

Roadside Vegetation Health Condition and Magnesium Chloride (MgCl₂) Dust Suppressant Use in Two Colorado, U.S. Counties

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Abstract. Many abiotic and biotic factors affect the health of roadside vegetation, including the application of magnesium chloride (MgCl₂) dust suppression products. Three hundred seventy kilometers (230 mi) of forested, shrubland, meadow, rangeland, riparian, and wetland roadside habitats were surveyed along major nonpaved 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 (less than 5% damage to crown or stem), depending on slope position from the road. Severely damaged (greater than 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 MgCl₂ application rates for roadside aspen, Engelmann spruce, and lodgepole and ponderosa pines. Further research is needed to determine the distribution of MgCl₂ ions, nutrients, and interactions between MgCl₂ and incidence of potential biotic damage agents in roadside soils and plants.

Key Words. Aspen; lodgepole pine; magnesium chloride (MgCl₂); ponderosa pine; road dust control; road stabilization.

Biotic and abiotic stressors may influence the health of roadside vegetation individually or by interacting with one another. Colorado, U.S. roadside vegetation may be exposed to stresses analogous to off-road vegetation, including fungal pathogens, parasitic plants, insects, or drought (Cranshaw et al. 2000). Roadside vegetation may also be exposed to more intense abiotic factors than off-road vegetation that include pollution (Lagerwerff and Specht 1970; Monaci et al. 2000), erosion of road materials (Kahklen 2001), and road maintenance practices such as dust suppressant application and a concomitant increase in soluble salts in roadside soils and vegetation (Strong 1944; Westing 1969; Stravinskiene 2001; Hagle 2002; Piechota et al. 2004). Woody vegetation, particularly coniferous trees, is a reliable bioindicator of abiotic stress because of its perennial nature, needle retention, and large surface area and biomass per tissue weight (Monaci et al. 2000).

Magnesium chloride (MgCl₂)-based dust suppression products are applied to nonpaved roads during spring and summer months for dust suppression and road stabilization purposes. Chloride-based dust suppressants are used to control erosion and fugitive dust and reduce maintenance costs on nonpaved roads by stabilizing soil and drawing moisture from the atmosphere to keep road surfaces damp (Addo et al. 2004; Piechota et al. 2004). Dust from nonpaved roads can contribute significantly to atmospheric particulate matter, which has numerous environmental and human health effects (Sanders et al. 1997; Environment Canada and Health Canada 2001; Singh et al. 2003). The U.S. Environmental Protection Agency has established air quality standards for fine particulate matter (PM-10). Municipal road and bridge departments in arid climates can suppress PM-10 emissions on nonpaved roads by applied chemical dust suppression products (Singh et al. 2003).

Investigations of sodium chloride (NaCl)-based deicing salts and roadside tree health began as early as the 1950s because of

concern over injured roadside trees, and thus the negative impacts of NaCl salts on roadside vegetation are well documented (French 1959; Shortle and Rich 1970; Hall et al. 1972; Hall et al. 1973; Dirr 1976; Hofstra et al. 1979; Viskari and Karenlampi 2000; Kayama et al. 2003; Czerniawska-Kusza et al. 2004). The most significant symptoms of NaCl damage to roadside trees are reduction in biomass, marginal or full leaf chlorosis and necrosis, withered leaf margins, branch dieback, or plant mortality (Westing 1969; Shortle and Rich 1970; Hofstra and Hall 1971; Hall et al. 1972, 1973; Dirr 1976; Hofstra et al. 1979; Czerniawska-Kusza et al. 2004; Trahan and Peterson 2007). Various biochemical and physical problems occur in plants growing in saline soils, attributable singly or in combination to ion toxicities and osmotic changes in the plant (Ziska et al. 1991; Munns 2002). Both sodium and chloride ions have been indicated as the causal agents of roadside tree dieback and other symptoms (Hofstra and Hall 1971; Hall et al. 1972; Lumis et al. 1973; Hofstra et al. 1979; Viskari and Karenlampi 2000; Czerniawska-Kusza et al. 2004).

