Environment and Natural Resources Research; Vol. 4, No. 1; 2014
ISSN 1927-0488 E-ISSN 1927-0496
Published by Canadian Center of Science and Education

Deicing Salts; Assessing Distribution, Ion Accumulation in Plants and the Response of Plants to Different Loading Rates and Salt Mixtures

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Received: December 9, 2013 Accepted: February 7, 2014 Online Published: February 19, 2014

doi:10.5539/enrr.v4n1p73 URL: http://dx.doi.org/10.5539/enrr.v4n1p73

Abstract

Deicing salts applied to mountain roads during winter periods provide safe driving conditions but these salts are eventually displaced to roadside areas where they can negatively impact soils, vegetation and water resources. The aim of this study was to confirm the linkage between deicing salt applications and salt accumulation in plants and salt accumulation in soils as a function of distance from roads. We also wantedto determine whether altering the deicing salt composition would lead to a more favorable plant response. In the Mt. Charleston area of southern Nevada, NaCl was applied by the State Department of Transportation in excess of 200 tons per State Highway during the winter prior to this study. Salts sampled with depth and distance from the roads at 15 locations revealed significantly higher salinity levels ($p < 0.05$) at the 1 m vs. 5 and 10 m distances, with electrical conductivities as high as 37 dSm^{-1}. In Ponderosa pine, Na and Cl concentrations were found to be elevated in needles revealing visual damage, whereas K concentrations were found to be significantly lower in damaged tissue ($p < 0.05$), resulting in Na/K ratios as high as 300 to 1. In a companion study we investigated the physiological response of 2 year old seedlings of aspen, Gambel oak and Woods' rose, to different salt loading rates comprised of different mixes of salts ($MgSO_4$, $CaCl_2$ or KCl) at different %NaCl composition (100, 90, 75 and 50%). As the $MgSO_4$ in the salt mix increased, sulfate concentration increased in the leaves of oak ($r = 0.73$, $p < 0.001$), reflecting the shift from Cl to SO_4 availability. The % SO_4 in the leaves of oak revealed a strong linear relationship ($r = 0.83$ $p < 0.001$) with leaf weight at final harvest, as well as higher chlorophyll (spad) measurements relative to control ($r = 0.89$ $p < 0.01$**)** and an earlier breaking of dormancy ($r = 0.65$, $p < 0.01$), as seedlings with 2.5% SO_4 in leaves at harvest broke dormancy 10 days sooner than those oak seedlings with only 1% SO_4 in the tissue. Based on results of this study , we believe a 25% substitution of $MgSO_4$ would be worthy of further field evaluations as a significant decline in leaf tissue Na andCl occurred at this level, while concentrations of Ca and SO_4 increased.

Keywords: salinity, montane forests, chlorophyll, delay in bud break

1. Introduction

Millions of tons of deicing salts are applied to US roads and highways each year to reduce the negative impact of snow and ice on safe driving conditions(Transportation Research Board, 1991; USEPA, 2010; Saltinstitute.org, 2013). The salt of choice has typically been sodium chloride because of its low cost and known effectiveness in lowering the freezing point of water. Upon the snow and ice melting, the salts become displaced from theroad surfaces,where the fate and transport of sodium chloride becomes an environmental concern (plants, soils and water resources). Although damage to vegetation is typically highest along roadsides (Thompson & Rutter, 1986; Richburg et al., 2001; Bryson & Barker, 2002; Czerniawska-Kusza et al., 2004; Keiko et al., 2006), these salts can often be displaced to nearby streams and water bodies and/or downward toward groundwater sources, where the rise in concentration is often subtle requiring the response to be tracked over decades (Langen et al., 2006; Meuthel et al., 2007; Kelly et al., 2010).

Salts can be found in many environments where weathering and precipitation reactions occur. Many rivers also carry substantial amounts of salts, however, salts are not normally found in mountain forest ecosystems. As such, the application of deicing salts to roadsin forest ecosystems should be viewed as a point source of contamination. Sodium chloride in particular has been shown to negatively impact overall growth, root extension, stomata regulation, and photosynthesisof plants (Bresler et al., 1982; Devitt et al., 1984a, 1984b; Tanji et al., 1990;

Viskari & Karenlampi, 2000). Sodium has also been linked to the dispersion of clay particles in soil, which can lead to the blockage of soil pores and a decline in infiltration and internal drainage (Bresler, 1982). In addition, sodium chloride has been shown to cause significantly higher levels of foliar damage associated with the application of saline water directly to the foliage (Townsend & Kwolek, 1987; Mantell et al., 1989; Quist et al., 1999; Wu et al., 1999; Jordan et al., 2001; Devitt et al., 2005; Akbar et al., 2006) which could occur through spray generated from traffic on icy salt applied roads (Cunningham et al., 2007). Research has also demonstrated greater plant damage associated with chloride-based salts as opposed to sulfate-based salts (Eaton, 1942; Devitt et al., 2005).

Reducing deicing salt loads and finding alternative approaches are needed to help reduce environmental damage to forest ecosystems.In southern Nevada, mountain roads receive deicing salts on an annual basis and have for many decades, typically from December to February (Nevada Department of Transportation, NDOT). Damage to roadside vegetation has drawn the attention of both mountain and non-mountain residents. To address concerns over the fate of deicing salts and salt damage to plants in forest ecosystems, we conducteda two-phase study. In the first phase, we monitored both soils and plants along mountain roads to assess salt accumulation with the aim of determining the effective zone of influence. In the second phase, we conducted a greenhouse study to assess the impact of different salt loading rates and ionic composition on plant response, with the aim of determining if a more favorable plant response could be obtained with different salt composition (Na and Cl substituted with other ions). We hypothesized that salt concentrations would be higher closer to the roads, that damaged vegetation could be linked to elevated sodium and chloride concentrations in the tissue associated with the deicing salt applications,and that plant'swould respond more favorably to salt loading rates comprised oflower sodium chloride composition.

2. Material and Methods

2.1 Field Study

The field study was conducted in the Mt. Charleston area in southern Nevada. Five sites were selected along routes 156, 157 and 158 (15 sites, Table 1). Sites were selected based on locations where runoff from roads would naturally occur and where vegetation existed. Road exposure, slope, and curbing made this process straight forward.

Table 1. Mount Charleston deicing salt monitoring locations, elevation, and dominant plant species

Site No.	Monitoring Loctions	Elevation	Dominant plant species
Site 1	N 36º15' 51.8" W 115º 36' 09.6"	2075 m	*Pinus ponderosa Lawson var. scopulorum Engelm*. Ponderosapine, *Pinusmonophylla Torrey & Fremont*. Single leaf pinyonpine, *Juniperusosteosperma (Torrey) Little*. Utah juniper, *Quercusgambelii Nutt.* Gambel oak, *Cercocarpusledifolius Nutt. Var. intermontanus N. Holmgren*. Curl leaf mountain mahogany, *Ericamerianauseosa (Pallas) G. L. Nesom & G. I. Baird.* Rubber rabbit brush, *Artemisia tridentata Nutt. ssp. tridentata*. Big sagebrush, *AmelanchierutahensisKoehne*. Utah serviceberry, *Sporoboluscryptandrus (Torrey) A. Gray*. Sand drop seed.
Site 2	N 36º 15' 41.5" W 115º 37' 35.1"	2167 m	*Pinus ponderosa*, *Cercocarpusledifolius*, Artemisia tridentate, *Symphoricarposlongiflorus A. Gray*. Desert snowberry, *Sporoboluscryptandrus*, *Apocynumandrosaemifolium L.* Spreading dogbane.
Site 3	N 36º 15' 36" W 115º 37' 54.7"	2210 m	Pinus ponderosa, Cercocarpusledifolius, *Abiesconcolor Gordon & Glend*. Lindley. White-fir, *Symphoricarposlongiflorus Ericamerianauseosa*, *Sambucusmexicana DC. Garryaflavescens S. Watson*. Silk tassel
Site 4	N 36º 15' 42.8" W 115º 39' 07.6"	2298 m	Pinus ponderosa, Abiesconcolor Rosa woodsii Lindley var. ultramontana (S. Watson) Jepson. Woods' rose, Sporoboluscryptandrus, Populustremuloides Michx. Quaking aspen, Cercocarpusledifolius Garryaflavescens
Site 5	N 36º 15' 29.4" W 115º 39' 01.2"	2313 m	Populustremuloides, Abiesconcolor, Pinus ponderosa, Ericamerianauseosa, Sambucus Mexicana.
Site 6	N 36º 16' 20.21"	2117 m	Pinusmonophylla, Cercocarpusledifolius, Ericamerianauseosa,

