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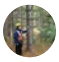

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Condition of Soils and Vegetation Along Roads Treated with Magnesium Chloride for Dust Suppression

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Abstract Investigations of vegetation stress along non-paved roads treated with a range of magnesium chloride ($MgCl_2$) 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 *Pinus contorta*, *Populus tremuloides*, *Picea engelmannii*, *Abies lasiocarpa*, and lower elevation plots dominated by shrubs and grasses. High concentrations of soil magnesium and chloride (400–500 ppm), high foliar chloride (2,000–16,000 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 ($r=0.53$ to 0.74, $p<0.0001$) while the incidence of biotic damages did not correlate well. Positive relationships between foliar chloride and magnesium chloride application rates were strong and can be used to predict foliar concentrations and subsequent damage to roadside trees.

Keywords Aspen · Dust abatement · Gravel roads · Engelmann spruce · Lodgepole pine · Magnesium chloride · Non-paved roads · Roadside vegetation · Road stabilizers · Salinity · Subalpine fir · Unpaved roads

1 Introduction

Magnesium chloride ($MgCl_2$) solution 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, which contributes to atmospheric particulate matter (Sanders et al. 1997). 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,

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county and state transportation departments apply chemical dust suppressants to non-paved roads during spring and summer months to comply 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 becoming more common in the United States due to increases in population growth and traffic demands, especially in arid regions (Piechota et al. 2004). However, there is concern that the use of chloride based dust suppressants may create environmental liabilities to roadside vegetation and soils. A limited amount of published research documenting environmental effects of dust suppressant application exists (Strong 1944; Hagle 2002; Piechota et al. 2004).

Plant injury as a result of deicing products, specifically sodium chloride (NaCl), was reported in Minnesota as early as the 1950s, where trees along city boulevards began showing what are now known as salt-related symptoms, specifically marginal burning and dieback of street trees (French 1959). Later studies focused on symptoms and toxicity thresholds of various roadside species throughout United States, Canada, and Europe, and the negative impacts NaCl can have on roadside soils and vegetation are well documented (Westing 1969; Shortle and Rich 1970; Hofstra and Hall 1971; Hall et al. 1972, 1973; Piatt and Krause 1974; Viskari and Karenlampi 2000; Dobson 1991; Norrstrom and Bergstedt 2001; Kayama et al. 2003; Czerniawska-Kusza et al. 2004). Some studies have also focused on the impacts of $MgCl_2$ deicing products (Trahan and Peterson 2007) and calcium chloride ($CaCl_2$) dust suppressants (Strong 1944; Hagle 2002) on roadside vegetation and soils. Several deicing investigations have attributed roadside plant damage to the combination of aerial spray of road salts, direct foliar contact with salt ions, and high soil salt concentrations (Hofstra and Hall 1971; Viskari and Karenlampi 2000; Trahan and Peterson 2007). Both dust suppression studies regarded aerial spray of dust suppressants as unlikely methods of damage (Strong 1944; Hagle 2002).

High concentrations of ions in the soil matrix alter plant growth and survival both indirectly and directly, via osmotic effects or through direct ion toxicity. At lower NaCl 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 (Kramer and Boyer 1995; White and Broadley 2001; Raveh and Levy 2005). Ions may also accumulate in leaf cells, causing toxicity through disturbances of metabolic pathways or ion imbalances at the cellular level (White and Broadley 2001; Yokio et al. 2002; Raveh and Levy 2005). The typical injury symptoms appear as browning of the leaves, beginning at the tip or margin, and progressing towards the base – the higher the salt content the greater the area of the leaves injured (Hofstra and Hall 1971; Hall et al. 1972; Dobson 1991; Romero-Aranda et al. 1998; Raveh and Levy 2005; Trahan and Peterson 2007). As leaves are weakened or killed, photosynthesis can be reduced due to premature leaf loss (Hofstra et al. 1979; Kayama et al. 2003; Trahan and Peterson 2007). Generally, in woody plants, both chloride and sodium ions accumulate in leaf tissue, while a larger proportion of sodium accumulates into woody tissue (Ziska et al. 1991; Raveh and Levy 2005). Leaf injury has been reported to occur when leaf chloride reaches 10,000 ppm (1.0% dry weight) in deciduous tree species and 5,000 (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).

Despite the known negative effects of NaCl deicing products, no conclusive studies have been published on the environmental effects of $MgCl_2$-based dust suppressants (Piechota et al. 2004). Most published research has been conducted by industry, and has primarily focused on the effectiveness and performance of dust suppressants (Muleeki and Cowherd 1987; Sanders et al. 1997; Addo et al. 2004; Travnik 2001; Piechota et al. 2004). The objectives of this research were to determine: (1) if components of $MgCl_2$ 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 Methods and Materials

2.1 Study Sites

Research was conducted along $MgCl_2$ treated and non-treated (control) roads in Larimer and Grand Counties of northern Colorado in 2004–2006 (Fig. 1). Plot elevation in Larimer County ranged from 1,750–3,210 m, and the vegetation types ranged from low elevation shrub and grass cover to subalpine fir and spruce forest. Grand County plots ranged from 2,490–2,740 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. 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 1 and 2). Quantitative calculations of application rates (total and average kg km^{-1} of $MgCl_2$ applied calculated from gal 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 (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 (Goodrich et al. 2008), 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 (60 roadside plots) (Fig. 1). Fifty-three drainage plots along 11 treated roads and 26 drainage plots along 7 non-