Compared with available information on NaCl, there is substantially less published research that documents the impact of dust suppressant constituents such as MgCl₂ on roadside environments. The use of chemical dust suppressants is increasing in the United States as a result of increases in population and traffic, especially in arid regions (Piechota et al. 2004). Potential impacts of chloride-based dust suppressants to roadside soils and vegetation may vary slightly from those related to deicing salt exposure, primarily through the timing of dust suppressants, which are applied to roads when roadside trees are actively growing and transpiring; the limitation of aerial drift and spray from dust suppression products (Strong 1944; Hofstra and Hall 1971; Trahan and Peterson 2007); and the absence of snowmelt to dilute soil salts (Trahan and Peterson 2007). The detrimental effects that high concentrations of soluble salts in roadside soils

cause to vegetation may be similar between both road maintenance practices. Roadside trees along nonpaved roads treated with $MgCl_2$ and calcium chloride 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).

A roadside survey was conducted along nonpaved roads both treated and nontreated 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, nonpaved county roads both treated and nontreated 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.

METHODS AND MATERIALS

Larimer County is located in north central Colorado (Figure 1). Elevation along study roads ranged from 1,753 to 3,210 m (5,785 to 10,593 ft) 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 (8,197 to 9,174 ft) (Figure 1). In 2004, Larimer County had 938 km (563 mi) of nonpaved roads and 60% of these roads were treated with $MgCl_2$ -based dust suppression products (563 km [338 mi]) (D.L. Miller, Larimer County Road and Bridge Department, 2006, pers. comm.). Grand County had 1,143 km (686 mi) of nonpaved roads in 2004 and approximately 25% of these roads were treated with $MgCl_2$ -based dust suppression products (292 km [175 mi]) (A. Green, Grand County Department of Road and Bridge, 2006, pers. comm.).

Two hundred sixty-seven kilometers (160 mi) of nonpaved roads were surveyed in Larimer County ($n = 33$ roads, 29% of

total county mileage). Ninety-seven kilometers (58 mi) were surveyed along nonpaved roads in Grand County ($n = 22$ roads, 8% of total county mileage) in spring and summer of 2004. Roads were selected to survey using county maps and information regarding $MgCl_2$ treatment, land ownership, and occurrence of continuous roadside vegetation of county-maintained or -owned roads (D.L. Miller, Larimer County Road and Bridge Department and A. Green, Grand County Department of Road and Bridge, 2006, pers. comm.). 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 implemented in the future. Therefore, the vegetation composition along surveyed roads does not accurately extrapolate up to actual percentages of different habitats along total nonpaved road mileage in each county. Road sections were eliminated from the survey if they occurred through 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 use, and potential habitat disturbance, although these types of roads are included in nonpaved road mileage in both counties.

On each road, two plots, 30.5 m (100.65 ft) wide by 6 m (19.8 ft) deep, were visually estimated on both sides of the road every 0.32 km (0.19 mi). 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 ($n = 2,055$ treated road plots, $n = 528$ nontreated road plots). 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 stem circumference greater than 50%, moder-