	W 115º 35' 41.6"		Amelanchierutahensis, Arctostaphylospungens Kunth. Mexican manzanita, Yucca baccata Torrey. Spanish bayonet, Banana yucca, Quercusgambelii, Garryaflavescens.
Site 7	N 36º 17' 17.7" W 115º 35' 46.3"	2252 m	Quercusgambelii, Cercocarpusledifolius, Pinusmonophylla, Juniperusosteosperma, Symphoricarposlongiflorus. Ericamerianauseosa, Amelanchierutahensis Gutierreziasarothrae (Pursh) Britton & Rusby. Broom snake weed.
Site 8	N 36º 18' 10.2" W 115º 36' 35.6"	2410 m	Pinusmonophylla, Ericamerianauseosa, Artemisia tridentate, Symphoricarposlongiflorus, Cercocarpusledifolius, Gutierreziasarothrae, Verbascumthapsus L. Wooly mullein, Sambucus Mexicana.
Site 9	N 36º 19' 38.7" W 115º 37' 26.2"	2509 m	Cercocarpusledifolius, Juniperusosteospewrma, Ericamerianauseosa, Gutierreziasarothrae, Pinusmonophylla, Ribescereum Douglas. Wax current.
Site 10	N 36º 20' 27.5" W 115º 38' 48.4"	2401 m	Pinus ponderosa, Cercocarpusledifolius, Abiesconcolor, Ericamerianauseosa, Gutierreziasarothrae.
Site 11	N 36º 18' 30.7" W 115º 40' 41.8"	2589 m	Abiesconcolor, Pinus ponderosa, Ericamerianauseosa, Symphoricarposlongiflorus, Ribescereum, Gutierreziasarothrae.
Site 12	N 36º 19' 16.4" W 115º 40' 16.8"	2536 m	Pinus ponderosa, Ribescereum, Abiesconcolor, Rosa woodsii.
Site 13	N 36º 19' 54.4" W 115º 39' 35.8"	2440 m	Pinus ponderosa, Ericamerianauseosa, Cercocarpusledifolius, Artemisia tridentate, Juniperusscopulorum Sargent. Rocky Mountain juniper, Ribescereum, Rosa woodsii.
Site 14	N 36º 21' 43.2" W 115º 38' 2.4"	2324 m	Juniperusosteosperma, Purshiastansburyana (Torr.) Henrickson. Stansburyanacliffrose, Artemisia tridentate, Pinusmonophylla, Cercocarpusledifolius.
Site 15	N 36º 21' 13.9" W 115º 38' 26.9"	2284 m	Ericamerianauseosa, Pinusmonophylla, Purshiastansburiana, Juniperusosteosperma, Artemisia tridentate, Gutierreziasarothrae, Cercocarpusledifolius.

Soil samples were obtained at each site by coring 5 cm diameter holes at 1 m, 5 m and 10 m from the edge of the road. Coring equipment was cleaned prior to sampling at each site.Soil samples were obtained in 20 cm increments to a depth of 100 cm to assess the vertical distribution of salts.Soil samples were placed in bags and returned to the laboratory where they were air dried and processed for saturation extracts (USSL, 1954). Soil solution was evacuated from the saturated soil pasteand placed in 50 ml glass vials and kept at 4 ^{o}C until ion analysis was complete. Electrical conductivity (ECe = electrical conductivity of saturation extract) was assessed with a Beckman Industrial conductivity bridge calibrated with 0.01 M KCl and adjusted to 25 ^{o}C.

Dominant plant species (Table 1) in the area where soil samples were obtained were sampled for leaf tissue. If visual damage to the leaves was observed, samples were separated based on leaves having visual damage vs. healthy leaveswith no visual damage (does visual damage signal salt accumulation?). All plant tissue was placed in bags and returned to the laboratorywhere the tissue was rinsed with deionized water and oven-dried at 70 ^{o}C for 48 hours. Tissue samples were ground and digested in nitric acid. Soil solution extracts and tissue digests were analyzed for all major cations and anions witheither a flame photometer (Cole Parmer Digital Flame analyzer, Chicago IL), atomic absorption spectrophotometer (Buck Scientific, East Norwalk CT), or ion chromatograph (Dionex120 Sunnyvale CA).

2.2 Greenhouse Study

A greenhouse experiment was conducted to assess the response of second-year seedlings of Woods' rose (*Rosa woodsii* Lindl.), aspen (*Populustremuloides* Michx.), and Gambel oak (*Quercusgambelii* Nutti.) to various salt treatments.These species were selected because they were all native to the mountain and available through the State Nursery. The salt treatments involved blendingNaCl with $MgSO_4$, KCl or $CaCl_2$ at 3 different loading rates (LR1 = 0.0969 g cm^{-2}, LR2 = 0.1937 g cm^{-2} (estimated loading rate on mountain roads during study) and LR3 = 0.2906 g cm^{-2}) and at 3 different substitution rates (90% NaCl, 75% NaCl and 50% NaCl). In addition, species

were also subjected to treatments of pure NaCl (LR1, LR2 and LR3) and zero salt additions (controls). Only in the case of $MgSO_4$ was the weight of salt adjusted for its state of hydration (heptahydrate). All treatments had 3 replicates.

Soil (sandy loam texture) for the seedling growing medium was acquired from the Mt. Charleston areanear the NDOT operations facility located at a lower elevation than the monitoring sites. Soil was packed in 9.5 L (2.5 gallon) nursery containers. Soils were then leached with deionized water prior to planting and maintained with deionized water throughout the late fall period. Salt was applied in 4 equal applications during the winter period (December, January and February) and irrigated with deionized water to simulate precipitation.

All plants were without leaves during the winter period. After the February application, weekly irrigations continued until the experiment was terminated in June. Irrigation amounts were based on historical rainfall amounts recorded in the Mt. Charleston area (NOAA, Dec-Maytotal, 39.3 cm). However, to avoid soil moisture deficit conditions, we applied water at approximately 1.5 times the historical rainfall amount (60 cm total at 10 cm per month) to compensate for the increased environmental demand under the greenhouse conditions compared to that at the higher elevation mountain locations. Weekly soil moisture content measurements (time domain reflectometry, Delta T Devices, Cambridge UK) in the 0-5 cm surface soil revealed that such an approach minimized soil moisture deficit conditions during the experimental period. Soil drainage occurred from all containers. No adjustments in irrigation were made based on species. Greenhouse temperatures during the growing period were maintained between 10 ^{o}C at night and 32 ^{o}C during the day. Date of leaf initiation was documented for all plants. Plants were monitored on a bimonthly basis for chlorophyll status using a Minolta Spad 502 chlorophyll meter (transmittance at 650 and 940 nm). At the June harvest, leaf dry weight and tissue ion content were assessed. Soil was screened and sampled from each container after plant harvesting. Soil saturation extracts generated soil solution that was used to assess electrical conductivity and all major cations and anions.

Data were analyzed using general descriptive statistics, Analysis of Variance (ANOVA), linear regression, and backward stepwise regression analysis to determine the statistical significance of experimental results. All tests were conducted using SigmaStat (Sigma Plot Version 11.0, Systat software). Terms were deleted in the backward regression analysis when p values for the t-test exceeded 0.05. To eliminate the possibility of multicollinearity, parameters were included only if variance inflation factors were < 2 and the sum of these factors was < 10 (SigmaStat).

3. Results

3.1 Field Study

Sites along all three state highways ranged in elevation (2075 to 2589 m). Aspect, slope, and field-inspected soil type also varied, which led to variation in species composition at the 15 sites. Most of the species were found at three or fewer sites (Table 1) with the exception ofpinyon pine (5 sites), ponderosa pine (8 sites) and mountain mahogany (11 sites). Based on records obtained from NDOT, the average amount of salt (rock salt~NaCl) applied to each of the state highways during the winter period of this study was 255 ± 14 tons.

Soil salinity wasassessed at the 15 roadside locations with depth and distance from the road (Figure 1). At the majority of sites, the soils were extremely rocky with a loamy sand to sandy loam textural component. Internal drainage appeared to be unimpaired. Soil salinity was highest at the one-meter sampling locations. ANOVAs revealed significant separation ($p < 0.05$) between the 1 m site and the 5 and 10 m sites when comparing soil salinity at each depth increment (Table 2). This was especially true at the 80-100 cm increment where the 1 m locations averaged 11.5 dSm^{-1} compared to the 5 m and 10 m locations, which averaged 1.5 and 1.9 dSm^{-1} respectively. A fully salinized profile was noted at site 2-1 (site-location), whereas at 3-1, 5-1, 7-1, 10-1, 12-1, 13-1 and 15-1, soil salinity (EC_e) increased with depth, reaching values approaching 40 dSm^{-1}in the 80-100 cm depth at site 5-1.