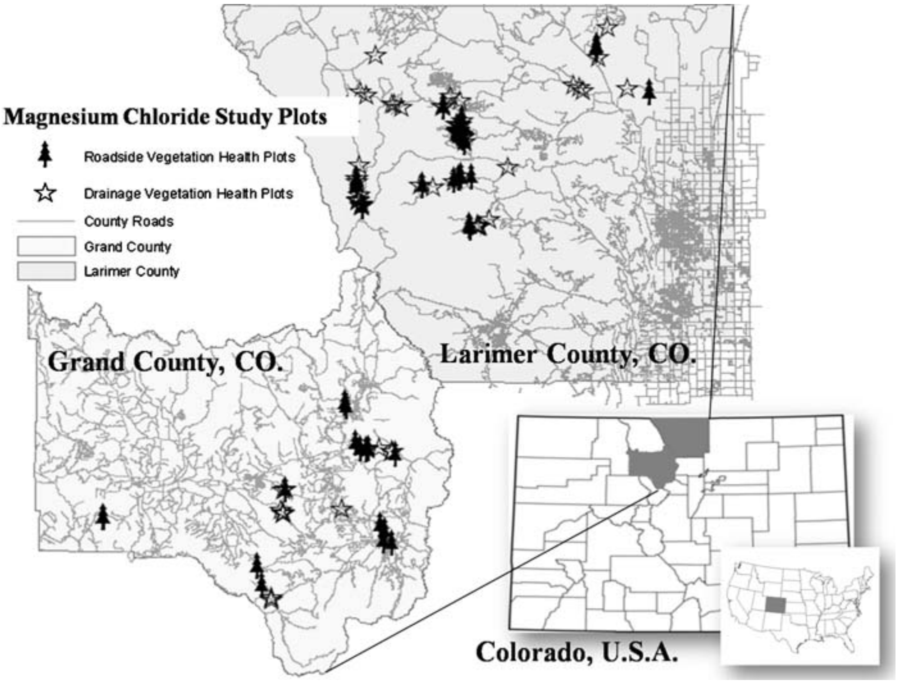

Fig. 1 Grand County and Larimer County, Colorado, U.S.A. borders, county road networks and roadside and drainage vegetation health plot locations

Table 1 Chemical composition of lignin sulfonate and $MgCl_2$-based dust suppression products applied in Larimer and Grand Counties, Colorado

	Lignin Sulfonate Solution			Magnesium Chloride Solution		
	Mean[a]	Standard Deviation (n=3)[b]	Range	Mean[a]	Standard Deviation (n=4)[b]	Range
pH[c]	4.17	0.06	4.1–4.2	8.8	0.05	8.8–8.9
Electrical Conductivity[c]	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	2000–2200	95,000	1730	93,000–97,000
Chloride	9,820	85	9740–9910	252,000	4240	249,000–258,000
Boron	16.7	5.7	10–20	190	14.1	180–210
Sodium	200	0	200–200	1,325	50	1300–1400
Potassium	700	0	700	1150	370	900–1700
Calcium	933	57.7	900–1000	150	57.7	100–200
Phosphate	63.3	5.7	60–70	72.5	20.6	50–100
Sulfate	130,000	4120	126000–134200	8,000	424	7600–8600
Ammonia	45,000	551	44000–45500	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[d]	<0.1	–	–	<0.1	–	–
Copper[d]	<0.1	–	–	<0.1	–	–
Aluminum[d]	0.12	0.03	0.1–0.15	<0.1	–	–
Zinc[d]	<0.1	–	–	<0.1	–	–

Magnesium chloride-based dust suppression solution provided by Larimer County Road and Bridge Department, Larimer County, Colorado. Lignin solution provided by EnviroTech Services, Greeley, Colorado 80634 (http://www.envirotechservices.com, 1-800-369-3878)

[a] All means reported in mg/L (ppm) except pH and electrical conductivity (mmhos/cm).

[b] Sample size (n) denotes the number of replications of each solution from the same source.

[c] 1:100 dilution used to analyze lignin solution, 1:1000 dilution used to analyze $MgCl_2$ solution.

[d] Elements below reported detection limits in one or both solutions

treated (control) roads were established in summers 2005 and 2006 in the same four vegetation types (79 drainage plots) (Fig. 1).

2.2 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. 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). 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. 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: diameter class (<5.1 cm, 5.1–15.3 cm, >15.3–30.6 cm, >30.6 cm) if over breast height (1.37 m) or for total height if below; health status, regardless of cause, (1: healthy, 2: mildly damaged, 3: severely damaged, 4: recently dead, 5: old dead, 6: cut or decayed stump); crown class (dominant, co-dominant, intermediate, understory or open); total percent crown (proportion of tree height with live, damaged or dead crown present); percent damaged crown (necrotic, banded, chlorotic or marginally burned needles or leaves); 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. Percent cover and health of woody and herbaceous plants were also recorded within each subplot with

11.5 m radius circle shrub plots at 3 and 12.2 m and two 0.75 m^2 ground cover 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). Plots ranged in elevation from 2,540–2,850 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. 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 2,680–3,210 m and had average slopes of −14 and 8%. 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 1,750–2,100 m, and the slopes averaged −7 and 12%. 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 (0–30.5 and 30.5–61.0 cm) at four distances from the road (0, 3.0, 6.1 and 12.2 m) in each subplot. 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.

2.3 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 meant as control samples, as 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. 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). 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.

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. Trembling aspen was the dominant species in 17 drainages along 5 treated roads and in 7 control drainages along 6 non-treated roads. 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. 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.

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 (0–30.5 cm) soil samples were taken at each distance from the

Table 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.[a]	Trt. Product[b]	General Soil Type	Parent Material	Hydro. Soil group[c]	Percent Clay	Percent Sand	Percent 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 metamorphic rock	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

[a] 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.