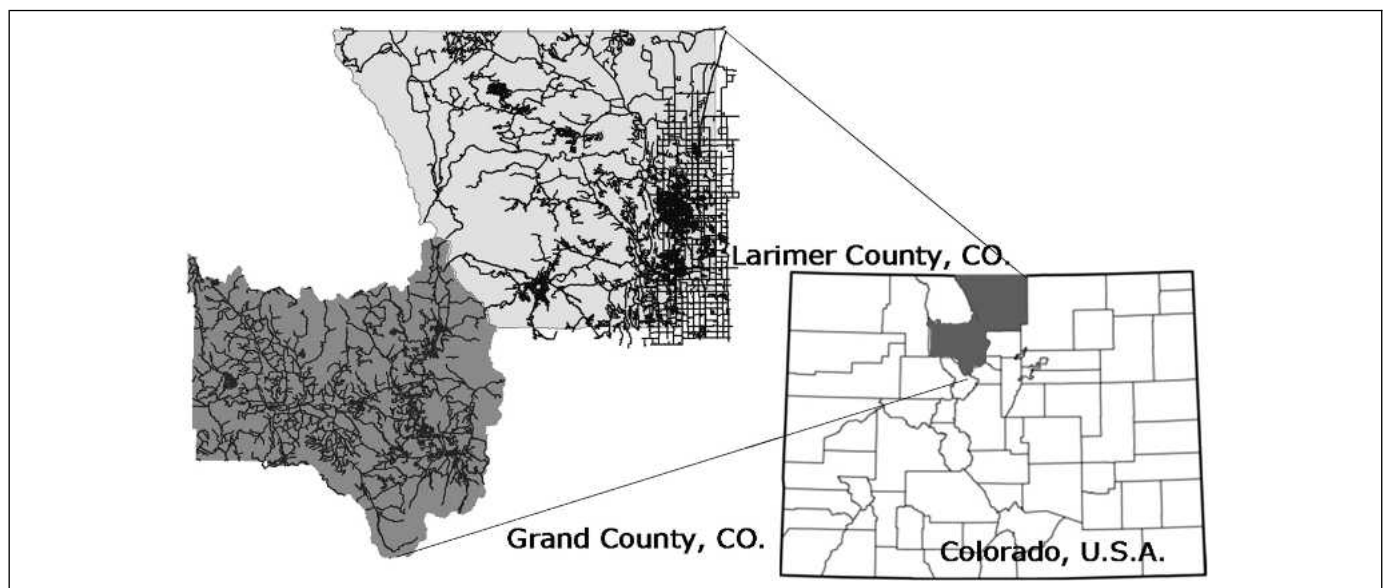


Figure 1. Borders and road networks of Grand and Larimer Counties, Colorado.

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

County roads varied in maintenance procedures, years of treatment, cumulative and average amount of MgCl₂ applied, and chemical specificity of dust suppressants. Quantitative calculations of application procedures and rates (total and average kg/km⁻¹ of MgCl₂ applied calculated from gal/mi⁻¹ of MgCl₂ solution applied, removing gallons of any other products applied such as lignosulfonates) were gathered for study roads following the survey (Larimer County Road and Bridge Department and Grand County Department of Road and Bridge, 2006, pers. comm.). Spatially gridded (800 m [2640 ft]), averaged monthly, and annual precipitation data for the climatologic period 1971 to 2000 (PRISM Group at Oregon State University 2006) were gathered at a midpoint on each study road after this survey ($n = 55$).

Statistical Analysis

Frequencies of habitat types and species composition were produced with The Frequency Procedure (SAS 9.1, Copyright 2002–2003; SAS Institute Inc., Cary, NC). Vegetation cover and health condition were analyzed by fitting random and fixed effects in The Mixed Procedure. Fixed effects included MgCl₂ application information (total and average kg/km⁻¹ MgCl₂ applied), slope position (upslope, downslope, or no slope from the road edge), county, and precipitation (summer: May to September, winter: October to 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 least significant difference 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 $P < 0.0001$, $P < 0.05$, or $P < 0.10$ on all tables and figures.

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). The major types along surveyed roads in both counties were forested or wooded roadside areas followed by shrubland and riparian zones (Table 1). Lodgepole pine (*Pinus contorta*) and trembling aspen (*Populus tremuloides*) were principle components of roadside-forested areas along roads surveyed in both counties (Table 2). Ponderosa pine (*Pinus ponderosa*) was the dominant roadside species in Larimer County but did not occur along roadsides in Grand County. Subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) occurred along roadsides in both counties, although Larimer County had more mileage of both than Grand County (Table 2).

Riparian and shrubland communities were also frequent along roadsides surveyed in both counties (Table 1). Dominant shrub

Table 1. Major habitat types, plot frequencies, and kilometers surveyed along nonpaved roads both treated and nontreated with MgCl₂-based dust suppression products in Grand and Larimer Counties, Colorado.

County	Habitat type	Plot frequency	Km (mi) of road cover
Grand	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 (0.0)
	Total	1125	96.2 (59.8)
Larimer	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	269.2 (167.3)

species throughout both counties in riparian habitats were willow (*Salix* spp.) and alder (*Alnus* spp.) species. Aspen was prevalent in riparian zones along with narrow-leaf cottonwood (*Populus angustifolia*) (Table 2). Big sagebrush (*Artemisia tridentata*) was the dominant shrub along roadsides in Grand County along with rabbitbrush species (*Chrysothamnus* spp.) (Table 2). In the foothills and eastern plains (Larimer County), some shrubland areas were dominated by shadscale or saltbush (*Atriplex confertifolia*) and rabbitbrush (Table 2). No prevalent herbaceous dominant ground cover species were identified in meadow or rangeland habitats along roads throughout the counties (Table 2). More meadow, rangeland, and shrubland kilometers were surveyed in Larimer County, accounting for the more diverse ground cover species richness in that county (Tables 1 and 2). Species occurring as more than 1% of total cover observed are

Table 2. Major dominant species and percent of roadside cover along nonpaved roads both treated and nontreated with MgCl₂-based dust suppression products surveyed in Grand and Larimer Counties, Colorado.