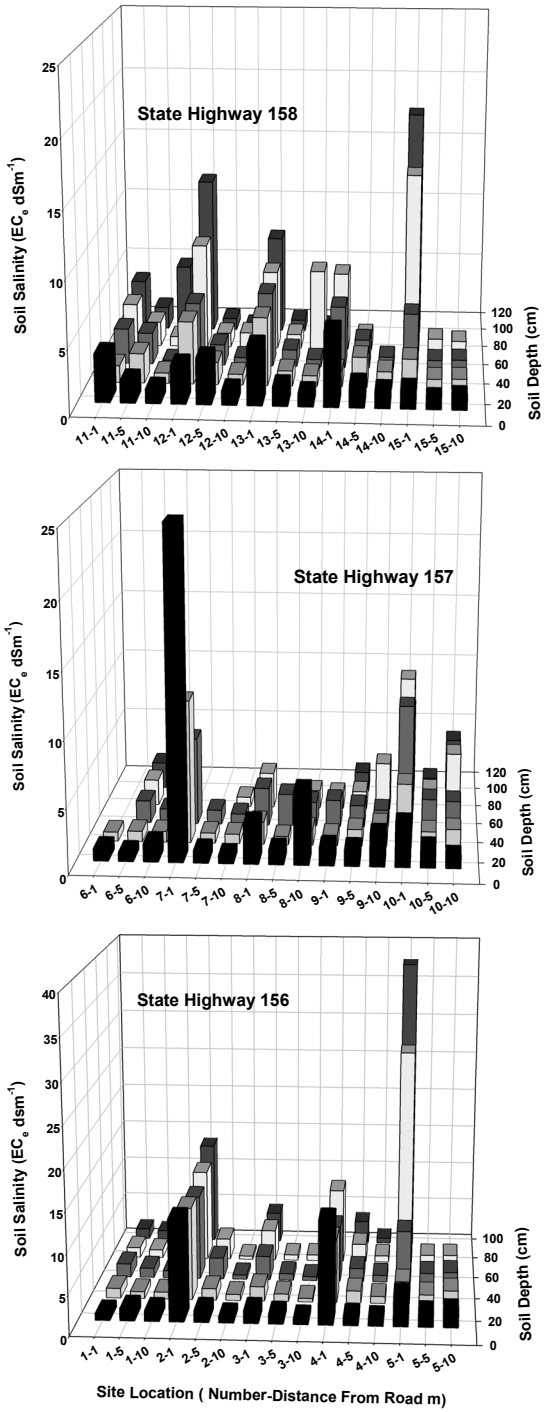

Figure 1. Soil salinity (EC_e dSm^{-1}) as a function of site location (15), distance from the road (m) and depth (0-20, 20-40, 40-60, 60-80 and 80-100 cm) for State Highways 156, 157 and 158 in the Mount Charleston area of southern Nevada

Table 2. Average electrical conductivity (dSm^{-1}) in soil saturation extracts based on soil depth and distance from road for all 15 site locations

Soil Depth (cm)	Distance From Road (m)		
	1	5	10
0-20	5.88[a]	1.42[b]	1.46[b]
20-40	3.94[a]	1.25[b]	1.00[b]
40-60	5.19[a]	1.67[b]	0.97[b]
60-80	8.04[a]	1.18[b]	1.65[b]
80-100	11.51[a]	1.53[b]	1.88[b]

Values at each depth followed with different letters are significantly different at the $p < 0.05$ level.

All plants have different salt tolerance levels with different thresholds that have to be exceeded before noticeable physiological response is observed (Maas & Hoffman, 1977). General listings exist at many web sites, often associated with University-based Cooperative Extension programming. Aspen is listed as asalt-sensitive species, Woods' rose as moderately sensitive, and Gambel oak as possessing moderate salt tolerance (Utah State University, www.treebrowser.org; Montana State University, http://waterquality.montana.edu; Minnesota tree care advocate, www.mntca.org/populus-tremuloides-quaking aspen). As such, we selected electrical conductivity values in the saturation extract of 4 dSm^{-1} and 2 dSm^{-1} to evaluate the extent of salt build up at all of the sites with depth. The percentage of samples exceeding the 4 dSm^{-1} value ranged from a low of 13% in the 0-20 and 20-40 cm increments to 33% in the 80-100 cm increments. The percentage of samples exceeding the 2 dSm^{-1} value ranged from a low of 22% in the 20-40 cm increments to 50% in the 80-100 cm increments.

Leaf samples were collected from the dominant species at each site and separated based on the presence of foliar damage. However, it should be noted that plant sampling rarely occurred in direct proximity to soil sampling locations, which were fixed at 1, 5 and 10 m along a perpendicular transect from the edge of the road, and only in a few locations did vegetation even exist at the 1m roadside locations. As such, no direct correlations existed between EC_e values or ion concentrations in the soil and specific ions in the tissue ($p > 0.05$). This lack of correlation may have directly resulted from the lack of paired sampling, but it may also have been associated with timing as salts were typically found elevated at deeper depths, which suggests that salt pulses may have already moved deeper by the September sampling. Whether or not correlations would have existed if sampling had occurred earlier in spring after the last snowmelt would be worthy of future research.

Tissue ion analysis, sorted by the presence of foliar damage, is reported for the major species sampled at the 15 locations in Table 3. ANOVAs comparing tissue ion percentages based on those species which had both adamaged vs. healthy tissue classification, revealed significant differences ($p < 0.05$) for Na (higher in damaged tissue) in ponderosa pine,pinyon pine, and when all species were combined. Chloride was found to be significantly elevated in damaged tissue in ponderosa pine,mountain mahogany, pinyon pine, and when all species were combined. K was found to be statistically lower in damaged tissue in ponderosa pine and pinyon pine.Whereas Ca was elevated in damaged tissue of ponderosa pine, and SO_4 was elevated in damaged tissue of Woods rose. The fact that many species showed no statistical separation in tissue ion concentrations based on a damaged vs. healthy classification suggests that a visual assessment might not always be a reliable indicator of salt accumulation for every species at these mountain locations and also suggests that each response will be species dependent. In Figure 2, percentClin the tissue of leavesis plotted as a function of percent Na, with highly significant linear correlations ($p < 0.001$) for ponderosa pine, mountain mahogany, and Woods' rose. In both ponderosa pine and mountain mahogany, when Na exceeded 1%, Cl increased, often found in excess of 0.5%. Direct correlations between %Na and %Cl suggest a direct linkage to the NaCl applied as deicing salt at these high-elevation montane forest sites. In the case of ponderosa pine, the ratio of %Na to %K separated ($p < 0.001$) based on a damaged vs. healthy tissue classification with some ratios in excess of 300 in plants showing visual damage. No correlations were found between ion concentrations in the plant tissue and ion concentrations found in the soil saturation extracts ($p > 0.05$), as such, ionic concentrations in the soil were not reported.

Table 3. Tissue ion concentration (%) of major species located at 15 locations on Mt. Charleston. ANOVA conducted on species with healthy vs. damaged tissue as well as a combination of all species

Species	Status	Na %	K %	Mg %	Ca %	Cl %	SO_4 %
Ponderosa Pine	Healthy	0.43^a	0.16^a	0.16^a	0.48^a	0.27^a	2.16^a
	Damaged	2.28^b	0.05^b	0.13^a	0.67^b	0.83^b	2.41^a
Mt. Mahogany	Healthy	0.45^a	0.33^a	0.18^a	1.37^a	0.27^a	5.84^a
	Damaged	1.07^a	0.44^a	0.18^a	1.53^a	0.57^b	7.12^a
Pinyon Pine	Healthy	0.32^a	0.34^a	0.15^a	0.80^a	0.13^a	1.66^a
	Damaged	3.25^b	0.03^b	0.16^a	1.14^a	0.81^b	2.41^a
Woods Rose	Healthy	0.27^a	0.71^a	0.26^a	1.80^a	0.21^a	2.50^a
	Damaged	0.42^a	0.59^a	0.25^a	1.53^a	0.37^a	3.59^b
White Fir	Healthy	0.56^a	0.34^a	0.20^a	2.74^a	0.65^a	2.73^a
	Damaged	0.48^a	0.22^a	0.25^a	2.30^a	0.14^a	2.93^a
Aspen	Healthy	0.40^a	0.90^a	0.22^a	1.79^a	0.75^a	1.50^a
	Damaged	0.47^a	0.77^a	0.24^a	1.39^a	1.09^a	1.76^a
Gambel Oak	Healthy	0.79^a	0.61^a	0.30^a	1.07^a	0.37^a	3.29^a
	Damaged	0.62^a	0.89^a	0.31^a	2.35^a	0.43^a	1.85^a
All Species *	Healthy	0.33^a	0.89^a	0.29^a	1.51^a	0.50^a	2.88^a
	Damaged	1.14^b	0.89^a	0.29^a	1.65^a	0.87^b	3.39^a

Concentrations followed by different letters signify significant differences ($p < 0.05$) when comparing healthy vs. damaged tissue.

* Other species included; Cliffrose, Utah juniper, Ribes, Service Berry, Rabbitbrush, Manzanita, Garrya, Indian Hemp.