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

[c] 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).

road. The three samples – one at plot center and one at 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. 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. Each drainage plot was established in 2005 or 2006, and sampled for foliage and soils only once.

2.4 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 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 (http://ag.agsource.com/lab_accuracy/quality_control.asp). Soil types, parent materials, physical properties of soils (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 Web Soil Survey (Soil Survey Staff 2008) (Table 2).

2.5 Statistical Analysis

Data were analyzed by fitting random and fixed effects using The Mixed Procedure, SAS 9.1 (Copyright 2002–2003 by SAS Institute Inc., Cary, NC, USA). 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 drainage 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, though summer precipitation was not always a significant variable in the models. Adjusted least square means (LS means) 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 $p<0.05$. Concentrations were $\log_{10}$ transformed to stabilize the variance of ion concentrations and LS means 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 manuscript. 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). Least square means 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.

3 Results

3.1 $MgCl_2$ 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 (Fig. 2a–b). Overall (combining both counties, all roads, plots, both depths and both years of sampling), chloride appeared to move downslope from treated roads in roadside soils 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) (Fig. 2a–b). In plots sampled for two consecutive years, significant accumulations of soil chloride were not measured from year to year when all samples were combined. Only directly off the road shoulder, chloride increased in upslope soils from 2004 to 2005 (250 to 410 ppm chloride, $p<0.0001$). 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 (0–30.5 cm) and lower (30.5–61.0 cm) soil horizon samples. 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

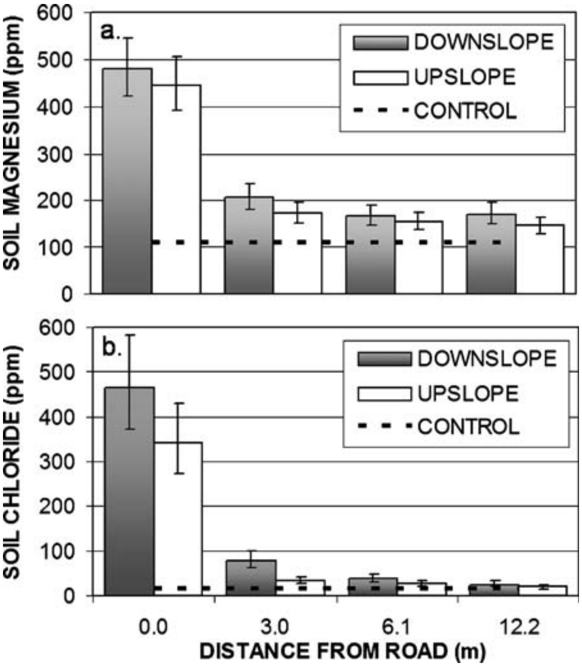

Fig. 2 Soil **a** chloride and **b** magnesium adjusted mean concentrations along roads in Larimer and Grand Counties, Colorado at four distances, both soil sampling depths, and both slope positions from the road (1,429 total soil samples, n=171–195 samples collected at each sampling distance separated by slope). *Dotted line* indicates control plot soil concentrations at each distance combining both slope positions (225 total soil samples, n=53–58 samples collected at each distance). Note: Concentrations back-transformed from $\log_{10}$ values and *error bars* indicate ±1.4 back-transformed standard errors (approximately ±1/2 Fisher's Least Significant Difference [LSD])

and sand were not significantly related to the distribution or concentration of chloride in roadside soils, although they did vary by road (Table 2). Site factors specific to each plot, including difference in percent slope and average summer precipitation, did not explain chloride concentrations along treated roads.

Roadside soil chloride concentrations increased as total and average application rates of $MgCl_2$ (total kg km^{-1} and average kg km^{-1} yr^{-1}) increased on roads (Fig. 3a–b). Using 368.59 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 km^{-1}·yr^{-1} of anhydrous $MgCl_2$ through 2005 (x=3,600 kg km^{-1} yr^{-1}). The total $MgCl_2$ applied ranged from 0–76,000 kg km^{-1} through 2005 (x=37,600 kg km^{-1}). Greater concentrations were measured in downslope soils than in upslope soils (Fig. 3a), so only these data are presented in Fig. 3b. The largest increase in downslope chloride was directly off the road shoulder at 0 m (Fig. 3b). 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

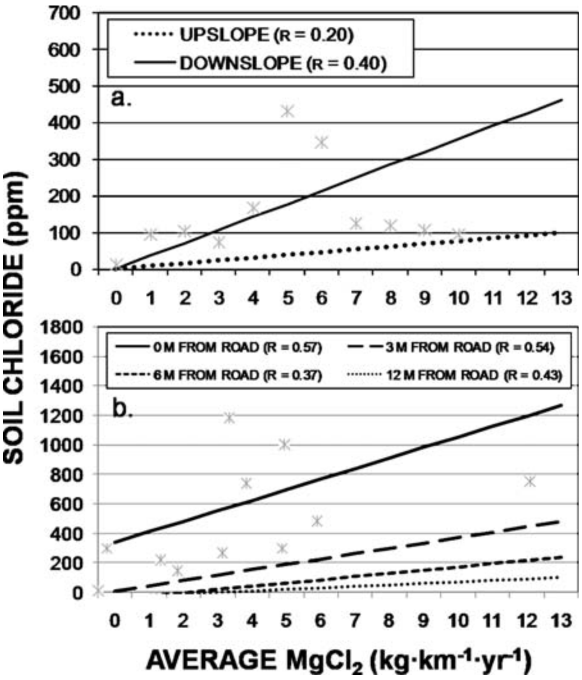

Fig. 3 Modeled increase in soil chloride concentration with average $MgCl_2$ applied to roads in Larimer and Grand Counties, Colorado at **a** both slope positions from the road (1694 total soil samples, n=819 samples upslope and n=875 samples downslope) and **b** in *downslope plots* only at four distances from the road (875 total soil samples, n=212–225 samples per distance from the road). *Asterisks* indicate LS means 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 **a** and LS means 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 **b**, 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 an *asterisk* are significant at p<0.0001. Soil concentrations were not $\log_{10}$ transformed to create predictive models