Species	Common name	Percent cover in each county	
		Grand	Larimer
<i>Pinus ponderosa</i>	Ponderosa pine	—	18.2
<i>Populus tremuloides</i>	Trembling aspen	18.8	17.1
<i>Pinus contorta</i>	Lodgepole pine	29.4	15.3
<i>Salix</i> spp.	Willow	11.6	7.8
<i>Artemisia tridentata</i>	Big sagebrush	14.8	0.3
<i>Chrysothamnus</i> spp.	Rabbitbrush	6.1	6.3
<i>Picea engelmannii</i>	Engelmann spruce	2.3	5.0
<i>Pseudotsuga menziesii</i>	Douglas-fir	1.2	4.9
<i>Alnus</i> spp.	Alder species	3.5	4.5
<i>Juniperus scopulorum</i>	Rocky Mt. juniper	4.0	3.4
<i>Abies lasiocarpa</i>	Subalpine fir	2.7	2.8
<i>Rhus trilobata</i>	Skunkbush	—	1.9
<i>Amelanchier alnifolia</i>	Serviceberry	1.6	—
<i>Populus angustifolia</i>	Narrowleaf cottonwood	1.2	1.8
<i>Pinus flexilis</i>	Limber pine	0.2	1.7
<i>Acer glabrum</i>	Rocky Mt. maple	0.3	1.4
<i>Atriplex confertifolia</i>	Saltbush	—	1.1

listed in Table 2. Dominant roadside vegetation identified were generally trees or woody shrub species along with a few herbaceous species that were easily identified from a distance; thus, counts do not encompass the entire range of species along non-paved roads in these counties.

Health Conditions of Dominant Roadside Vegetation

The majority of roadside vegetation surveyed along nonpaved roads was considered healthy, depending on slope position from the road (72.3% to 79.3%). 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 2). Although some proportion of severely damaged vegetation was observed at all slope positions from the road center, a larger percentage occurred downslope compared with upslope positions ($P < 0.0001$; Figure 2).

Overall, plant species along roads treated with $MgCl_2$ dust suppression products had a larger proportion of severely damaged vegetation than species along nontreated roads (Table 3). These percentages varied by species, and the health condition of some were not significantly different between road treatments (Table 3). For several species, the average amount of $MgCl_2$ applied ($kg/km^{-1}/yr^{-1}$) 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 2,583 plots (Table 2). Lodgepole pine occurred along roads with no $MgCl_2$ treatment through roads treated with approximately 7,500 $kg MgCl_2$ per km per year ($26,600 lb/mi^{-1}/yr^{-1}$). A higher percentage of severely damaged lodgepole pine was observed along

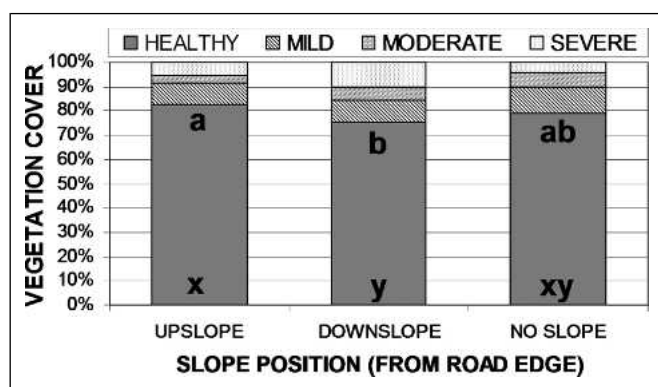


Figure 2. Roadside vegetation health condition adjusted means along nonpaved roads both treated and nontreated with $MgCl_2$ -based dust suppression products in Larimer and Grand Counties by slope position from road edge (healthy = less than 5% damage, mild = 5% to 25% damage, moderate = 26% to 50% damage,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

Table 3. Percentage of species healthy and severely damaged along nonpaved roads treated and nontreated with $MgCl_2$ -based dust suppression products in Grand and Larimer Counties, Colorado.²