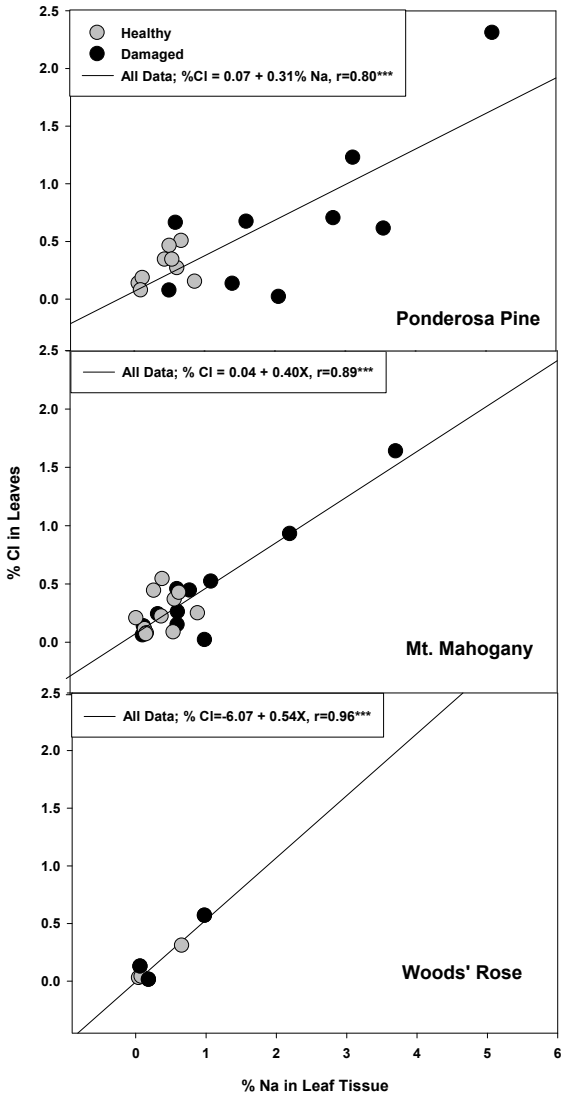

Figure 2. Percent chloride (Cl) as a function of percent sodium (Na) in the leaves or needles of Ponderosa Pine, Mt. Mahogany and Woods' Rose. Tissue was separated based on the presence or lack of visual damage. Level of significance is denoted by *, ** or *** which refers to p values of < 0.05, < 0.01 and < 0.001 respectively

Ions that are taken up but not required (Na) or required in small amounts (Cl), will often imbalance the uptake of other cations and anions (Grattan & Grieve, 1999). In Figure 3, this negative interaction is demonstrated for $\%SO_4$ in ponderosa pine ($p < 0.05$), %Mg in Woods' rose ($p < 0.001$) and $\%SO_4$ in white fir ($p < 0.05$). Stepwise multiple regression analysis was used to assess these effects, and the results are summarized in Table 4.

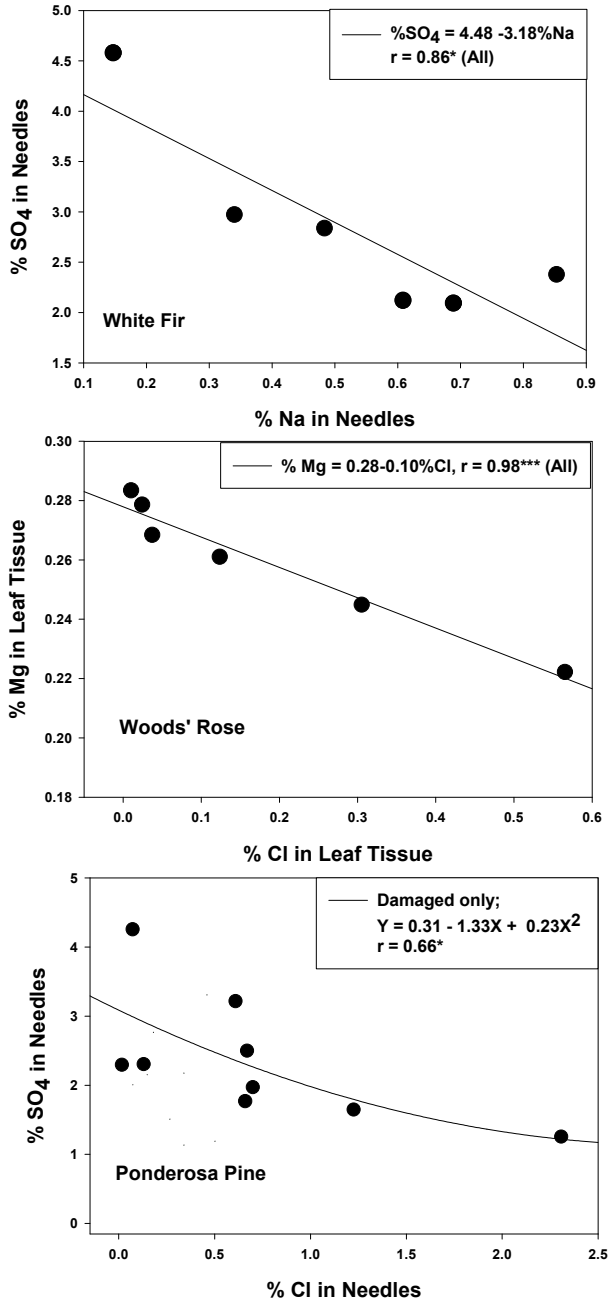

Figure 3. Ion interaction reported for White Fir (%SO_4 vs. %Na), Woods' Rose (%Mg vs. %Cl) and Ponderosa Pine (% SO_4 vs. %Cl). Level of significance is denoted by *, ** or *** which refers to p values of < 0.05, < 0.01 and < 0.001 respectively

Table 4. Backward stepwise regression analysis, assessing the interaction of tissue ion concentrations on specific ions (combined species and individual species)

All Species				
Ion %	**r^2**	**Equation**	**Ion % Increase or Decrease**	**p-value**
Mg ↑	0.51	%Mg = 0.181 - 0.0917 (%Na) + 0.216 (%Cl)	Na ↓ Cl ↑	< 0.001
Cl ↑	0.57	%Cl = -0.286 + 0.350 (%Na) + 2.373 (%Mg)	Na ↑ Mg ↑	< 0.001
Na ↑	0.34	%Na = 0.888 - 2.799 (%Mg) + 0.973 (%Cl)	Mg ↓ Cl ↑	< 0.001
White fir				
Mg ↑	0.99	%Mg = -0.0953 - 0.300 (%Cl) + 0.132 (%SO_4)	Cl ↓ SO_4 ↑	< 0.001
Cl ↑	0.95	%Cl = -0.305 -3.235 (%Mg) + 0.426 (%SO_4)	Mg ↓ SO_4 ↑	< 0.01
SO_4	0.99	%SO4 = 0.732 + 7.571 (%Mg) + 2.277 (%Cl)	Mg ↑ Cl ↑	< 0.001
Aspen				
Mg	0.62	%Mg = 0.455 - 0.290 (%K)	K ↓	< 0.05
K ↑	0.81	%K = 0.516 - 2.984 (%Mg) + 0.586 (%SO_4)	Mg ↓ SO_4 ↑	< 0.05
Pinyon pine				
Mg ↑	0.67	%Mg = 0.0898 + 0.0370 (%SO_4)	SO_4 ↑	< 0.05
Cl ↑	0.86	%Cl = -0.112 + 0.213 (%Na) + 0.225 (%Ca)	Na ↑ Ca ↑	< 0.01
Na ↑	0.85	%Na = 0.577 - 0.982 (%Ca) + 4.178 (%Cl)	Ca ↓ Cl ↑	< 0.05
SO_4 ↑	0.67	%SO_4 = -1.291 + 19.520 (%Mg)	Mg ↑	< 0.05
Ca ↑	0.67	%Ca = 0.578 + 3.405 (%Cl) - 0.759 (%Na)	Na ↓ Cl ↑	< 0.05
K ↑	0.62	%K = 1.147 - 5.351 (%Mg)	Mg ↓	< 0.05
Woods' Rose				
Mg ↑	0.95	%Mg = 0.278 - 0.102 (%Cl)	Cl ↓	< 0.001
Cl ↑	0.98	%Cl = 1.633 + 0.225 (%Na) - 5.896 (%Mg)	Na ↑ Mg ↓	< 0.01
Na ↑	0.90	%Na = -3.512 + 3.011 (%Cl) + 12.773 (%Mg)	Mg ↑ Cl ↑	< 0.01
K ↑	0.84	%K = 4.534 - 14.869 (%Mg)	Mg ↓	< 0.01
Ponderosa pine				
Mg ↑	0.19	%Mg = 0.0694 + 0.0297 (%SO_4)	SO_4 ↑	< 0.05
Cl ↑	0.62	% Cl = 0.0654 + 0.309 (%Na)	Na ↑	< 0.001
Na ↑	0.70	%Na = 0.795 - 3.793 (%K) + 2.077 (%Cl)	K↓ Cl ↑	< 0.001
SO_4 ↑	0.44	%SO4 = 2.955 - 1.896 (%Cl) - 4.091 (%K)	K ↓ Cl ↓	< 0.01
K ↑	0.47	%K = 0.381 - 0.0351 (%Na) - 0.0985 (%SO_4)	Na ↓ SO_4 ↓	< 0.01
Mountain mahogany				
Cl ↑	0.79	%Cl = 0.0385 + 0.399 (%Na)	Na ↑	< 0.001
Na ↑	0.77	%Na = 0.073 + 1.98 (%Cl)	Cl ↑	< 0.001

If ion is not listed, no significant regression equation existed.