generally negligible and occurred 0–6.1 m from the road. Along treated roads, electrical conductivity (EC) was highest close to the road (x=2.02 mmhos/cm) and decreased as distance from the road increased, returning to the control plot average (x=0.25 mmhos/cm) at 6.1 m from the road. Treatment of roads with $MgCl_2$ did not alter the pH of roadside soils, with mean pH along control roads ranging from 5.5–6.5, and soils along treated roads ranging from 6.4–6.8. Along both treated and control roads, percent soil organic matter was lowest directly off the road shoulder (x=0.97% at 0 m) and increased as distance from the road increased (x=2.2% at 12.2 m from the road).

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. Typical ratios in soils along control roads (x (Ca:Mg) = 10.94, x (K:Mg) = 1.0) were significantly higher than cation ratios directly off treated roads at 0.0 m (x (Ca:Mg) = 3.5, x (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. Mean sodium concentrations ranged from 22.5 ppm directly off treated roads to 11.7 directly off the shoulder of control roads. Sulfur concentrations decreased from 15.5 ppm in soils close to treated roads, compared to 4.5 ppm along control roads. Soil boron concentrations were highest at 1.2–1.4 ppm along treated road shoulders and were 0.7 ppm along control roads. 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 (x=0.6 ppm, range 0.58–0.77), when compared to control roads (x=0.5 ppm, range 0.42–0.50).

3.2 $MgCl_2$ in Drainage Plot Soils

The length of a drainage plot, as defined by the distance from the road where trees displayed crown damage, was positively related to several main site factors. The best model to predict plot length, 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 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 (0–12.2 m) between low, medium and high impact plots (Fig. 4a–c). In low impact drainages, soil chloride concentrations decreased as distance from the road increased, and remained higher than control plots through 24 m (Fig. 4a). All 19 medium impact plots and 7 of the 10 high impact plots had more soil chloride than typical control soils (20–30 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 (Fig. 4b–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 (Fig. 4d–f). In high impact drainages, magnesium concentrations decreased where the majority of plots ended at 62–73.0 m from the road (n=7 plots), but remained high in the three high impact plots that were 98.0 m long (Fig. 4f).

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 (Fig. 4g–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 (Fig. 4g–h). In high impact plots longer than 73 m, depth of sedimentation increased towards the end of the plots (Fig. 4i). The best

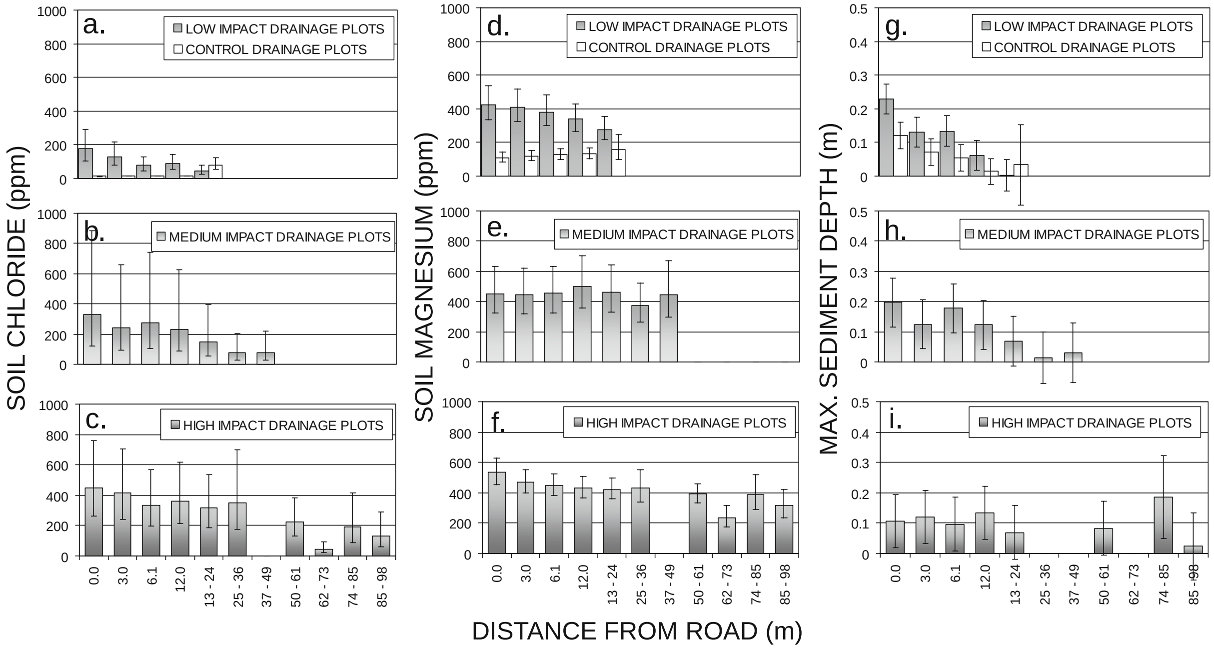

Fig. 4 Soil **a–c** chloride, **d–f** magnesium, and **g–i** maximum sedimentation adjusted means measured in control (n=26), low (n=24), medium (n=19) and high (n=10) impact drainage plots along roads in Larimer and Grand Counties, Colorado sampled in 2005 or 2006. Note: Concentrations back-transformed from $\log_{10}$ values and *error bars* indicate ±1.4 back-transformed standard errors (approximately ±1/2 Fisher's Least Significant Difference)