	Healthy vegetation cover (%)		Severely damaged vegetation cover (%)	
	Nontreated roads	Treated roads	Nontreated roads	Treated roads
All vegetation combined	89.2	78.3***	4.0	7.6***
<i>Abies lasiocarpa</i>	99.2	87.8	0.8	4.3
<i>Acer glabrum</i>	79.2	69.5	19.7	30.3
<i>Alnus</i> spp.	73.9	75.3	10.5	19.3
<i>Artemisia tridentata</i>	98.1	98.7	1.1	1.3
<i>Chrysothamnus</i> spp.	68.6	89.1*	0.0	6.3
<i>Juniperus scopulorum</i>	95.4	62.3**	0.6	1.9
<i>Pinus contorta</i>	65.9	58.7*	6.2	13.3**
<i>Pinus flexilis</i>	49.8	58.6	1.1	17.3
<i>Picea engelmannii</i>	94.8	75.4***	2.5	3.1
<i>Pinus ponderosa</i>	98.0	69.2***	0.0	5.4***
<i>Populus angustifolia</i>	98.3	68.4	0.1	6.5
<i>Populus tremuloides</i>	85.0	74.1***	7.4	12.3**
<i>Pseudotsuga menzeisii</i>	95.3	93.7	2.0	5.7
<i>Salix</i> spp.	80.3	71.9*	7.6	11.8

²Levels of significance are between road treatments for healthy and severely damaged vegetation.

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

treated roads compared with nontreated roads (Table 3). Higher mean percentages of severely damaged lodgepole pine occurred downslope from the road (15.7%) compared with 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 nonpaved roads as the average amount of $MgCl_2$ applied increased (Figure 3A). The percentage of severely damaged trees downslope from the road increased with average application rate, whereas upslope trees did not (Figure 3A). 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 2,583 plots, but only occurred along Larimer County roads. Ponderosa pine grew along a range of treated and nontreated roads, up to $16,600 kg/km^{-1}/yr^{-1}$ ($59,000 lb/mi^{-1}/yr^{-1}$). A higher percentage of severely damaged ponderosa pine was observed along treated roads compared with nontreated roads (Table 3). The percent of severely damaged trees increased at both slope positions with an increase in average application rate (Figure 3B). The average percent of ponderosa pine with severe damage was higher downslope from the road (5.3%) compared with upslope from the road (2.2%), although the rate of increase with application rates was equal between slope positions (Figure 3B).

Aspen (*Populus tremuloides*)

Aspen was prevalent along roadsides throughout both counties and was a species component in 17.9% of plots. Aspen occurred