When the analysis was conducted for each species separately, higher adjusted coefficients of determination were achieved describing a wider degree of ion interaction not revealed when all of the species were combined. For example, magnesium concentrations in the tissue of white fir increased as chloride concentrations decreased and sulfate concentrations increased ($r^2 = 0.99$, $p < 0.001$), sodium concentrations increased in pinyonpine as calcium concentrations decreased and chloride concentrations increased ($r^2 = 0.85$, $p < 0.01$), and chloride concentrations increased in Woods rose as sodium concentrations increased and magnesium concentrations decreased ($r^2 = 0.98$, $p < 0.001$).

3.2 Greenhouse Study

All Aspen seedlings were either dead (99%) or in an extended state of dormancy at the end of the monitoring period (1%). Only two Aspen seedlings developed leaves, which quickly abscised during the experimental period. It should be noted that all aspen seedlings were fully leafed out and appeared healthy prior to the winter period. Oak seedlings experienced significant mortality and/or extended dormancy in both the KCl and $CaCl_2$ treatments. In the case of the $MgSO_4$ treatment, the majority of oak seedlings leafed out and maintained leaves throughout the experimental period, but loss of replication prevented the use of ANOVA. Therefore, only stepwise regression analysis was used to analyze data when all oak seedlings were pooled together ($MgSO_4$ treatment).

Survivability, assessed by evaluating the vascular tissue of the main trunk/branches at harvest, revealed that the loading rate and not the type of salt or salt composition was controlling survivability in oak ($r^2 = 0.21$, $p = 0.01$). Whereas themajority of Woods roseseedlings at the LR1 level under all salt treatments leafed out and kept leaves for the entire experimental period, and seedling mortality only occurred at the higher loading rates (LR2, LR3). Survivability in Woods' rose was described based on loading rate and salt mixing levels ($r^2 = 0.39$, $p = 0.001$). Although full data setswere not obtained for the higher loading rates, ANOVA was possible at the LR1 level.

3.2.1 Oak

Soil salinity (EC_e) at harvest in the salt treatments of oak separated based on the specific salt mixed with NaCl ($MgSO_4$ 8.95 dSm^{-1}, $CaCl_2$ 11.92 dSm^{-1} and KCl 16.44 dSm^{-1}, $p < 0.001$) and loading rate (LR1; 9.24 dSm^{-1}, LR2; 12.57 dSm^{-1} and LR3; 15.50 dSm^{-1}, $p < 0.001$). These values were not statistically different from the LR1, LR2 and LR3 of the 100% NaCl but they were significantly higher than the control soil (4.26 dSm^{-1}). No separation in EC_eoccurred based on % salt mix with NaCl (90%, 75% or 50%). No statistical relationships existed between soil salinity and plant physiological measurements in oak ($p > 0.05$).

The concentration of each ion in oak was regressed against all other ions to evaluate both positive and negative interactions (Table 5). Eighty seven percent of the variability in Cl in oak leaves could be described by knowing both the Na and the K concentrations in the leaf tissue, with both ions increasing as theCl increased (%Cl = -1.01 +3.46% Na + 2.57% K, $r^2 = 0.87$, $p < 0.001$), whereas the concentration of Na andK were both described solely by Cl with both increasing as the Cl concentration increased ($r^2 = 0.82$ $p < 0.001$ and $r^2 = 0.58$ $p < 0.001$, respectively). As the % Na and %Cl increased with the addition of deicing salts ($MgSO_4$ only evaluated in the case of oak), K elevated significantly compared to the other major cations, Ca and Mg. Control plants receiving no additional salts maintained extremely low concentrations of both Na (0.02%) and Cl (0.04%). As the $MgSO_4$ in the salt mix increased, SO_4 increased in the leaves (%SO_4 = 4.30 -0.018 % NaCl - 1.56 % K, $r^2 = 0.54$, $p < 0.001$), reflecting the shift from Cl to SO_4 availability. Ca and Mg were both weakly correlated ($r^2 = 0.23$, $p < 0.05$) with each other. However, onlyCa concentrations in the soil were found to be related toleaf tissue ion concentrations, revealing a decreasing curvilinear relationship ($r^2 = 0.42$, $p < 0.05$). In no cases involving oak did the regression equations accept either the NaCl % or the loading rate to describe any of the leaf level tissue ion concentrations.

Table 5. Backward stepwise regression analysis, assessing the interaction of tissue ion concentrations on other ion concentrations, sodium chloride percentage (%NaCl) in the salt mix and the loading rate (LR)

Woods' Rose		**All loading Rates $MgSO_4$**		
Ion (%)	**r^2**	**Equation**	**Ion Increase or Decrease**	**p-value**
Mg ↑	0.62	%Mg = 0.181 + 0.167 (%Ca)	Ca ↑	<0.001
Na ↑	0.78	%Na = 1.394 – 0.544 (%Ca) + 0.149 (%Cl)	Ca ↓ Cl ↑	<0.001
SO_4 ↑	0.65	$\%SO_4$ = 1.667 – 0.0086 (%NaCl) + 0.201 (%Ca)	NaCl ↓ Ca ↑	<0.001
Cl ↑	0.65	%Cl = -5.803 + 2.40 (LR) + 0.0969 (%NaCl)	LR ↑ NaCl ↑	<0.001
K ↑	0.41	%K = -0.667 + 0.176 (LR) + 0.0060 (%NaCl) + 0.376 (%Mg)	LR ↑ NaCl ↑ Mg ↑	<0.001
Ca ↑	0.28	%Ca = 1.136 – 0.460 (%Na) + 2.369 (%Mg)	Na ↓ Mg ↑	<0.001
Oak		**$MgSO_4$ and Control**		
Ion (%)	**r^2**	**Equation**	**Ion Increase or Decrease**	**p-value**
Cl ↑	0.87	%Cl = -1.012 + 3.457 (%Na) + 2.565 (%K)	Na ↑ K↑	<0.001
SO_4 ↑	0.54	$\%SO_4$ = 4.298 – 0.0182 (%NaCl) – 1.555 (%K)	NaCl ↓ K ↓	<0.01
Ca ↑	0.23	%Ca = 0.182 + 2.342 (%Mg)	Mg ↑	<0.05
Mg ↑	0.23	%Mg = 0.175 + 0.124 (%Ca)	Ca ↑	<0.05
K ↑	0.58	%K = 0.479 + 0.100 (%Cl)	Cl ↑	<0.001
Na ↑	0.82	%Na = -0.0076 + 0.183 (%Cl)	Cl ↑	<0.001

Tissue ion concentration in the leaves reflect the interaction of the total ion and biomass accumulation. In the greenhouse experiment, we analyzed only the leaf tissue, but we recognize that roots and shoots would also accumulate ions that could possibly shift fundamental relationships between ions in the leaf tissue. We also only sampled at the final harvest but realizethat the concentrations of many ions will vary over time (Lumis et al., 1976). In Table 6, we evaluated the relationships between %ions in the leaf tissue and also the total ion accumulation (mg) in the leaves at harvest. Higher significant correlations were found when the relationships were based on total ion accumulation (mg) in the leaves (5 out of 5 comparisons). In particular, the relationship between total ion accumulation of Mg and SO_4 in the leaves had anrvalue of 0.95 compared to 0.67 based on the ion concentration. The relationship between total ion content (mg) of Ca and Mg, which was weakly correlated based on concentration, was highly correlated based on ion content (mg, r = 0.85***) indicating that small unsynchronized shifts in leaf weight and ion accumulation can have a significant impact on ion concentration and subsequent correlations.