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 and boron were the only elements significantly higher in drainages along treated roads compared to control roads (treated $x = 11.6 \pm 2.0$ ppm sulfur and $x = 1.2 \pm 0.2$ ppm boron; control $x = 3.0 \pm 0.6$ ppm sulfur and $x = 0.5 \pm 0.2$ ppm boron). Both were in highest concentrations close to the road and decreased with distance ($x = 14.7 \pm 1.7$ ppm sulfur and $x = 1.3 \pm 0.3$ 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).

3.3 *Pinus contorta* (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 (Fig. 5a–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 (Fig. 5a–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 (0–3 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 (2940 ppm and 2860 ppm chloride).

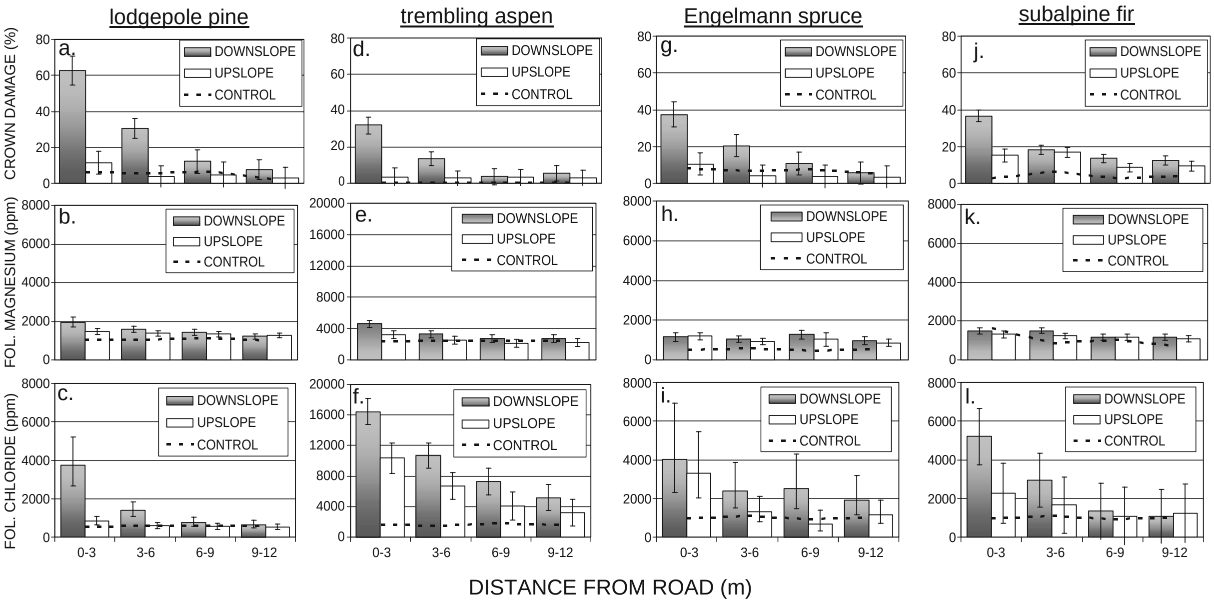

Fig. 5 Lodgepole pine ((**a–c**) $n=2024$ trees visually assessed along treated roads and 487 trees along control roads, $n=471$ treated road foliar samples collected and $n=141$ control road foliar samples, respectively), trembling aspen ((**d–f**) $n=2851$ and 521 trees and $n=420$ and 42 samples), 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 ±1/2 Fisher's Least Significant Difference)

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 ($x=5{,}670$ ppm) and concentrations were similar between two- ($x=8{,}630$ ppm) and three-year old ($x=9{,}000$ ppm) and needles. 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 3-year old needles). Magnesium increased with needle age to a similar extent as chloride, where two- and three-year old needles ($x=2{,}400$ and 2,600 ppm, respectively) were higher in magnesium than the current-years needles ($x=1{,}450$ ppm).

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 (Fig. 6a). 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 km^{-1} yr^{-1} and roadside lodgepole pine tissue had approximately 4,000 ppm chloride and approximately 4000 kg km^{-1} yr^{-1} was associated with 6,000 ppm chloride (Fig. 6a).

3.4 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 (data not shown). Lodgepole in drainages along $MgCl_2$ –treated roads had 20 to 35% mean crown damage of which the majority was tip burn. 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