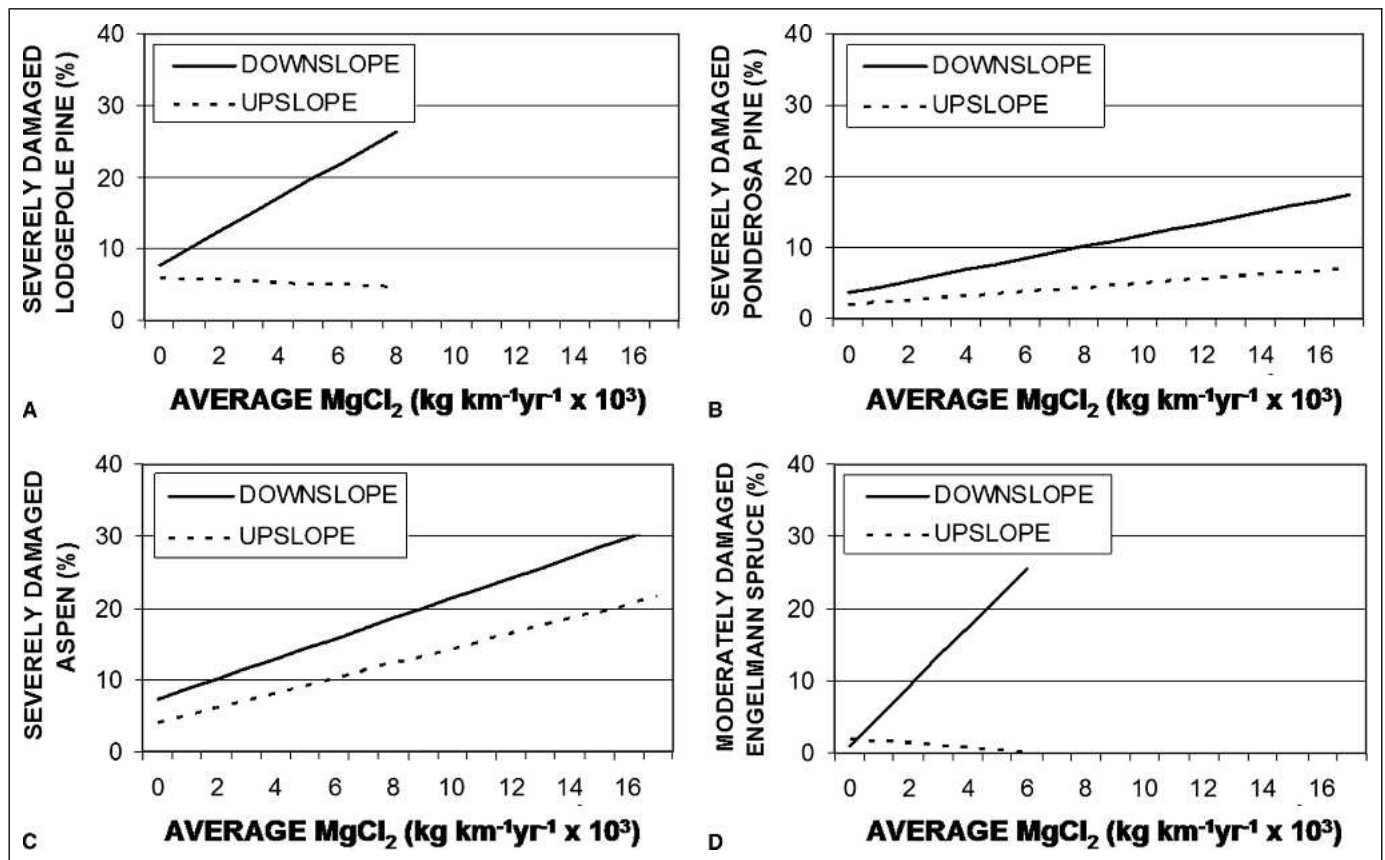


Figure 3. Modeled percent severely damaged lodgepole pine (A), ponderosa pine (B), and trembling aspen (C) and moderately damaged Engelmann spruce (D) adjusted means along nonpaved roads both treated and nontreated with MgCl₂-based dust suppression products in Larimer and Grand Counties by slope position and increasing amount of MgCl₂ applied per year (kg/km⁻¹/year⁻¹). The solution function in SAS 9.1 used to generate slopes for each species and slope position and only site factors that were significant at $P < 0.05$ are illustrated.

along nontreated roads through roads treated with approximately 16,600 kg/km⁻¹/yr⁻¹ (59,000 lb/mi⁻¹/yr⁻¹). A higher percentage of severely damaged aspen was observed along treated roads compared with nontreated roads (Table 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 MgCl₂ applied at similar rates both upslope and downslope from the road (Figure 3C).

Engelmann Spruce (*Picea engelmannii*)

Engelmann spruce occurred as a component of 99 plots along roads ranging from no MgCl₂ application to approximately 5,900 kg/km⁻¹/yr⁻¹ (21,000 lb/mi⁻¹/yr⁻¹). No significant differences occurred between the percent of severely damaged Engelmann spruce on treated versus nontreated roads, although a lower percentage of nondamaged (healthy) Engelmann spruce was observed along treated roads (Table 3). More moderately damaged (26% to 50% damage) spruce occurred along treated roads (15.9%) compared with nontreated roads (0.3%) and also occurred downslope (7.2%) compared with upslope from the road (1.8%) (Figure 3D). 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 MgCl₂ in downslope trees (Figure 3D).

Alder (*Alnus* spp.) and Willow (*Salix* spp.)

Proportions of alder species considered healthy or severely damaged did not significantly differ between treated and nontreated roads (Table 3). A larger proportion of healthy-appearing willow species occurred along nontreated roads compared with treated roads, although no significant differences existed when comparing severely damaged willow (Table 3). A negative relationship existed between healthy willow and average MgCl₂ application rate, in which 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 with upslope from the road (84.9%).