Table 6. Linear regression results (correlation coefficients - r) for leaf tissue ion concentration (%) and total leaf ion accumulation (mg) for Woods' rose and oak where at least one correlation assessing the tissue ion status was significant at the $p < 0.05$ level

Species	Other Salt Addition	X-Axis	Y- Axis	r for % Ion	p-value for % Ion	r for Ion Accumulation (mg)	p-Value for Ion Accumulation
Oak	$MgSO_4$	K	Mg	0.41	NS	0.79	0.01
Oak	$MgSO_4$	K	SO_4	0.63	0.05	0.71	0.01
Oak	$MgSO_4$	Mg	Ca	0.57	0.05	0.85	0.001
Oak	$MgSO_4$	Mg	SO_4	0.67	0.05	0.95	0.001
Oak	$MgSO_4$	Ca	SO_4	0.37	NS	0.82	0.001
Woods' rose	$MgSO_4$	Na	K	0.56	0.01	0.71	0.001
Woods' rose	$MgSO_4$	Na	Ca	0.72	0.001	0.10	NS
Woods' rose	$MgSO_4$	Na	Cl	0.78	0.001	0.83	0.001
Woods' rose	$MgSO_4$	Mg	Ca	0.72	0.001	0.88	0.001
Woods' rose	$MgSO_4$	Mg	SO_4	0.55	0.01	0.88	0.001
Woods' rose	$MgSO_4$	Ca	SO_4	0.69	0.001	0.88	0.001
Woods' rose	KCl	Na	Mg	0.28	NS	0.77	0.001
Woods' rose	KCl	Na	Ca	0.05	NS	0.79	0.001
Woods' rose	KCl	Na	Cl	0.30	NS	0.82	0.001
Woods' rose	KCl	Na	SO_4	0.27	NS	0.83	0.001
Woods' rose	KCl	Cl	K	0.79	0.001	0.86	0.001
Woods' rose	KCl	Cl	Mg	0.24	NS	0.97	0.001
Woods' rose	KCl	Cl	Ca	0.54	0.05	0.97	0.001
Woods' rose	KCl	Cl	SO_4	0.09	NS	0.87	0.001
Woods' rose	KCl	K	Mg	0.34	NS	0.87	0.001
Woods' rose	KCl	K	Ca	0.35	NS	0.81	0.001
Woods' rose	KCl	Mg	Ca	0.64	0.01	0.98	0.001
Woods' rose	KCl	Mg	SO_4	0.18	NS	0.92	0.001
Woods' rose	KCl	Ca	SO_4	0.05	NS	0.89	0.001
Woods' rose	$CaCl_2$	Na	Cl	0.88	0.001	0.80	0.001
Woods' rose	$CaCl_2$	Cl	Ca	0.71	0.01	0.09	NS
Woods' rose	$CaCl_2$	Mg	Ca	0.40	NS	0.76	0.001
Woods' rose	$CaCl_2$	Mg	SO_4	0.45	NS	0.73	0.01
Woods' rose	$CaCl_2$	Ca	SO_4	0.54	0.05	0.88	0.001

The concentration of SO_4 in the leaves of oak revealed a strong linear relationship ($r = 0.83$, $p < 0.001$) with leaf weight at harvest (Figure 4), suggesting that higher SO_4 as substantiated by the control treatment would be associated with greater leaf growth. Increasing the SO_4 to Cl ratio in the salt mix led to higher SO_4 content in the leaves, which appears under the conditions of this experiment to be a good indicator of a more favorable ion composition for the growth of oak. In the $MgSO_4$ treatments,oak seedlings with elevated SO_4concentration had higher spad measurements relative to the control (RelativeSpad = 0.48 + 0.20 $\%SO_4$, $r = 0.89$, $p < 0.001$, Figure

4) and broke dormancy sooner (delay = 24.0 -6.65%SO_4, r=0.65, $p < 0.01$, Figure 4). This suggests a lower level of stress on these seedlings as seedlings with 2.5% SO_4 at harvest broke dormancy 10 days sooner than those oak seedlings with only 1% SO_4. No other ions showed a correlation with bud break in oak ($p > 0.05$).

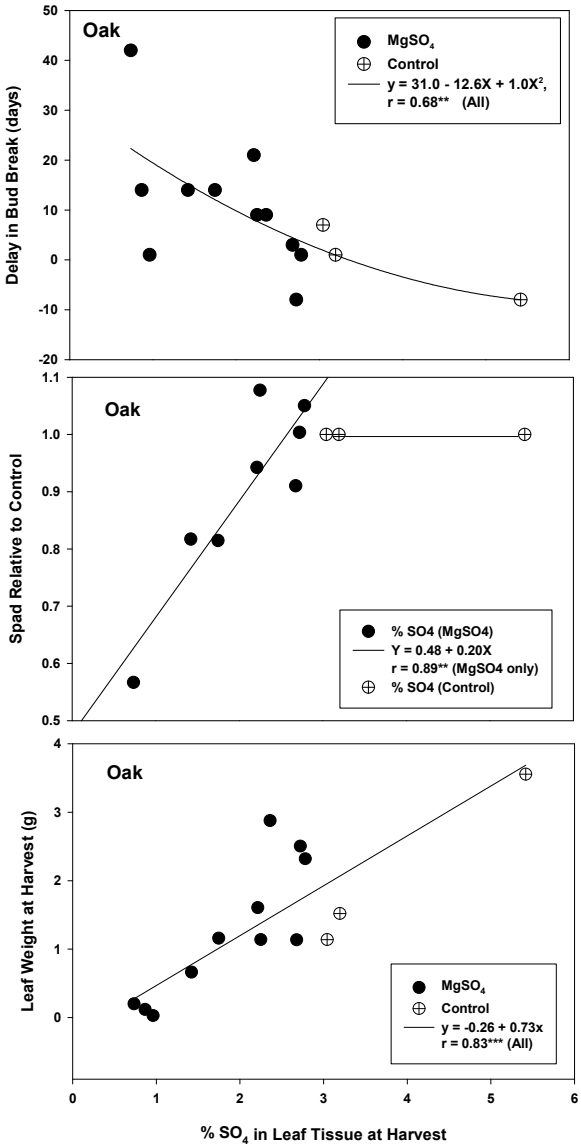

Figure 4. Physiological response of Gambel Oak to $MgSO_4$ treatments. Delay in bud break, spad readings relative to control and leaf weight at harvest as a function of SO_4 concentration in the leaf tissue. Level of significance is denoted by *, ** or *** which refers to p values of < 0.05, < 0.01 and < 0.001 respectively

3.2.2 Woods' Rose

Soil salinity (EC_e) at harvest in the salt treatments of Woods' rose revealed a significant salt type by load rate interaction ($p < 0.001$). Statistical separation occurred at the higher load rates in the KCl and $CaCl_2$ treatments with no separation within $MgSO_4$ treatments at all three load rates. EC_e in the $MgSO_4$ treatments was not significantly different from the NaCl treatments ($MgSO_4$ 11.25, 11.40 and 11.96 dSm^{-1} in the LR1,LR2 and LR3 treatments compared to 10.85, 10.46 and 14.04 dSm^{-1} in the NaClLR1, LR2 and LR3 treatments). No significant relationships existed between soil salinity and plant physiological measurements in Woods' rose ($p > 0.05$).

Tissue ion concentrations in Woods' rose were evaluated at the LR1 level based on ANOVA (Table 7) as seedlings in all three salt treatments ($MgSO_4$, KCl and $CaCl_2$) at this lower loading rate were still alive at the end

of the experiment. The %SO_4 in harvested leaves separated based on salt type ($p < 0.02$) with statistically higher SO_4 concentrations in the leaves of seedlings growing in the $MgSO_4$ treatment (1.57% SO_4) compared to the $CaCl_2$ treatment (1.11% SO_4). Mg concentrations revealed both a salt type ($p < 0.001$) and loading rate ($p = 0.04$) effect. Mg in the leaves of Woods' rose was significantly higher in the $MgSO_4$ (0.47%) and $CaCl_2$ (0.63%) treatments than in the KCl treatments (0.24%) with the 50% NaCl/$MgSO_4$ treatments having a significantly higher Mg concentration (0.57%) than the 90% salt mix (0.33% Mg). Ca concentrations in the leaves of Woods' rose separated based on salt type ($p < 0.001$) with both $MgSO_4$ (2.31% Ca) and $CaCl_2$ (1.87% Ca) separating from the KCl treatment (1.07% Ca). Whereas Kconcentrations separated based on both the salt type ($p = 0.04$)and the salt mix ($p = 0.01$). The K concentration in the leaves of Woods' rose in the $MgSO_4$ treatment (0.78 % K) was significantly lower than the K (1.27%) in the leaves of the $CaCl_2$ treatment, with significant separation between the 90% NaCl/$MgSO_4$ treatment (1.38% K) compared to the 50% treatment (0.74% K).