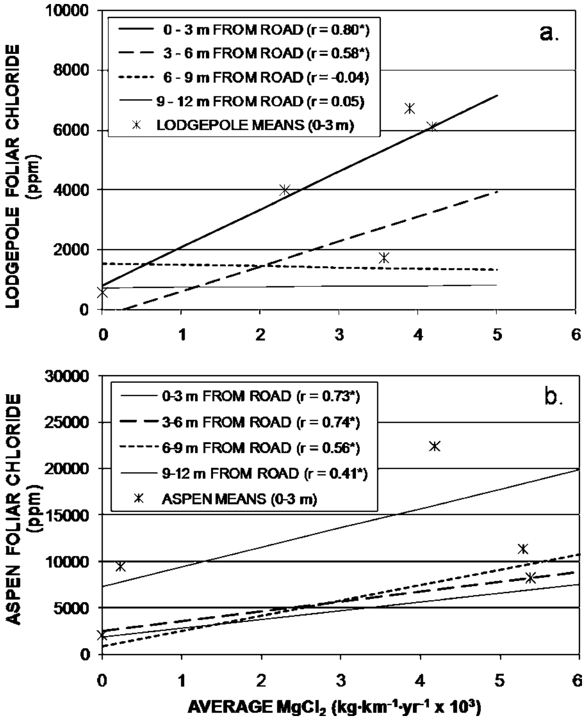

Fig. 6 Modeled increase in **a** lodgepole pine and **b** aspen foliar chloride concentrations with increasing average $MgCl_2$ applied to roads in Larimer and Grand Counties, Colorado in *downslope plots* only at four distance intervals from the road. *Asterisks* indicate means of foliar chloride for each species at 0–3 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 an *asterisk* are significant at $p<0.0001$. Foliar concentrations were not $\log_{10}$ transformed to create predictive models

control roads, and mean chloride concentrations were similar between low, medium and high impact drainages (Fig. 7a–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 (Fig. 7a). In high impact drainages, concentrations were elevated through 61.0 m from the road, and trees between 62 and 85.0 m from the road had similar chloride concentrations as trees in control plots (Fig. 7b–c). Though damage was apparent on trees past 62 m, most were not sampled because foliage was too high to reach 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 ($p=0.01$, data not shown).

3.5 *Populus tremuloides* (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 (Fig. 5d–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 (5–35%) and foliar chloride concentrations (7,000–17,000 ppm) were higher in trees downslope from the road, when compared to upslope trees through 9.1 m from the road (Fig. 5d and f). Aspen leaves had low magnesium concentrations (2,000 ppm) past 3.0 m from the road (Fig. 5e). 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 2,000–4,000 ppm. Aspen accumulated more chloride than any other tree sampled, although mean crown damage was lower than conifers at similar distances from the road (Fig. 5d and f). 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.

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 ($p=0.02$, Fig. 6b). 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 (Fig. 6b). The correlation between application rate and foliar chloride within the first 3.0 m from the road was similar to trees further (3 to 6.1 m) from the road ($r=0.73$ and

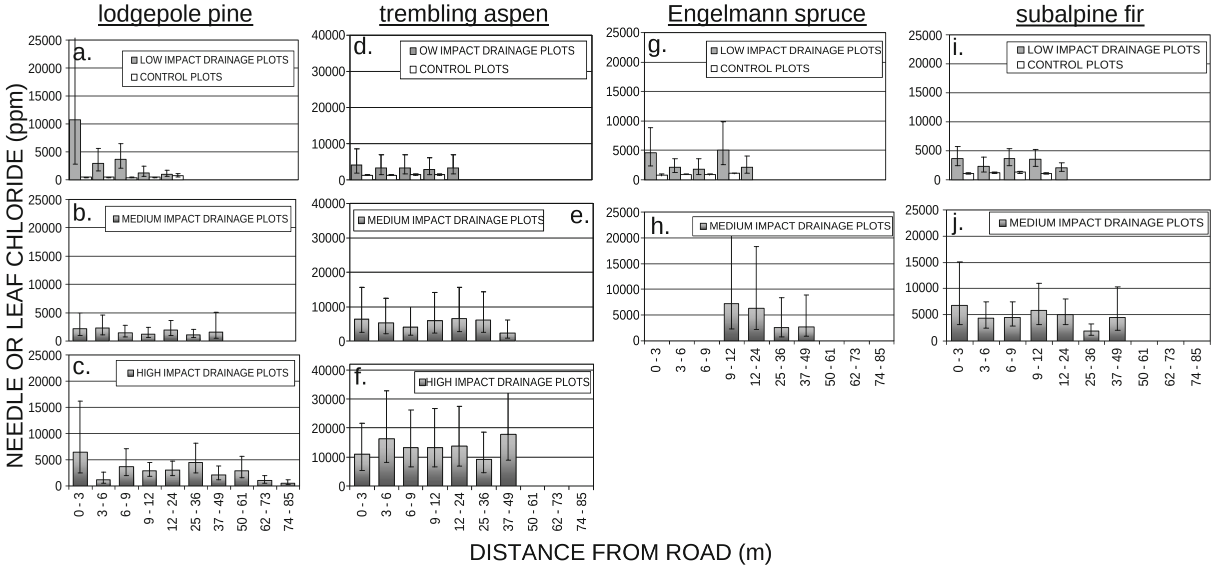

Fig. 7 **a–c** Lodgepole pine adjusted foliar chloride means at various distance intervals in control (**a** 82 foliar samples), low (**a** 43 samples), medium (**b** 73 foliar samples), and high (**c** 49 samples) drainage plot impact classes. **d–f** Trembling aspen adjusted foliar chloride means at 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 foliar samples), low (**i** 43amples), and medium (**j** 32 samples) impact drainage plots. Drainage plots sampled in Grand and Larimer Counties, Colorado in 2005 or 2006. Means back-transformed from $\log_{10}$ data transformations, *error bars* indicate ±1.4 back-transformed standard errors (± approximately 1/2 Fisher's Least Significant Difference)

$r=0.74$, 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 ($r=0.56$, $p<0.0001$).

3.6 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 (data not shown). 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 and was in similar concentrations 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 48 m from the road (Fig. 7d–f). There were no aspen trees to sample towards the end of high impact drainages (50–85 m) because they were dying or dead with no foliage, thus defoliated aspen trees probably had high concentrations of foliar chloride before the leaves dropped (Fig. 7f). 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. Like foliar chloride in aspen trees, magnesium appeared to remain high past the interval of sampled trees in high impact plots. 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 ($p=0.0009$).