Big Sagebrush (*Artemisia tridentata*) and Rabbitbrush (*Chrysothamnus* spp.)

No significant differences between healthy and severely damaged cover existed for big sagebrush with respect to MgCl₂ application (Table 3). Significantly more healthy-appearing rabbitbrush occurred along nontreated roads (89.1%) than treated roads (68.6%), although no significant differences occurred when comparing severely damaged rabbitbrush plants (Table 3).

Influence of Precipitation Rates

Average yearly precipitation along surveyed roads was similar between counties in this study (43.7 cm/year in Grand County

and 42.6 cm/year in Larimer County), although Grand County appeared to receive a larger proportion of its precipitation during nonsummer months than Larimer County in the form of snowfall (23.9 cm/winter in Grand County compared with 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 nontreated roads compared with treated roads (all analyses $P < 0.0001$), as was elevation on nontreated roads ($P < 0.0001$), indicating some relationship among elevation, precipitation, and the probability that a road will or will not be treated with dust suppressants.

DISCUSSION

Habitat and Species Composition

We observed some variation of roadside habitat types and species composition between counties, although many commonalities occurred. Species within forested and wooded habitats provided the best means to measure health conditions of dominant vegetation along nonpaved roads because of their prevalence along both treated and nontreated roads surveyed. Also, large woody vegetation proved to be easier to identify and estimate crown conditions compared with smaller, seasonal-dependent graminoids, forbs, and shrubs in nonforested habitats. Although most tree species' percent cover accurately represents coverage in county roadside forested areas, it may not accurately reflect percent coverage along all nonpaved 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 nonpaved roads with $MgCl_2$ -based dust suppression products correlated to the increase in foliar damage, hence the decline in health condition of several roadside species (Table 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, *Salix* species, common rabbitbrush, and *Juniperus scopulorum* (Rocky Mountain juniper) all had significantly lower percentages of healthy cover along treated roads (Table 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 biologic diagnostic tests of vegetation health (Stravinskiene 2001). The higher severity of damage seen 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 is known to move through the soil matrix downslope with water movement through 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 base do not receive the amount of salt compared with downslope sides and soils and foliage do not display as much damage, although 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 also observed severely damaged vegetation in upslope areas, which we speculate may be the result of upslope trees with extended roots under the road or roadside drainage ditches. We speculate that $MgCl_2$ moves with water through the soil matrix into roadside soils and is taken up by plant roots. 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, although species were not stratified over all precipitation levels to accurately model these results. Precipitation may also 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, and accurate precipitation and soil chemistry data are required to deduce the effects of precipitation and $MgCl_2$ interactions on roadside vegetation health.

Other Potential Stress Agents to Roadside Vegetation

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 as a result of the removal of surface cover and modifications or compaction to natural soil structure. Erosion of surface particles from nonpaved roads is influenced by traffic, precipitation incidence and intensity, and road maintenance procedures such as grading (Kahklen 2001). Sedimentation, although a possible explanation for declining tree health downslope from the road, does not explain the increase observed in severely damaged vegetation upslope from the road (in aspen and ponderosa pine) with an increase in $MgCl_2$ application rates to the extent that exposure to $MgCl_2$ ions in the soil matrix does.

The relationships observed among increasing visible damage, increasing MgCl₂ application rates, and the increase in damage observed in the downslope positions from the road also help rule out biotic damage causes such as common fungal pathogens or insects as the sole agents responsible for declining roadside vegetation condition. Potentially, stress induced by an increase in MgCl₂ exposure to roadside environments may predispose vegetation to such biotic stresses, and a more intensive study to quantify these relationships is currently underway.

CONCLUSIONS

The majority of roadside vegetation surveyed along nonpaved roads in both counties was considered healthy or only mildly damaged, and the degree of this damage was dependent on species and slope position. Although some severely damaged vegetation occurred along most roads regardless of maintenance or MgCl₂ treatment procedures, a higher occurrence of severe damage was observed on many roadside species along roads treated with MgCl₂. From this survey, we conclude that some species growing alongside nonpaved roads in Larimer and Grand Counties, Colorado, were negatively affected by the application of MgCl₂-based dust suppression products. Visible health condition declined in relation to increasing MgCl₂ application rates for several species and was potentially directly and indirectly related to maintenance procedures by the position they were from the road center. Further research to more extensively study the distribution of MgCl₂ ions, nutrients, and incidence of potential biotic damage agents in roadside soils and foliage along these nonpaved roads is needed.