Table 7. Tissue ion concentrations (%) in Wood's rose at final harvest based on salt treatment and % NaCl in the deicing salt at loading rate 1

Salt	Na (%)	K(%)	Mg(%)	Ca (%)	Cl (%)	SO_4 (%)
$MgSO_4$	0.53^a	0.78^a	0.47^a	2.31^a	2.99^a	1.57^a
KCl	1.73^b	0.95^{ab}	0.24^b	1.07^b	7.06^b	1.28^{ab}
$CaCl_2$	1.41^b	1.27^b	0.63^a	1.87^a	6.78^b	1.11^b
% NaCl						
100	1.57^a	0.52^a	0.69^a	1.94^a	7.75^a	1.05^a
90	1.93^a	1.38^c	0.33^b	1.48^b	5.86^b	1.30^{ab}
75	1.17^b	0.87^b	0.43^{ab}	1.79^{ab}	5.84^b	1.14^a
50	0.57^c	0.74^b	0.57^a	1.97^a	5.11^b	1.52^b
0	0.09^d	0.77^b	0.52^a	2.35^a	0.38^c	2.11^c
Significance						
Salt (S)	< 0.001	0.04	< 0.001	< 0.001	< 0.001	0.02
%NaCl (%)	< 0.001	0.01	0.04	NS	NS	NS
S x %	< 0.001	NS	NS	NS	0.02	NS

Concentrations followed by a different letter are significantly different at the $p < 0.05$ level.

Only in the case of the $MgSO_4$ treatment did we have seedling survival at all loading rates to enable ANOVA based on loading rate and the salt mix (Table 8). Concentrations of Clin the leaves of Woods' rose within the $MgSO_4$ treatment separated statistically at all loading rates (4.18% at LR1, 6.73% at LR2 and 8.98% at LR3). The Cl concentration in the 100% NaCl treatment was statistically higher (8.19% Cl) than both the 75% (6.31% Cl) and the 50% (3.94% Cl) treatments. Concentrations of SO_4in the leaf tissue separated based on both the loading rate ($p = 0.01$) and the salt mix ($p < 0.001$) with statistically higher %SO_4 in the Woods' rose seedlings under the LR1 treatment (1.44% SO_4) compared to the LR2 (1.22% SO_4) and LR3 (1.10% SO_4) treatments. As the percent $MgSO_4$ increased, the SO_4concentration in the tissue also increased across all loading rates (100% NaCl 0.93%, 90% NaCl 1.19%, 75% NaCl 1.31% and 50% NaCl 1.58%) with the 75% and 50% treatments statistically higher than the 100% NaCl. Concentrations of Ca ($p = 0.01$), Mg ($p < 0.001$), K ($p < 0.001$) and Na ($p = 0.03$) all revealed significant interactions between loading rate and salt mix. The highest Kconcentration occurred in the 100% NaCl at all 3 loading rates. Concentrations of Na revealed a 52 - 71% reduction when the 100% NaCl and the 50% NaCl treatment ($MgSO_4$) were contrasted within the 3 loading rates.

Table 8. Tissue ion concentrations (%) at harvest in Wood's rose in the $MgSO_4$ treatment, based on the loading rate and % NaCl in the deicing salt mixture

Loading Rate	Na	K	Mg	Ca	Cl	SO_4
L1	0.79^{a}	0.19^{a}	0.52^{a}	2.22^{a}	4.18^{a}	1.44^{a}
L2	1.86^{b}	0.28^{a}	0.38^{b}	1.05^{b}	6.73^{b}	1.22^{b}
L3	2.32^{c}	0.47^{b}	0.31^{b}	0.72^{b}	8.98^{c}	1.1^{b}
%NaCl						
100	2.09^{a}	1.26^{a}	0.46^{a}	1.27^{a}	8.19^{a}	0.99^{a}
90	1.80^{ab}	0.20^{c}	0.27^{b}	0.98^{a}	7.10^{ab}	1.19^{ab}
75	1.47^{bc}	0.18^{c}	0.47^{a}	1.75^{b}	6.31^{b}	1.31^{b}
50	0.98^{c}	0.27^{c}	0.50^{a}	1.66^{b}	3.94^{c}	1.58^{b}
0	0.09^{d}	0.77^{b}	0.52^{a}	2.35^{c}	0.38^{d}	2.11^{c}
Significance						
Loading Rate (LR)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.01
% NaCl (%)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
LR x %	0.03	< 0.001	< 0.001	0.01	NS	NS

Concentrations followed by different letters are significantly different at the $p < 0.05$ level.

We were able to assess variables influencing the concentration of specific ions in the tissue of Woods' rose by using backward stepwise multiple regression analysis (Table 7). In the $MgSO_4$ treatment, we considered all ions along with the loading rate and the salt mix %. All ions could be modeled when a combination of these variables was considered. Seventy eight % of the variability in the concentration of Na (↑) could be described by knowing the concentration of Ca (↓) and the concentration of Cl (↑), ($Na = 1.39 – 0.54Ca + 0.15Cl$, $r^2 = 0.78$, $p < 0.001$) and 78 % of the variability could also be described for the concentration of Ca, with %Ca increasing as the %Na decreased and the %Mg increased (% $Ca = 1.14 - 0.46\%\ Na + 2.37\%\ Mg$, $r^2 = 0.78$, $p < 0.001$). Only in the case of % SO_4 was the sodium chloride % included in the regression equation and only in the case of % Cl and % K was the loading rate included.

In Table 6 we report for Woods' rose the simple linear correlations between ions based on concentration and total ion accumulation. As was reported for oak, total ion accumulation in the leaves (mg) had higher correlations than those based on % (21 out of 24 comparisons), reflecting the impact of unsynchronized shifts in leaf biomass and ion accumulation on tissue ion concentrations and subsequent correlations. The concentration of SO_4 in the soil extract was the only ion to correlate with its tissue ion concentration ($\%SO_4 = 0.96 + 0.01\ SO_{4\ soil}$, $r = 0.45$, $p < 0.001$, all data). However, these higher tissue SO_4 concentrations were still below the concentration found in 2 out of the 3 control plants. As the %Na in the leaves of Woods' rose increased, %Cl increased in a curvilinear fashion ($\%Cl = 0.89 + 7.21\%Na – 1.77(\%Na)^2$, $r = 0.77$, $p < 0.001$, all data) with significantly lower %Cl in the leaf tissue of $MgSO_4$ treatment plants. As the SO_4 percentage in the salt mix increased with the addition of $MgSO_4$ to the NaCl, the $\%SO_4$ replacing %Cl in the leaves of Woods' rose increased ($\%SO_4 = 1.79 – 0.08\%Cl$, $r = 0.58$, $p < 0.001$, all data).

The physiological response of Woods' rose to the salt mixes was evaluated by assessing leaf weight at harvest, leaf spad measurements (chlorophyll assessment), and delay in bud break. Higher leaf weight at harvest was associated with lower loading rates (LR1, LR2 and LR3), higher $\%SO_4$ and lower %K in the tissue (Leaf weight $= 1.86 + 0.99\%SO_4 – 0.51\%K – 0.38Load$, $r^2 = 0.50$, $p < 0.001$). Within the MgSO4 treatment, $\%SO_4$ in the leaves was highly correlated with the leaf weight at harvest ($r = 0.73$, $p < 0.001$) (Figure 5). Spad readings relative to the control decreased as the %Na in the leaves increased when all treatments were considered together (Figure 5, Relative Spad = 0.98 -0.23%Na, $r = 0.75$, $p < 0.001$). The amount of the variation that could be accounted for increased slightly when multiple regression analysis included the K concentration (Spad = 0.93 +

0.06%K – 0.24%Na, $r^2 = 0.63$, $p < 0.001$). Spadreadings also showed significant separation (ANOVA) based on loading rates within the $MgSO_4$ treatment (LR1; 0.86 spad relative to control vs. LR3; 0.53 spad relative to control). When all data were combined, the correlations with bud break were poor, but when bud break in the $MgSO_4$ treatment was plotted against the Ca concentration in the leaves of Woods rose at harvest, a significant decline in the delay occurred associated with higher Ca levels in the leaves (Figure 5, Delay = 49.8 -18.2%Ca, $r = 0.73$, $p < 0.001$).