3.7 *Picea engelmannii* (Engelmann spruce) and *Abies lasiocarpa* (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 (Fig. 5g and j). Crown damage in spruce and fir trees was higher in downslope plots compared to control trees through 6.1 m from the road (Fig. 5g and j). In both species, trees downslope from the treated road had more than typical control chloride concentrations up to 6.1 m from the road (Fig. 5i and l). In spruce trees, foliar magnesium fluctuated with distance and was consistently higher in trees along treated roads compared to control concentrations (500–1,500 ppm) at all distances from the road (Fig. 5h). In fir trees, magnesium concentrations were similar in trees along both roads (Fig. 5k). 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.

3.8 Engelmann Spruce and Subalpine fir in Drainage Plots

There were no high impact drainages sampled for spruce or fir trees. Mean crown damage ranged from 11–17% in treated road drainages and was less than 3% in control drainages. Crown damage was a mix of fully necrotic tissue and tip burn (data not shown). 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, Fig. 7g–h). In treated road drainages, foliar chloride concentrations past 24.0 m were comparable to control trees (Fig. 7g–h). 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 14–32% in treated drainages, and was a mix of fully necrotic tissue and tip burn (data not shown). Foliar magnesium concentrations generally declined in all drainages as distance from the road increased and was highest in trees in medium impact drainages. 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 (Fig. 6i–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).

3.9 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 3). Foliar boron was highest close to and downslope from the road (80 ppm), as compared to control concentrations (10 ppm). 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 (5.4 ppm) drainage plots, though concentrations fluctuated by distance. Low and high impact drainages contained the highest concentrations of foliar manganese (946 and 1010 ppm) compared to 430 ppm along control roads.

Aspen leaf boron was in higher concentrations along treated roads (65.5 ppm) compared to control roads (3.8 ppm). In drainages, aspen foliar manganese and boron were the only elements significantly higher along treated roads than control roads (treated: x= 197–487 ppm manganese and x=39.6–52.5 ppm boron; control: x=9.2 ppm manganese and x= 24.4 ppm boron). 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

Table 3 Mean foliar ion concentrations in four tree species along treated and control study roads

		Mean Concentrations[a] (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					*			*		*	**	

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

Engelmann spruce foliage sampled along the treated road when compared to the control road (Table 3). With the exception of total foliar nitrogen, which was highest close to the road (1.1% at 0 m from treated roads compared to 0.7% control) and formed a negative relationship with distance, no macronutrient concentration had any coherent pattern with road distance or slope position. Foliar boron concentrations (x= 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 (x=41.3 ppm). Manganese was also higher in medium impact drainages (x=2,810 ppm), as compared to low (x=679 ppm) and control (x= 199 ppm) impact plots. 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 3) and all elements decreased as distance from the road increased. In drainages, iron was the only micronutrient in higher concentrations in fir foliage along the treated road (x=201–282 ppm) than the control road (x=99.7 ppm).

3.10 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). Needle chloride concentrations were consistently higher than twig chloride concentrations, and were better correlated with crown damage (data not shown). 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).

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. Foliar potassium and phosphorus formed weak negative correlations with damage observed in aspen ($r={}^{-}0.15$ to ${}^{-}0.24$). 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, $p<0.0001$).

Needle chloride and boron concentrations both strongly correlated with total damage observed in Engelmann spruce ($r=0.72$ and 0.64, $p<0.0001$). Magnesium concentrations correlated 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, $p<0.001$).

3.11 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.). 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. Engelmann spruce and subalpine fir were both affected by foliar diseases, stem cankers, defoliating insects, and also had high incidences of stand competition in the lower canopy. 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 ($r<0.20$).

"Unknown damage," which was generally symptomatic of recorded 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, $p<0.0001$) and drainage vegetation health plots ($r=0.63$ and 0.47, $p<0.0001$). 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 $r=0.86$, $p<0.0001$). "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, $p<0.0001$).

3.12 Shrub 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 1–4 scale, 1 being healthy with <5% damage and a status of 4 given to dead plants. *Rosa* species and *S. canadensis* both had significantly lower health status ($x=1.27$ and 1.44, respectively) close to the road when compared to plants further away from the road ($x=1.14$ and 1.12, respectively). *J. communis* was in worse health along treated roads ($x=1.43$) than along non-treated roads ($x=1.04$). *A. uva-ursi* was in worse health downslope from the road ($x=1.27$), when compared to upslope areas ($x=1.05$). The major grass and sedge genera in roadside vegetation health plots were: *Carex* (L.) species, *Poa* species including Kentucky bluegrass (*P. pratensis* L.) and alpine bluegrass (*P. alpina* L.), smooth brome (*Bromus inermis* Leyss.), fescue species (*Festuca* L.), blue grama (*Bouteloua gracilis* [Willd. ex Kunth] Lag. ex Griffiths), and *Phleum* species including field Timothy (*P. pretense* 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. In non-forested plots, the major shrub was 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, *Bromus inermis* and *Bouteloua gracilis*.

