainage vegetation health plot with sediment on ground.

Figure 6.10. Engelmann spruce / subalpine fir drainage vegetation health plot.


Figure 6.11. Non-forested, shrubland drainage plot with culvert.


Figure 6.12. Non-forested, shrubland drainage plot.

Figure 6.13. Sediment and water in Engelmann spruce / subalpine fir-dominated drainage vegetation health plot.

Figure 6.14. Sediment buildup from road material at bases of aspen trees in drainage vegetation health plot.

Examples of foliar damage on roadside trees


Figure 6.15. Marginal burning on trembling aspen leaves.


Figure 6.16. Close to complete needle burn on lodgepole pine.


Figure 6.17. Needle tip burn on subalpine fir.

Figure 6.18. Needle burn on older needle growth of Engelmann spruce foliar samples.

Common biotic damages on roadside trees

Figure 6.19. Cytospora canker on trembling aspen stem.


Figure 6.20. Bark beetle galleries on lodgepole pine stem.


Figure 6.21. Symptoms of Cooley spruce gall adelgid on Engelmann spruce branch tip.


Figure 6.22. Needlecast fungal fruiting bodies on lodgepole pine needles.


Figure 6.23. Stem cankers and animal damage on aspen stems.

Figure 6.24. Dwarf mistletoe foliar brooms on lodgepole pine.

Sampling roadside soils, vegetation and water

Figure 6.25. Collecting and sieving soil samples in the field.

Figure 6.26. Collecting foliar samples in the field.

Figure 6.27. Recording ground cover percent and plant health.

Figure 6.28. Collecting foliar samples with a pole pruner.


Figure 6.29. Collecting stream water samples in the field.


Figure 6.30. Measuring stream depth and water flow in the field.

Figure 6.31. View of stream site from the road.

Dust suppression application

Figure 6.32. Magnesium chloride-based dust suppression product application.

Figure 6.33. Sign warning traffic of dust suppression maintenance practices ahead on road.