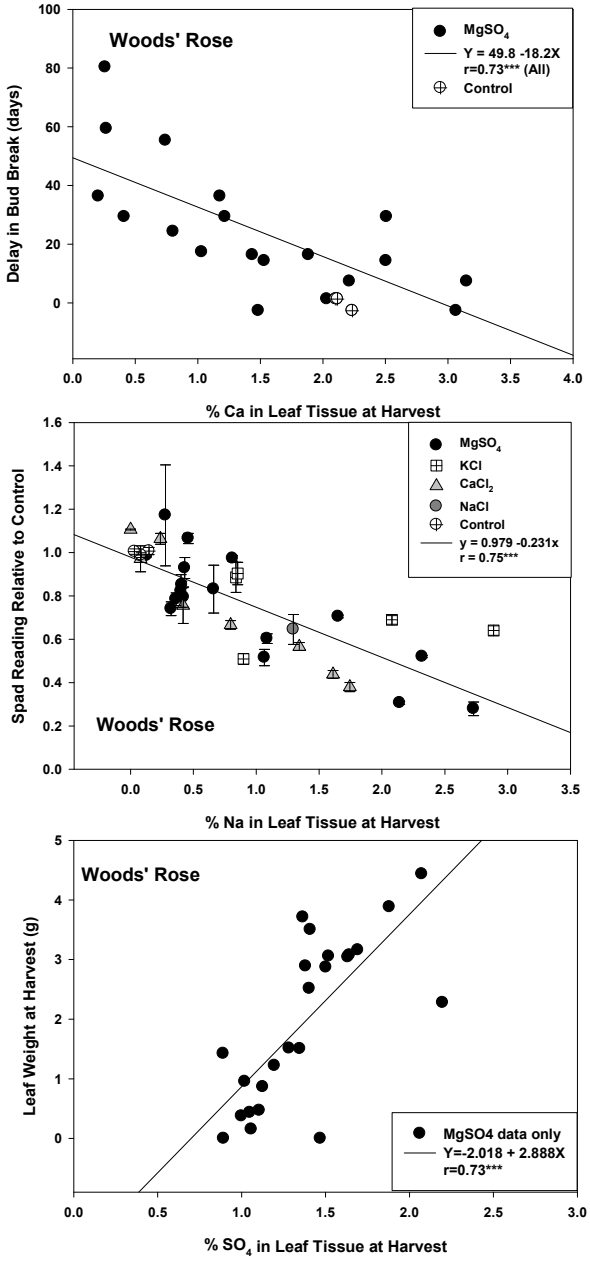

Figure 5. Physiological response of Woods' Rose to various salt treatments. Delay in bud break, spad readings relative to control and leaf weight at harvest as a function of different cations in the leaf tissue. Level of significance is denoted by *, ** or *** which refers to p values of < 0.05, < 0.01 and < 0.001 respectively

4. Discussion and Conclusions

The surfaces of mountain roadsarecatchment areas for rain water. The water in essence is "harvested" and redirected to smaller areas at down gradient locations. For example, if 2.5 cm of precipitation fell on 152 m of downward sloping road surface that was 7.9 m in width and all of the runoff found its way into a 152 m^2 runoff area, this would equate to a depth of 19.75 cm of water in addition to the 2.5 cm that would have fallen directly on the area. Thus, the runoff area would have received approximately 9 times the amount of water as the non-runoff areas, significantly altering the water balance at these locations on the mountain. Unfortunately, these waters also bring displaced deicing salts. Although areas adjacent to roads would have first contact with salts, infiltration in the larger runoff areas may not be uniform as areas adjacent to the road would have smaller opportunity timesfor water infiltration and the displacement of salts downward. Much of the water would quickly travel to lower depressions at a greater distance from the road. Results showing elevated salt levels at 1 m from the road compared to 5 and 10 m from the road reflect this scenario. These higher salts contribute to a less favorable environment for seedling establishment, which may have contributed to the lack of vegetation at these 1 m sites in our study (we also recognize that road work may also have contributed). In addition, most of the soils at our mountain locations were rocky in nature, and this may havefacilitated macro pore by-pass opportunities under saturated flow conditions (Devitt et al., 2002) thatwould most likely occur after each large snow melt event.Such by-pass could lead to the possibility of numerous salt plumes occurring on the mountain.

Over 200 tons of predominantly NaCl are distributed over each of the 3 state highways on Mt. Charleston each year (NDOT, personal communication). If such an approach is taken for the next 50 years, 10,000 tons of additional salts would be applied. These salts must go somewhere,as only minimal amounts of salts at the 5 and 10 m distances were observed. We believe these salts have already entered into deep downward displacement toward groundwater sources.In the case of Mt Charleston, these sources of watereventually recharge the Las Vegas valley floor aquifer (Devitt et al., 2002). Assessment of the groundwater chemistry in the mountain block recharge system should be evaluated. The Cary Institute of Ecological Studies (Kelly et al., 2010) reports that there can be a legacy effect of deicing salts in groundwater systems that can take decades before steady salt concentrations are reached. We measured saturation extract soil salinity (EC_e) as high as 37 dSm^{-1}at a 1 m location, which adjusted to field-based soil moisture content, would exceed salinity levels in seawater (54 dSm^{-1}). Such salt levels observed in the pristine montane forests in this study were directly linked to the deicing salt applications as significant correlations between elevated leaf tissue Na and Cl concentrations were noted in a number of species.

Deicing salts comprised of primarily NaCl impose both a general salt effect and a specific ion effect on plants. Mixing salts, as was tested in the greenhouse study, would not lead directly to a reduced overall salt load, but it would lead to more favorable ionic ratios in the soil solutionas both the percentage of Na and Cl ions wouldbe reduced with the counter balance of other cations and anions such as Mg and SO_4. We pursued this line of reasoning in the second phase of the study by investigating different deicing salt compositions and loading rates. We selected the mixing approach because the ratios would be assured at the time of application. Thus, wherever the water salt displacement occurred, the ratios would be maintained up to the point of infiltration. Others have suggested the application and incorporation of products such as gypsum to areas adjacent to roads (Douglas, 2009; Johnson & Sucoff, 1999), but due to its low solubility and required knowledge of proper placement and incorporation, it is questionable whether more favorable ionic ratios would be maintained over the time of displacement.This approach would also represent additional salts, not a substitution of salts. It should also be noted that $MgCl_2$ is oftenused by manystate transportation departments as part of their deicing strategy (Lewis, 1999; Shi et al., 2009). However, we have previously reported on high foliar damage when such salts are sprayed directly onto leaves, which may be related to its low point of deliquescence (Devitt et al., 2005).We recognize that additional work would be needed to determine how mixing other salts with NaCl would alter deicing capabilities compared to pure NaCl and how this would alter cost (price of salt, transportation, storage, mixing, caking).

Only at the lowest loading rate (half the current loading rate on the mountain) were we able to observe more favorable responses in seedlings of both oak and Woods' rose, and only in the $MgSO_4$ mixes did we observe more favorable responses at all three loading rates in Woods' rose. We must also acknowledge the distinct differences between the field study and the greenhouse study if we are going to understand the significance of the results: (1) mature trees and shrubs were monitored on the mountain whereas 2 year old seedlings were monitored in the greenhouse study, (2) salt was applied to the entire confined root system of the seedlings in the greenhouse study whereas an unknown root exposure to salinity occurred in the field, (3) water balance in the greenhouse was based on historical mountain precipitation records whereas water balances in the mountain

locations sampled would have reflected degrees of rain water harvesting, (4) mountain soils were extremely rocky whereas the soil obtained from NDOT for the greenhouse study was screened to remove rocks greater than 2.5 cm in diameter and mixed with soil from the 3.8 L nursery containers (seedlings) provided by the State Division of forestry.Even with these caveats, we believe that results from the greenhouse experiment have relevance to the field. In particular, seedling damage would be high under the current deicing salt loading rates on the mountain, especially at areas close to the road. Plantresponse would be species dependent (Lumis et al., 1976; Townsend & Kwolek, 1987) with Woods rose demonstrating greater tolerance than Gambel oak which demonstrated greater tolerance than aspen. In both oak and Woods' rose, decreased leaf weight, delay in bud break (Roth & Wall, 1976) and a decline in leaf level spad measurements were observed as levels of stress increased, suggesting that such parameters would be worthy to monitor in the field. Only in the case of Woods' rose could we make a direct comparison of the results from the greenhouse and field studies. Results were similar, with Cl increasing in the leaf tissue as Na accumulation increased, with a distinction that Ca accumulation decreased in the leaves of plants grown in the greenhouse whereas Mg decreased in the leaves of plants sampled in the field. This difference in Ca and Mg was related to the presence of elevated Mg in the greenhouse experiment with the added $MgSO_4$. However, in the field higher SO_4 concentrations (3.59%) in the leaves of Woods rose were associated with leaves revealing visual damage while in the greenhouse experiment higher concentrations of SO_4 were associated with plants at the lowest loading rate (control 2.11%) and at the highest $MgSO_4$ substitution rate (1.58%) revealing greater growth, higher leaf chlorophyll status and earlier breaking of dormancy. The higher sulfate concentrationsin damaged leaves from the field could not be described by ion interaction (regression analysis) but simply by the presence of chlorosis and necrosis. No other species revealed statistical separation in SO_4 concentrations in the field based on visual damage. Additional research will be needed to fully understand these differences.

We conclude that more research is needed to assess and increase the efficacy of alternative deicing salt approaches. Based on the ANOVA results reported in Table 8 , we believe a 25% substitution of $MgSO_4$ would be worthy of further field evaluations as a significant decline in leaf tissue Na and Cl occurred at this level along with an increase in concentrations of Ca and SO_4. Greater precision is also needed in the application of deicing salts that is based on timing, location, and loading rates. Finally, increased monitoring is needed to assess the current health of forest ecosystems and water resources in areas where deicing salts are applied. Future research must also address the linkage in water quality between mountain and valley systems.

Acknowledgements

We wish to thank the Nevada Division of Lands for financial support of this research project, and the cooperation of the Nevada Department of Transportation at both the State and Clark County office.

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