4 Discussion

4.1 $MgCl_2$ 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 1), a fairly low percentage of these ions accumulated in roadside soils; and along straight segments of road, ion movement from the road was fairly limited. The 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 directly off treated road shoulders; sodium, boron and sulfur were in highest concentrations close to treated roads as these chemicals are components of the lignin sulfonate and $MgCl_2$ products used (Table 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. We speculate that the majority of ions remained in the road base with $MgCl_2$ treatments, and a large proportion of those that did move off treated roads were either 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 large proportion of ions moved downwards. 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. Previous studies have 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). Our results concur with these findings, although we speculate that upslope trees have high ion concentrations for different reasons. As opposed to the aerial spray that upslope trees receive along NaCl-treated highways, upslope trees along non-paved roads may have extended root systems into roadside ditches or under the road base, where they are exposed to chloride and magnesium ions in the soil matrix. Another major contrast between this work and previous studies on deicing salts is the distance of ion movement from straight 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 from fast moving traffic (Trahan and Peterson 2007), while our data indicates that when $MgCl_2$ moves from the road base through the soil matrix only about 6.1 m of roadside environments are affected.

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 (400–500 ppm) close to the road and were dramatically lower

(<100 ppm) 3.0 m from the road (Fig. 2a–b). In high impact drainages, for example, chloride concentrations ranged from 200–400 ppm to 85.0 m from the road (Fig. 4c). 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 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 was, the steeper the ditch slope and the area of road base that drained water towards the ditch and the plot were positively related to the amount of sediment and $MgCl_2$ ions in the drainage, likewise influencing how far ions and sediment occurred from the road. $MgCl_2$ may build up in drainages due to the lack of ion mobility downward when sediment piles 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.

4.2 $MgCl_2$ 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, 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, 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 also did not find strong correlations between soil chloride and foliar chloride or damage (2007). They did, however, have 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 with precipitation events, and 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, but was kept in mind for this study. The foliar ion concentrations of trees in this study were primarily through 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 (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), while our study had 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 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 50–60% of the crown at foliar chloride levels as low as 3,000 to 4,000 ppm (0.3 to 0.4% dry weight); with complete necrosis of the crown at 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 6,000–7,000 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, as it probably varies with moisture stress, root morphology and transpiration rates, and it is not plausible for us 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 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 are 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 concentrations could contain residual surface salt deposits. In addition, several of these studies took place in eastern United States, which historically receives 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 and exhibited the lowest incidence of visible damage. Mean background concentrations of aspen leaves were generally less than 2,000 ppm chloride, and trees along treated roads were measured with over 30,000 ppm. As 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. The impact of high soil chloride on aspen health may take several years to cause measurable declines in health, as the new leaves appeared to accumulate the same amount of chloride as previous season's leaves, with crown damage remaining fairly consistent. 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 would be needed to determine mortality rate relationships to foliar chloride concentrations.

4.3 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 the road and down-slope from the road increased. The accumulation of chloride ions in foliar tissue over time provides for a better predictor variable to quantify the movement of $MgCl_2$ products into roadside environments. Both roadside lodgepole and aspen foliage had stronger correlations with application rates than soil ion concentrations; and with only the knowledge of application rate, this allows for a more accurate prediction of how far $MgCl_2$ ions have moved into roadside environments. The lowest rate of $MgCl_2$ application where lodgepole pine was sampled was approximately 2300 $kg{\cdot}km^{-1}{\cdot}yr^{-1}$, and lodgepole pine tissue along that road had approximately 4000 ppm chloride. On average, 50–60% mean crown damage was observed on lodgepole pine with these concentrations of foliar chloride. A rate of approximately 4000 $kg{\cdot}km^{-1}{\cdot}yr^{-1}$ was associated with 6000 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 $MgCl_2$.

4.4 $MgCl_2$ 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 while containing high concentrations of magnesium and chloride ions. The pathways or 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.

4.5 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 fairly 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, and 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 stress to saline 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 similar cellular and whole plant responses as NaCl. Further studies to deduce the effects of $MgCl_2$ on foliar concentrations of essential plant elements in these species would clarify these preliminary speculations.

Sulfur, a component of lignin sulfonate and $MgCl_2$ dust suppression products applied (Table 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, presumably from vehicular emissions, but not concluded as a primary damaging agent (Trahan and Peterson 2007). 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 toxicity levels of boron are known to be very close (Mengel and Kirkby 2001; Marschner 2002; Tester and Davenport 2003). In citrus leaves, less than 25 ppm boron is considered a deficiency, while over 200 ppm may be toxic (Bennet 1993). In stone fruit crops (peaches and nectarines), anything over 100 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). 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 of its similar mobility and storage as chloride (Marschner 2002). However, 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), and none of these symptoms were observed on leaves in our study. Further studies are necessary to determine the toxic effects of boron, in addition to chloride, on roadside vegetation.

5 Conclusions

$MgCl_2$ ions moved downslope of straight road segments to approximately 3.0–6.1 m into soils and roadside trees, and when concentrations were high, ions were evenly distributed between the upper and lower soil profiles. The worst case scenarios for $MgCl_2$ movement were in 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 with the spatial patterns of damage observed along treated roadsides.

Trees in these plots were measured and sampled for only two growing seasons, so determining the time it takes to cause irreversible damage and mortality to roadside trees is difficult. Based on the high correlation values, yearly accumulation of chloride, and increase in chloride and damage by needle age it appears that the chloride component in $MgCl_2$ based dust-suppression products induced the crown damage observed on roadside trees – leading to the death of some proportion of trees in our roadside and drainage plots. While strong correlations between foliar chloride and leaf necrosis were apparent, we cannot completely rule out that other abiotic factors did not play a role in crown damage observed, in addition to chloride toxicity. Water potentials or other measurements of abiotic plant stress were not collected on roadside trees, although drought and dehydration effects may have potentially worsened stress caused by $MgCl_2$ ions. To deduce the specific timeline of these processes, further long term research is needed in the field and a controlled setting, with yearlong observations of symptoms and consecutive measurements of foliar and soil ion contents.

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