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Résumé. Plusieurs facteurs biotiques et abiotiques affectent la santé de la végétation le long des voies de circulation, dont l'application d'abats-poussière à base de chlorure de magnésium ($MgCl_2$). Trois cent vingt kilomètre d'habitats forestiers, arbustifs, en prairie, montagneux, riverains et humides ont été inventoriés le long de routes majeures non pavées au sein de deux comtés du Colorado. La composition en espèces dominantes et les dommages visibles sur la végétation ligneuse le long de la route ont été quantifiés. La majorité (72,3 à 79,3%) de la végétation inventoriée le long des routes était considérée comme en bonne santé (<5% de dommages à la cime ou aux tiges), et ce dépendant de la position de la pente par rapport à la route. La végétation fortement endommagée (>50% de dommages) variait de 6,4 à 11,4% du couvert le

long des routes, et ce avec une fréquence de végétation endommagée se trouvant plus fréquemment au bas de la pente de la route. Le pourcentage de plantes avec des dommages sévères ou modérés augmentait avec l'accroissement des taux d'application de $MgCl_2$, et ce chez le peuplier, l'épinette d'Engelmann, le pin tordu latifolié et le pin ponderosa. Une recherche plus poussée est nécessaire pour déterminer la distribution des ions de $MgCl_2$, des éléments minéraux ainsi que des interactions entre le $MgCl_2$ et l'incidence du potentiel de dommages par les agents biotiques au sein des sols et des plantes le long des routes.

Zusammenfassung. Viele abiotische und biotische Faktoren beeinflussen die Gesundheit des Straßenbegleitgrüns, einschließlich der Applikation von Magnesiumchlorid ($MgCl_2$). 370 Kilometer von unterschiedlichen Straßenv egetationen (Wald, Büsche, Wiese, offener Boden, Feuchtgebiete) entlang nicht asphaltierter Hauptstraße in zwei Gemeinden in Colorado wurden untersucht. Die Artenzusammensetzung und die sichtbaren Schäden an den holzigen Gewächsen wurden quantifiziert. Die Mehrzahl (72,3 – 79,3%) des untersuchten Straßengrüns war weitgehend gesund (< 5% Kronen- oder Stammschäden) in Abhängigkeit von der Hanglage zur Straße. Schwer geschädigte Vegetation (> 50% Schaden) betrug 6,4 – 11,4% des Straßengrüns, die meiste Vegetation stand auf abfallenden Böschungen zur Straße. Der Anteil von Pflanzen mit schweren oder mittleren Schäden stieg mit einer höheren $MgCl_2$ -Applikation bei folgenden Baumarten: Espe, Engelmann-Fichte, Küsten- und Ponderosa-Kiefer. Es ist weitere Forschung notwendig, um die Verteilung von $MgCl$ -Ionen, Nährstoffen und Interaktionen zwischen $MgCl$ und Anzeichen potentieller biotischer Schadensfaktoren bei Straßengrün zu untersuchen.

Resumen. Muchos factores bióticos y abióticos afectan la salud de la vegetación en las carreteras, incluyendo la aplicación de productos en polvo a base de cloruro de magnesio ($MgCl_2$). Se evaluaron 370 km de bosques, arbustos, humedales y hábitat riparios a lo largo de áreas no pavimentadas en dos condados de Colorado. Fue cuantificada la composición de las especies dominantes y los daños visibles de la vegetación maderable a lo largo de la carretera. La mayoría (72.3–79.3%) de vegetación inventariada fue considerada saludable (<5% de daño a la copa o tronco), dependiendo de la posición de la pendiente de la carretera. La vegetación severamente dañada (>50% daño) varió de 6.4 a 11.4% de cobertura, con la vegetación más severamente dañada en la pendiente inferior de la carretera. El por ciento de plantas con severo o mediano daño incrementó con el aumento de aplicaciones de $MgCl_2$ para álamo, pinabete Engelmann y pino ponderosa. Se requiere más investigación para determinar la distribución de los iones de $MgCl_2$, nutrientes e interacciones entre $MgCl_2$ y la incidencia del potencial de daño biótico en suelos y plantas en la carretera.